POWER GENERATION FROM GEOTHERMAL RESOURCES: CHALLENGES AND OPPORTUNITIES

by

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B.S., Chemical Engineering
National Technical University of Athens, 1997

Submitted to the Department of Civil and Environmental Engineering and
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in Partial Fulfillment of the Requirements for the Degrees of

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ABSTRACT

As we enter the 21st century, increasing concerns about global warming have stimulated an upsurge of interest in the use of non-fossil energy technologies for electricity production. As a result there is an opportunity for expansion of geothermal resource development. This thesis examines power generation technology for two distinct categories of geothermal resources: Hydrothermal and Hot Dry Rock (HDR).

The thesis assesses growth opportunities for, and challenges to, the full deployment of geothermal power systems in the electricity market. It analyzes the key impediments that have and will affect the attractiveness of geothermal technologies, describes policy measures that can be adopted to overcome these impediments, and draws conclusions and recommendations for R&D on geothermal systems.

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The future is not some place we are going to, but one we are creating.

-John Schaar, Futurist

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Chapter 1

Thesis Objective and Overview

Objective

The development of geothermal resources can be divided into three periods: from 1950's to 1970's, from 1970's to mid-80's, and from mid-80's till today. The first period is characterized by the introduction of geothermal energy into electricity markets as countries like Italy, the US, New Zealand, and Mexico started commercial power production from geothermal plants. During the second period, the world installed geothermal capacity grew substantially, mainly due to the oil crises of 1973 and 1979. During the third period, the collapse of oil prices and the rapid deployment of high-efficiency, low-cost natural-gas-fired combined cycle systems resulted in a slowdown in the growth of geothermal energy capacity.

As we enter the 21st century, increasing concerns about global warming have stimulated an upsurge of interest in the use of non-fossil energy technologies for electricity production. As a result there is an opportunity for expansion of geothermal resource development. This thesis examines power generation technology for two distinct categories of geothermal resources: Hydrothermal and Hot Dry Rock (HDR). The objective of this thesis is to answer the following questions:

(1) What are the major impediments to the development and deployment of hydrothermal resources and HDR?

(2) What actions should be taken to overcome these impediments?

Overview

The thesis consists of eight chapters: Chapter 1 states the thesis objective. Chapter 2 introduces the concept of geothermal energy and outlines the different types of geothermal resources. Chapter 3 presents a historical overview on the uses of geothermal energy, and then discusses the current status of the geothermal power industry worldwide. Chapter 4 evaluates the contributions of geothermal systems to CO_2 emission reductions and to environmental quality in general. Chapter 5 describes the characteristics of geothermal power systems and examines their potential for technological advances that would result from enhanced research and development (R&D). Chapter 6 assesses the economics of electricity generation from hydrothermal and hot dry rock, and details the capital, operating, and maintenance costs of geothermal power systems. Chapter 7 discusses the strategic plan of the Geothermal Energy Program of the U.S. Department of Energy, with particular emphasis on the components of the plan pertaining to Enhanced Geothermal Systems (EGS). Chapter 8 synthesizes the thesis' findings and provides conclusions and recommendations.

Chapter 2

Geothermal Resources

2.1 Geothermal energy

Geothermal energy is thermal energy emanating from the earth's interior. It is generated in part from the decay of radioactive elements, such as potassium, uranium and thorium, which takes place in the earth's crust and mantle (Armstead, 1983; Brower, 1992; Kappelmeyer, 1982). The heat is transferred from the mantle to the earth's crust mostly by conduction, but also by convective flow of circulating fluids and by mass transfer of hot magma. The rate at which temperature increases with depth is expressed as degrees per unit of depth and is called temperature or geothermal gradient.

For non-volcanic areas the average temperature gradient of the earth is about 20°C/km to 30°C/km (Shepherd W. and Shepherd D. W, 1997). However, some geographical regions due to tectonic and volcanic activity have much higher gradients.

High-grade regions are usually near continental plate boundaries such as the western part of North America, Central America, the Caribbean Archipelago, the western belt of South America, Alaska, New Zealand, Indonesia, Philippines, Japan, the Chinese coastal regions, the areas of the Mediterranean coast, Central Europe, Iceland, Kenya, and Ethiopia (Figure 2.1). High-grade areas can have average gradients in excess of 80°C/km and are potential sources for competitive energy production in today's energy markets.

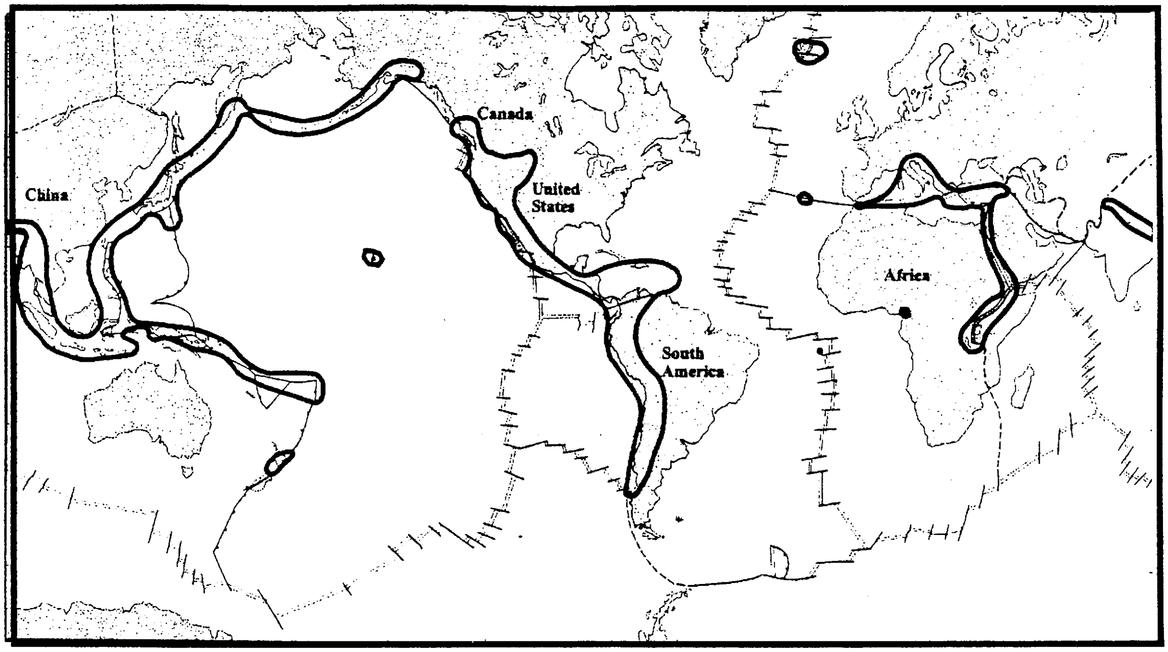

Figure 2.1 High-grade geothermal regions of the world
(The regions enclosed by dark black lines show the high-grade geothermal regions of the world. The zigzag lines indicate tectonic boundaries)

Source: Energy & Geoscience Institute at the University of Utah (1998).

Types of Geothermal Resources

The term "Geothermal Resources" includes a rich diversity of energy resources that may be classified into four categories with respect to their geological, chemical, thermodynamic and hydrological characteristics: hydrothermal resources, hot dry rock (HDR), geopressured resources, and magma. A more detailed description of each type of geothermal resources is given in the following sections of this chapter. However, the focus of this thesis is on power generation from hydrothermal resources and hot dry rock, and therefore, the other types of geothermal resources will be outlined only briefly.

Figure 2.2 shows the different types of geothermal resources versus their natural permeability. Hydrothermal resources are inherently permeable. This means that fluids can flow from one part of the reservoir to other parts with low pressure drops or gradients. Typically, hydrothermal systems convey heat energy to the earth's surface through producing steam or hot water from wells that penetrate into the reservoir. On the other hand, HDR resources are impermeable rock formations or have very low permeability. Thus, they are incapable of yielding a high fluid output without artificial stimulation. The permeability levels of geopressured resources range from low to medium. Magma has high or low permeability depending on whether it is in the form of molten rock or in the form of solidified mass respectively.

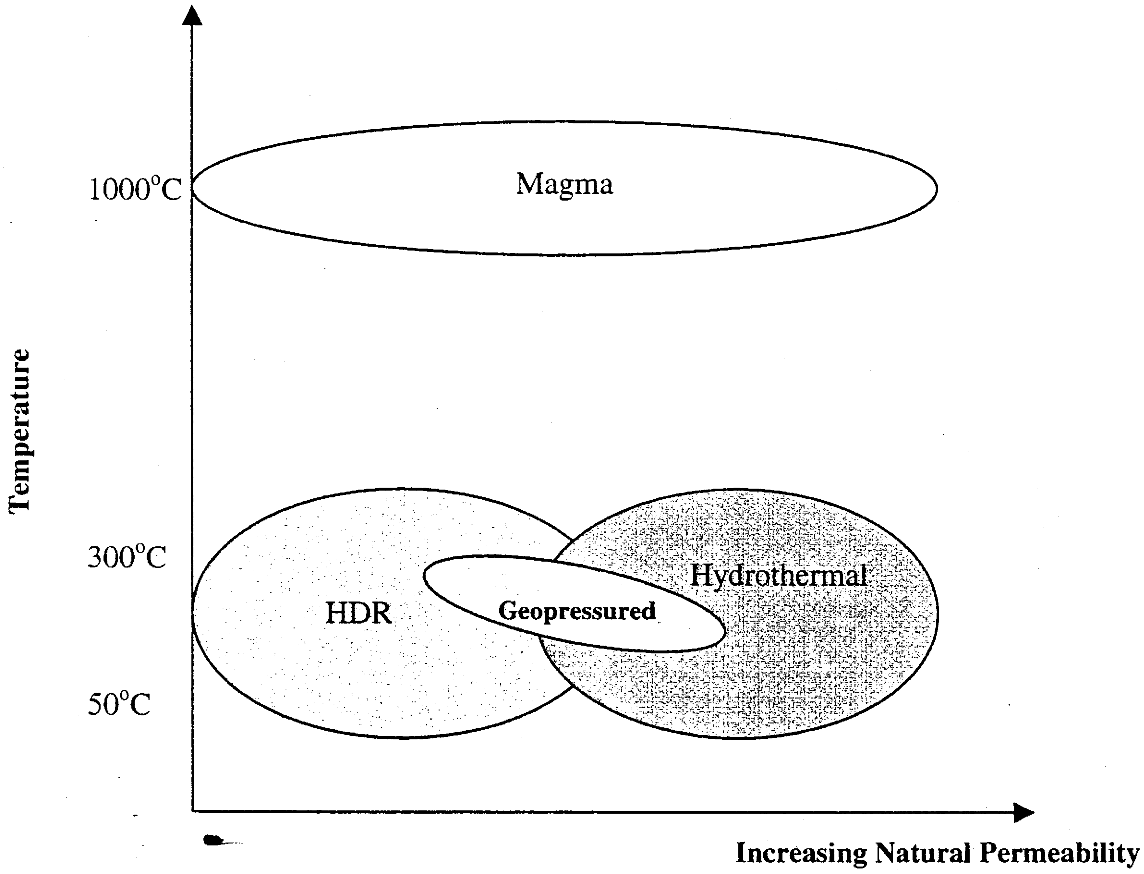

Figure 2.2 Geothermal Resources vs. Permeability

Another difference among geothermal resources is the amount of natural fluids they contain. Figure 2.3 shows the different types of geothermal resources in respect to the existence of natural fluids. Hydrothermal resources are fluid efficient, whereas HDR contains very little *in situ* fluids. The intersecting region between HDR and hydrothermal resources is called Hot Wet Rocks (HWR). They contain geofluids that are not sufficient for commercial exploitation. Generally, geopressured resources consist of large amounts aqueous brines saturated with methane in contrast to magma resources, which because of their high temperatures, do not contain any natural aqueous fluids.

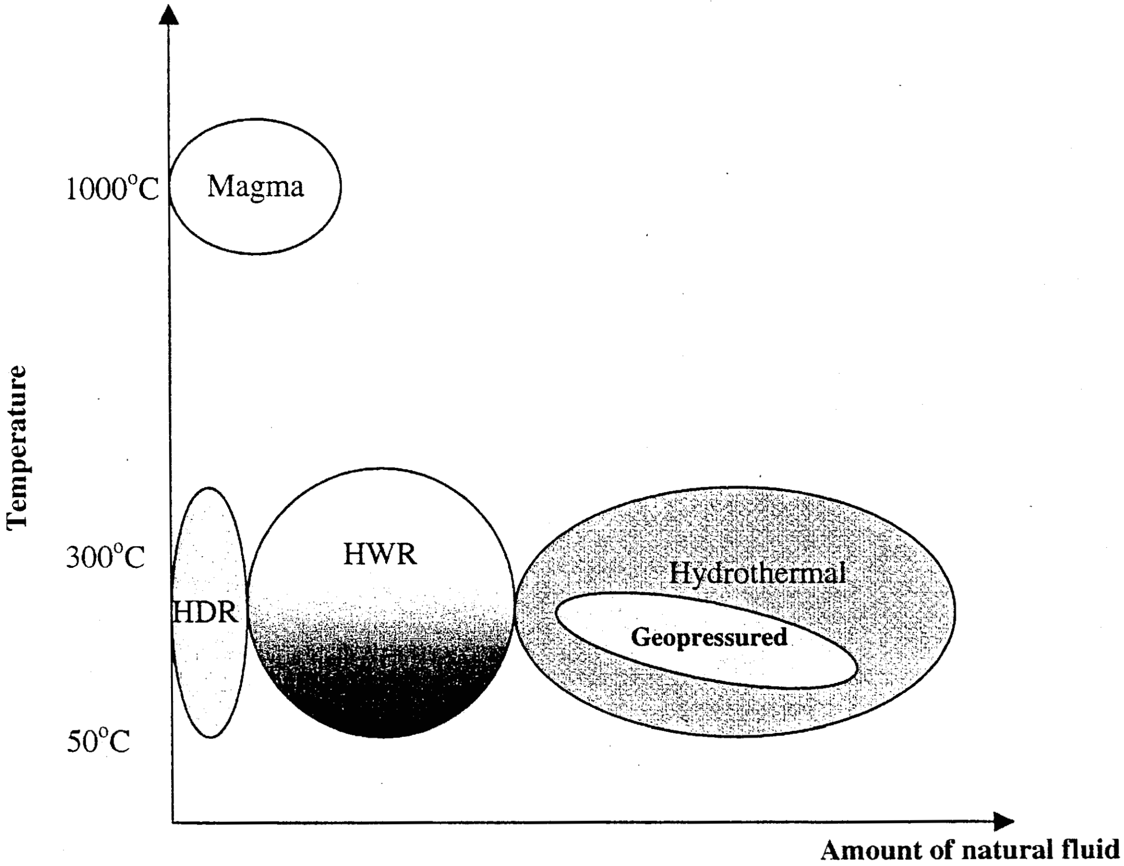

Figure 2.3 Geothermal Resources vs. amount of natural fluids

2.2 Hydrothermal resources

Hydrothermal resources consist of naturally occurring hot steam or hot water that is trapped inside permeable formations. Such resources are found at depths of approximately 0.1 km - 4.5 km below the earth's surface (IEA, 1987). This form of energy is the only geothermal resource commercially employed at the present time. High temperature hydrothermal resources are used to generate electricity, whereas low to moderate temperature hydrothermal resources have a variety of direct-heat applications such as space heating, greenhouse heating, vegetable drying, pulp and paper processing, timber drying, fish farming, etc.

Hydrothermal resources are divided into two categories (Figure 2.4) according to the predominant heat transportation medium, vapor-dominated and liquid-dominated resources (Chilingar *et al*, 1982; Muffler and White, 1975).

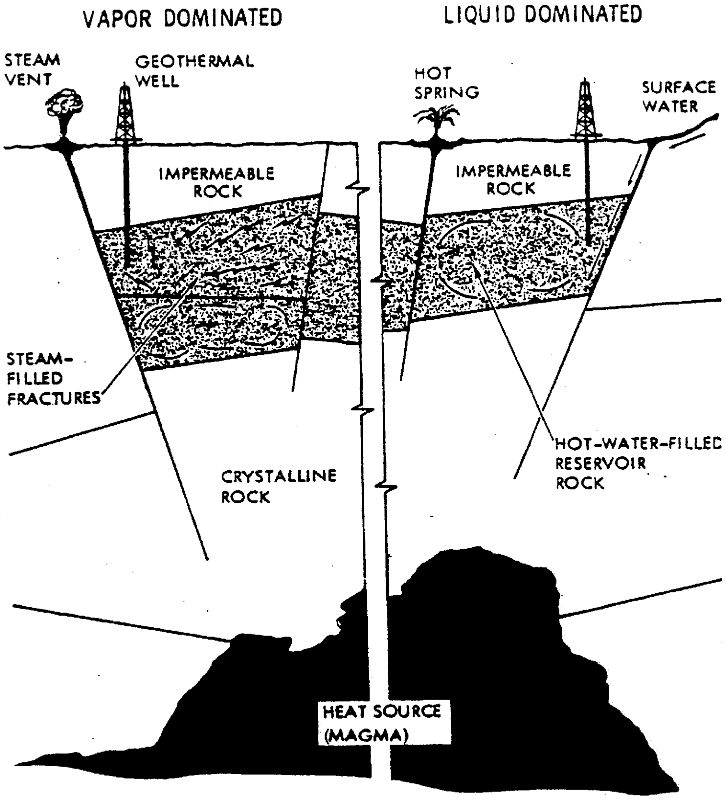

Figure 2.4 Hydrothermal resources Source: Leibowitz (1978)

Vapor-dominated hydrothermal resources produce saturated to slightly superheated steam at temperatures from 250°C to 320°C containing little or no aqueous salts and only small amounts of particulate matter and non-condensable gases, such as carbon dioxide and hydrogen sulfide.

Vapor-dominated systems are of superior quality for electricity production because they usually cause little corrosion problems due to their low salinity, and because the steam can be expanded directly in turbines to generate power. Only very few vapor dominated systems have been discovered in the world. The best known are the Larderello field in Italy and The Geysers region in the USA.

Liquid-dominated hydrothermal resources contain liquid water or brine solutions of various concentrations and are much more abundant than vapor-dominated reservoirs. Their temperatures range from 90°C to 360°C and are categorized by the USGS (1970) as low (less than 90°C), moderate (90-150°C), and high temperature (greater than 150°C).

Scientists believe that hydrothermal systems that may become depleted of naturally occurring fluid or steam in the future may be treated as hot dry rock systems from which the heat can be recovered by artificial water injection (Cappetti, 1998; Duchane, 1996).

2.3 Hot Dry Rock

The greatest portion of the earth's heat is stored in the rock mass itself rather than in indigenous geofluids. This rock mass is located from 2 to 10 km below the Earth's surface where temperatures are between 150°C and 650°C (IEA, 1987). This resource is known as Hot Dry Rock (HDR). Although the temperature of HDR is sufficiently high to raise steam for electricity production, thermal energy is not easily recovered because the rock has low natural permeability and low porosity as it contains very little *in situ* fluid.

Some like to use the term "Hot Wet Rock" to describe formations with low permeability containing geofluids that are not sufficient for commercial exploitation. In this thesis, we apply the term HDR for both dry and wet formations.

The main difference between heat extraction from hydrothermal resources and hot dry rock is that, in the former, we harvest the heat contained in the vapor or steam, whereas in the latter, we harvest the heat contained in the rock mass. Hot Dry Rock resources may be classified according to their geothermal gradient as low ($\nabla T \cong 30^{o}C/km$), mid ($\nabla T \cong 50^{o}C\ /km$), and high ($\nabla T \cong 80^{o}C\ /km$) grade (Tester and Herzog, 1991). HDR geothermal energy is believed to constitute the largest geothermal resource base and to have ubiquitous distribution. The challenge is to develop a technology that will enable us to extract this energy in an economically feasible way.

In 1970, scientists in Los Alamos National Laboratory in the U.S. developed the concept of “heat mining” for low permeability formations (Figure 2.5): Heat stored in hot dry rock can be extracted by introducing water into the rock from an injection well, circulate it through an artificially created heat exchange system in the rock, and bring it back to the surface through a production well.

A heat exchange system is a network of hydraulically-connected fissures in the rock that can be activated or formed by hydraulic or explosive fracturing. Hot rocks that contain open natural fractures are good candidates to be used for heat mining. Usually, however, these natural cracks are tightly sealed from deposition of minerals. In this case, activation or stimulation is required to reopen them. On the other hand, if the rock is totally competent, then artificial cracks must be created (Armstead and Tester, 1987).

Although thirty years have passed since the initial development of heat mining and thermal energy extraction from HDR resources has been demonstrated, the resource has yet to be commercially exploited. This thesis examines the major barriers to the development of hot dry rock and how to overcome them.

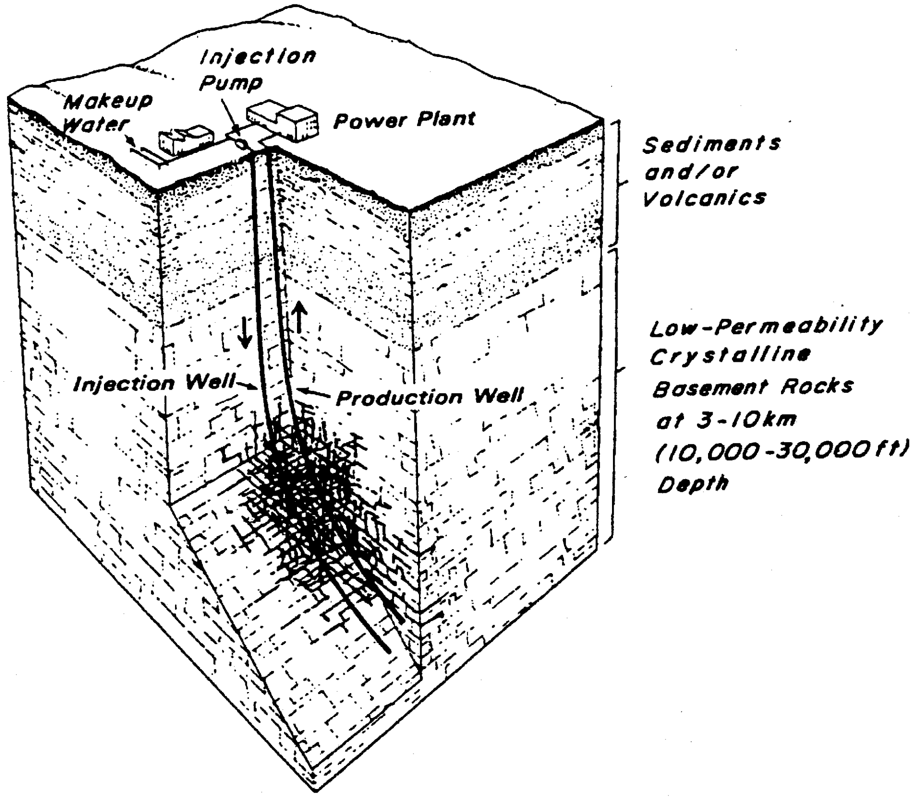

Figure 2.5 The concept of HDR "heat mining" Source: Tester, Brown, and Potter (1989)

The first experiments to prove the scientific feasibility of heat mining from HDR were conducted at Fenton Hill, New Mexico, in the USA. The Los Alamos National Laboratory under the sponsorship of the US Department of Energy used the site for research on Hot Dry Rock from 1974 to 1995.

The research efforts at Fenton Hill started with the development of the "Phase I" or "Research" HDR System. The experiments showed that the reservoir underwent a very rapid thermal degradation. For this reason, a deeper, larger and hotter reservoir was constructed named "Phase II" or "Engineered" HDR System.

The "Phase II" HDR system demonstrated the viability of tapping geothermal energy from HDR reservoirs. It also revealed that the key problem in achieving reservoir productivities comparable to commercial hydrothermal systems is lowering flow impedance which results from the low permeability of HDR formations as we have already discussed in previous sections of this chapter.

The first long-term flow test in a HDR geothermal reservoir was carried out for more than 3 years at the Rosemanowes in Cornwall, England, from 1985 to 1988. The British project succeed in advancing the scientific understanding of heat mining, but the temperature of the reservoir was not high enough to allow for commercial exploitation of the HDR resource (Duchane, 1998).

Currently, three HDR geothermal fields are operating on an experimental basis at Soultz-sous-Forêts in France, Ogachi and Hijiori in Japan (Duchane, 1998; Baugärtner *et al., 1998;* NEDO 1997). Both Japanese projects have encountered significant problems with low recovery of the injected water, which ranges from 25% to 50%. These problems are being investigated.

The HDR experimental site at Soultz is operating under the auspices of the European Commission as a European collaborative program between France, Germany, Great Britain, Italy and Switzerland. The project is coordinated by a team of three senior researchers who are established permanently at the site (Garnish *et al*, 1994).

In 1997, after a decade of efforts, a four-month forced circulation test proved that it is possible to maintain fluid circulation without water losses and almost no drawdown (Baumgärtner *et al.*, 1998). An industrial consortium has been founded by Electricité de Strasbourg (France) and Pfalzwerke (Germany) to oversee the future industrial development of the site. Other potential partners, including ENEL (Italy), EDF (France), and RWE (Germany), retain an option to join at a later stage. Recently, the existing wells were deepened to a depth of 5 km. The future goals of the European HDR program are evaluating the geological conditions at this depth and examining the feasibility of a five megawatt pilot plant for the generation of electricity from the Soultz HDR site.

In Australia, Hot Rock Energy Pty Ltd, a consortium of private companies, is currently planning to develop a commercial HDR system at the Hunter Valley of New South Wales, which could supply 20% of Australia's electricity needs for 50 years (Hot Rock Energy Pty Ltd, 1997).

2.4 Geopressured resources

Geopressured resources are hot brine deposits containing dissolved methane captured between sedimentary strata under very high pressure at depths of 3 km to 6 km. Temperatures range from 130°C to 260°C (IEA, 1987; Brower 1992).

U.S.DOE's geopressured-geothermal R&D activities have resulted in the identification of geopressured systems in the Northern Gulf of Mexico in Texas, Louisiana, and Mississippi. In addition, the R&D program demonstrated the feasibility of adapting oil & gas well equipment and drilling technology to the production of geopressured brines. Although the basic technology exists to tap these hot brines, the resource will be an attractive source of energy only if it becomes cost-effective to capture simultaneously the thermal energy from the hot fluids, the mechanical energy from the high pressures involved, and the chemical energy from burning the recovered methane (Tester, 1982).

2.5 Magma

Magma, the top layer of the earth's mantle, consists of hot molten rock. It can reach temperatures from 650°C to 1200°C. It is usually found at depths greater than 35 km below the surface of the earth. Thus, extracting thermal energy from magma is the most difficult for all resource types. In some geographical areas, due to tectonic and volcanic activity, molten magma has thrust upward to form magma bodies near the earth's surface and can be found at accessible depths from near the surface (active volcanoes) to about ten kilometers. Because of the extremely high temperatures, however, current drilling methods cannot be used effectively for this type of resource.

In 1998, scientists at Sandia National Laboratories resumed exploratory drilling activities at the Long Valley caldera in California in order to locate magma (molten rock) deep under the mountain terrain. Once the location of the magma is identified, the well will serve as a downhole observatory for testing prototype devices, equipment, and materials for exchanging heat with magma.

The project had originally started in 1989 as part of the DOE Magma Energy Program but was canceled in 1990. DOE funded the second phase of the project in 1991, but again drilling operations were curtailed due to lack of funding. This is the third phase of the project and is funded by the California Energy Commission, US Geological Survey, DOE, and the International Continental Drilling Program (ICDP) (SNL, 1998).

2.6 Resource base estimates

Armstead and Tester (1987) evaluated resource bases for non-renewable and renewable resources (Figure 2.6 and Figure 2.7). They defined resource base as "the total quantity of any energy commodity that is believed to exist in all the world--identified, inferred and undiscovered but suspected of probably existing-- and which may become technically recoverable within the foreseeable future regardless cost." The authors argue, however, that the degree of uncertainty in these numbers is high, and they can only be used to provide a rough prediction of the magnitude of each resource type.

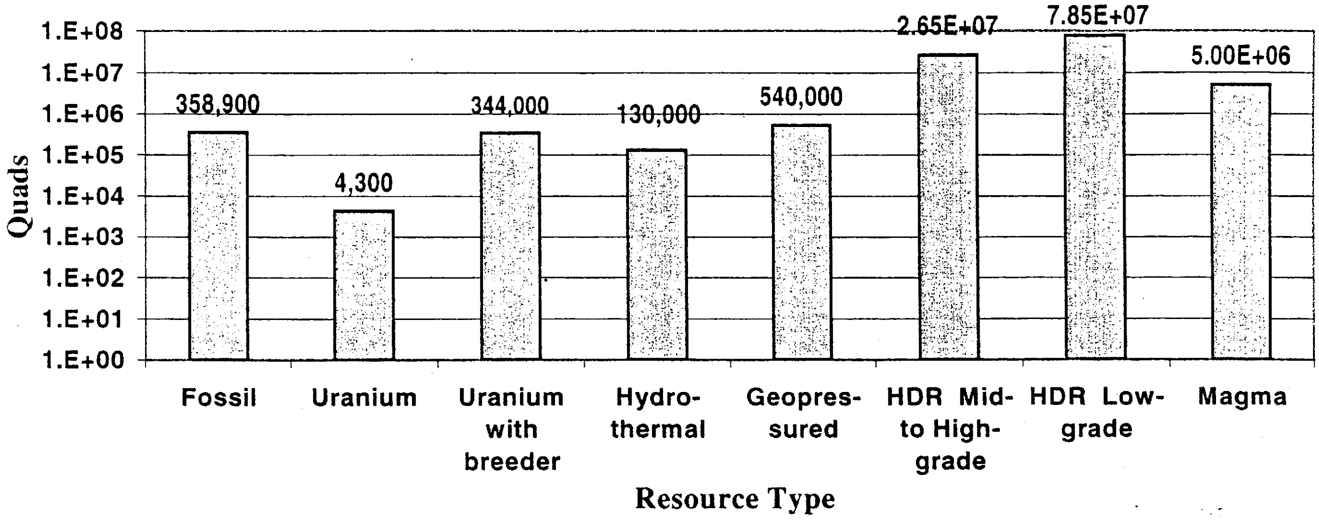

Figure 2.6 Worldwide resource base estimates for non-renewable resources.

1. **Geopressured resource base estimate includes hydraulic and methane energy content**
2. **Magma to depths of 10 km and initial rock temperatures > 650°C**
3. **HDR to depths of 10 km and initial rock temperatures > 85°C**
4. **Low-grade: ∇T < 40°C/km**
5. **Mid- to High-grade: ∇T > 50°C/km**

Source: Armstead and Tester (1987)

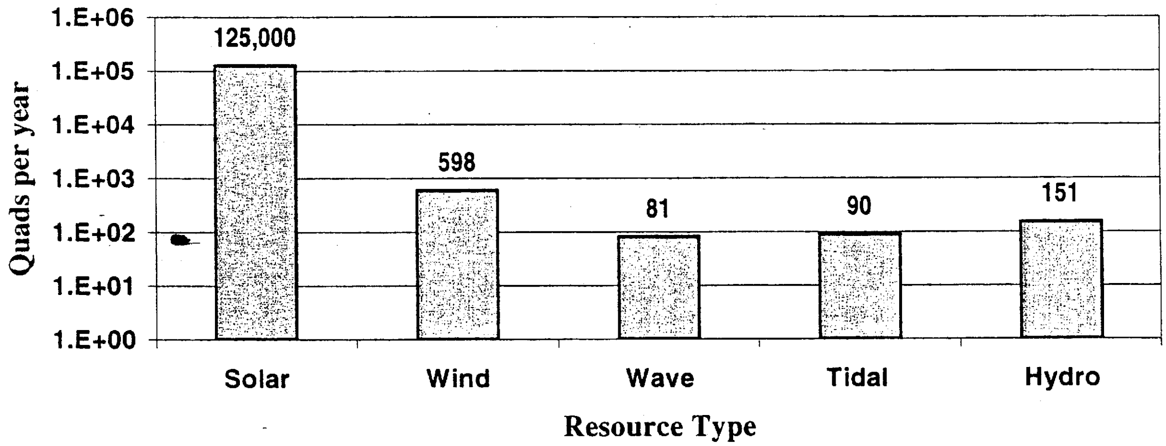

Figure 2.7 Worldwide resource base estimates for renewable resources.

Source: Armstead and Tester (1987)

Solar and wind are the largest renewable resources. However, they have an intermittent nature, i.e. they can produce energy when the wind is blowing and the sun is shining, respectively. Thus, solar and wind technologies should be connected with storage systems so that they can operate during periods of no or low wind and when the sun is obscured. Hydropower is the leading renewable resource of continuous nature, but it adversely impacts fish and plant ecosystems as well as the quality of water, spurring environmental concerns and generating resistance to a further expansion of the exploitation of this resource.

Regarding non-renewable resources, geothermal is by far the largest one. Although limited to a few geographic regions in the world, the estimated hydrothermal resource base is still large at about 130,000 quads. To date only high-grade hydrothermal resources have found commercial applications. Geopressured resources and magma have a substantial resource base, however, at this time, technology has not advanced to the point where they can be cost effectively exploited. Furthermore, their geographic occurrence is limited. In contrast, HDR has a ubiquitous distribution, and a resource base of over 100 million quads which is many orders of magnitude greater than fossils and uranium together. It is clear, that the widespread application of geothermal energy, will probably be determined by the enhancement of HDR systems. Considering that the current world annual energy consumption is now about 350 quads and is expected to reach 612 quads in 2020 (EIA,1999) geothermal resources and especially HDR can play a major role in satisfying the increasing energy demands of our planet for a substantial period of time.

Chapter 3

The Status of Geothermal Power Industry in the World

3.1 Historical Overview

Archeological findings show that geothermal heat from natural sources was exploited for cooking of food, thermal bathing, therapeutic and recreational purposes and other direct uses for many centuries in countries such as Italy, Greece, China, Japan, and India (Armstead, 1983; Cataldi and Chiellini, 1995; Chandrasekharam, 1995; Wang, 1995; Sekioka, 1995).

In contemporary times, geothermal energy is used for both electricity production and for domestic and industrial direct heat applications. The key parameter that determines the preferred use of a geothermal resource is its temperature. Figure 3.1 shows typical utilization temperatures for a variety of applications of geothermal energy.

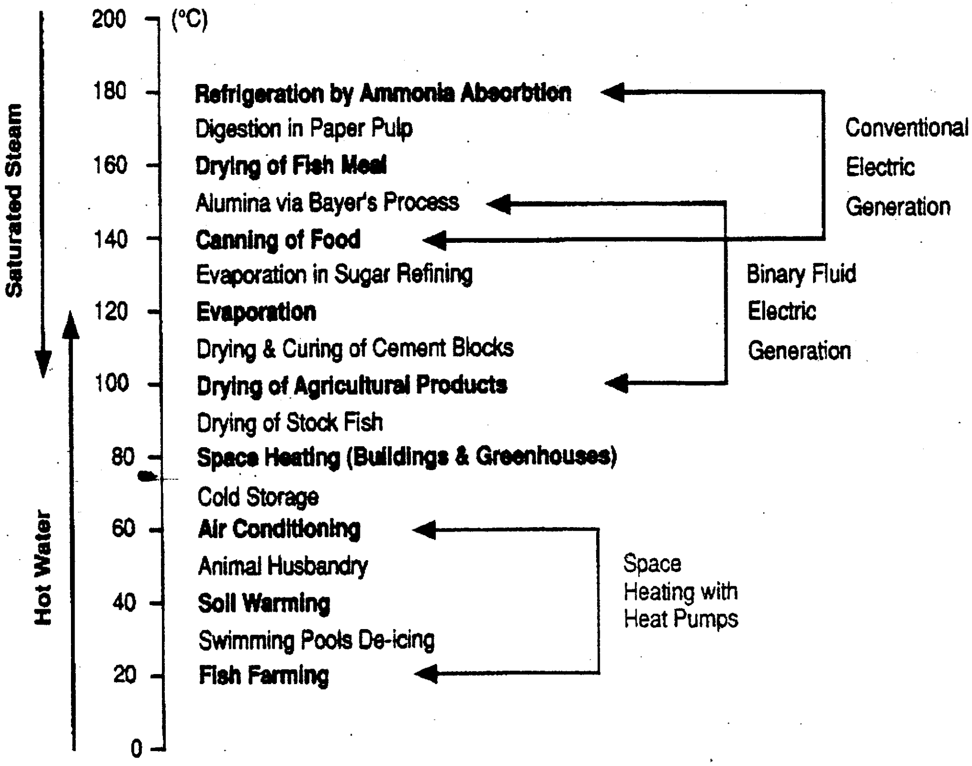

Figure 3.1 Uses of geothermal energy for various temperatures

Source: Lindal (1973)

If temperatures are high enough, about 140°C or more, geothermal energy can be effectively used for electricity production. However, some power systems, such as these employing binary cycles with lower-boiling point working fluids can operate at temperatures below 140°C. Resources with temperatures between 80°C and 180°C are used for space and process heating, and below 80°C for air conditioning, soil warming and fish farming.

Electricity from geothermal energy was generated for the first time at Larderello, in Italy, in 1904, when Prince Piero Ginori Conti lit five bulbs with a dynamo coupled to a steam-driven piston motor (Barbier, 1984). In 1913, Italy was the first country to build a geothermal power plant with a 250kW capacity. For forty two years, Italy was the only country in the world that produced electricity from geothermal resources (Cataldi and Sommaruga, 1986). In 1955, the first large-scale (362 MWe) geothermal power plant went on line, at Wairakei, New Zealand. In 1960, the United States opened its first geothermal 368 MW_e unit at The Geysers, and the commercial exploitation of geothermal energy started spreading worldwide. The growth pattern of geothermal power from the early 1900s up to 1998 is given in Figure 3.2.

After World War II, the development of geothermal resources can be divided into three periods: From 1950 to 1970; from1970's to mid-80's and from mid-80's till today. During the first period, the world installed geothermal capacity grew substantially at an average annual rate of about 5.6% as countries like the US, New Zealand and Mexico followed Italy in the construction of geothermal power plants. From 1970 to 1985, the growth of geothermal installed capacity soared to an annual average of 13.5%. This surge was due to a dramatic rise of crude oil prices after the two oil crises in 1973 and 1979, when the Organization of Petroleum Exporting Countries (OPEC) decided to put restrictions on petroleum supplies. Concerns about further oil price increases, natural security issues, and dependence upon foreign supplies fueled mainly U.S. interest in constructing geothermal power plants.

The third period is marked by the collapse of oil prices. During this period, the growth of world geothermal energy capacity declined significantly to about 4.2% per annum. The U.S. geothermal power industry has exhibited a negligible growth rate of 0.33% since 1990 (see Table 3.1). This can be attributed to two factors: First, the low cost of power from natural gas systems, which can produce electricity at a price of 2.5 to 3.5 1997 U.S.¢/kWh, at a time when hydrothermal power systems generate electricity at a price of 4 to 6 1997 U.S.¢/kWh. Second, the low demand for additional power capacity mainly because of the surplus of capacity buildup in the previous years.

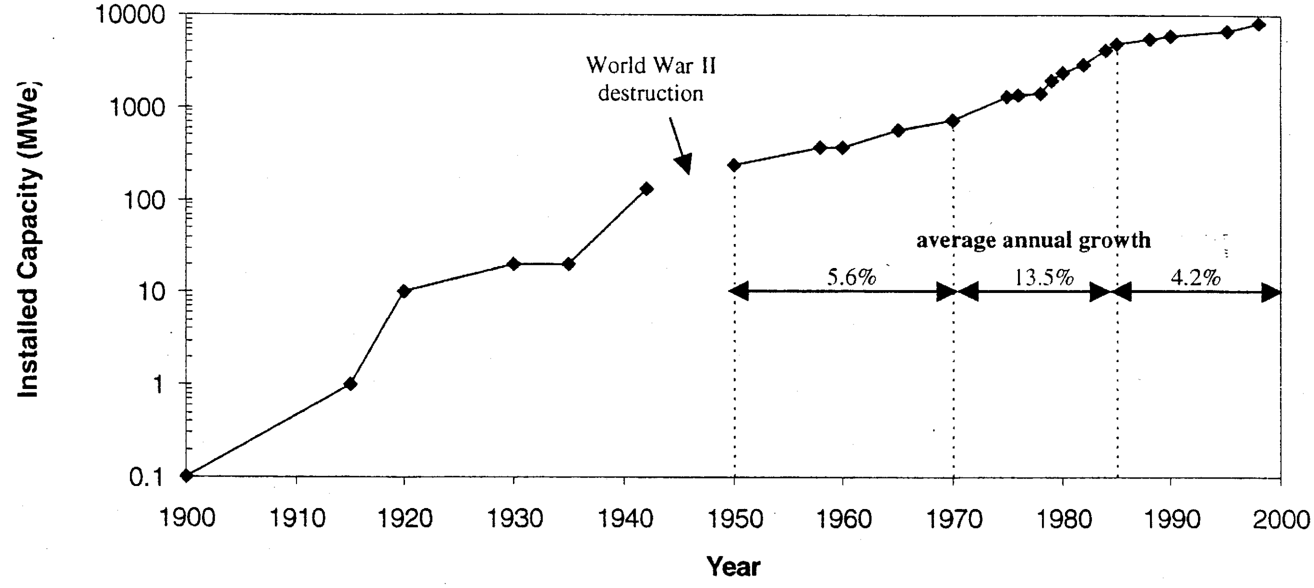

Figure 3.2 Growth pattern of installed geothermal capacity from the 1900s up to 1998.
(average annual growth 1950-1970: 5.6%; 1970- 1985: 13.5%; 1985- 1998: 4.2%)

Sources: Armstead (1983); Brown *et al.* (1993); Goodman (1980); Rowley (1982); Huttrer (1995); IGA (1998).

3.2 Current Status

Currently, approximately 8,240MWe of geothermal power are produced in 20 countries in the world (Table 3.1). Virtually, all of it comes from naturally occurring hydrothermal resources.

Table 3.1 Installed Geothermal Electricity Capacity (MWe) in the World

Region\Year	1976	1979	1985	1990	1995	1998
Africa						
Kenya	0	0	45	45	45	45
Total	**0**	**0**	**45**	**45**	**45**	**45**
Asia						
China	0	0	14.3	19.2	28.78	32
Indonesia	0	0	32.25	144.75	309.75	589.5
Japan	68	218	215.1	214.6	413.7	530
Philippines	0	223	894	894	1191	1848
Thailand	0	0	0	0.3	0.3	0.3
Total	**68**	**441**	**1155.7**	**1272.85**	**1943.53**	**2999.8**
Oceania						
Australia	0	0	0	0	0.17	0.4
N. Zealand	202	202	202	283.2	286	345
Total	**202**	**202**	**202**	**283.2**	**286.17**	**345.4**
Latin America and Caribbean						
Argentina	0	0	0	0.67	0.67	0
Costa Rica	0	0	0	0	55	120
El Salvador	60	60	95	95	105	105
Guatemala	0	0	0	0	0	5
Mexico	78.5	150	645	700	753	743
Nicaragua	0	0	35	70	70	70
Guadeloupe (France)	0	0	4.2	4.2	4.2	4.2
Total	**138.5**	**210**	**779.2**	**869.9**	**987.9**	**1047.2**
North America						
USA	522	674	2022.1	2774.6	2816.7	2850
Total	**522**	**674**	**2022.1**	**2774.6**	**2816.7**	**2850**
Europe						
Iceland	2.5	34	39	44.6	49.4	140
Italy	421	421	519.2	545	631.7	768.5
Azores (Portugal)	0	0	3	3	5	11
former USSR	5.7	5.7	11	11	11	11
Turkey	0.5	0.5	20.4	20.4	20.4	20.4
Total	**429.7**	**461.2**	**592.6**	**624**	**717.5**	**950.9**
World	**1360.2**	**1988.2**	**4796.6**	**5869.52**	**6796.77**	**8238.3**

Sources: Goodman (1980); Huttrer (1995); International Geothermal Association (1998).

The leading countries (Figure 3.3) are the USA (2850MWe), the Philippines (1848MWe), Italy (768.5MWe), Mexico (743MWe), Indonesia (589.5MWe), Japan (530MWe), and New Zealand (345MWe). A regional breakdown of installed geothermal capacity in 1998 is given in Figure 3.4.

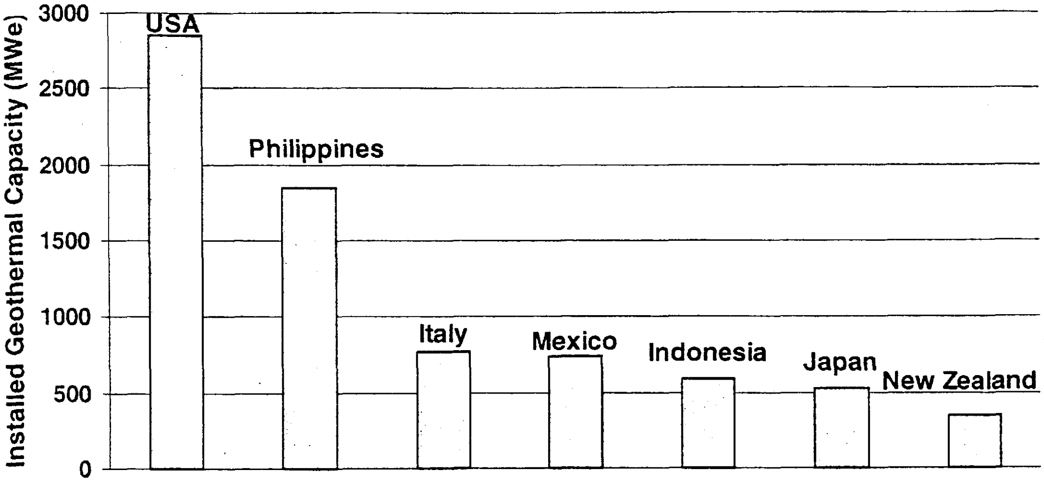

Figure 3.3 Top Geothermal Power Producing Countries in 1998

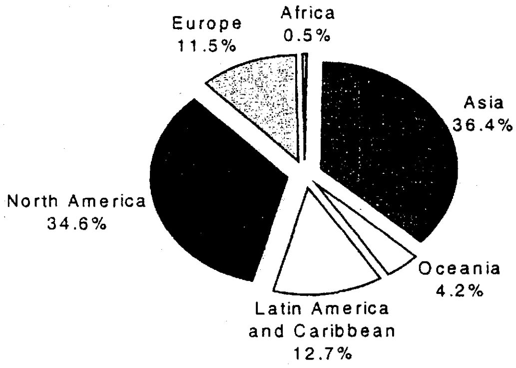

Figure 3.4 Regional distribution of installed geothermal capacity in 1998

Figure 3.5 illustrates the trend in geothermal capacity from 1980 to 1998. Asia has demonstrated a rapid growth the last ten years, with Indonesia and the Philippines having average annual growths of 19% and 9.5% respectively (see Table 3.1). Currently, many international companies are pursuing geothermal development and power generation opportunities in the Philippines, and to a limited extend in Indonesia. The United Nations Development Program (UNDP) has initiated exploration programs in many developing countries which have materialized in many cases into geothermal projects. This was the case in Kenya and in Latin America (WEC, 1993, 1994). The U.S. geothermal industry competes with New Zealand, Japan, and Italy for developing and managing geothermal projects worldwide, and with Mexico for projects mainly in Latin America. For the U.S. and other developed countries the involvement in geothermal development projects abroad can prove: (1) a low-cost greenhouse gas option to meet their commitments stemming from the Kyoto agreement, (2) an opportunity to sell technology and services, and (3) significant leveraging to achieve further advances in geothermal technology for domestic use (EPRI, 1998a, 1998b).

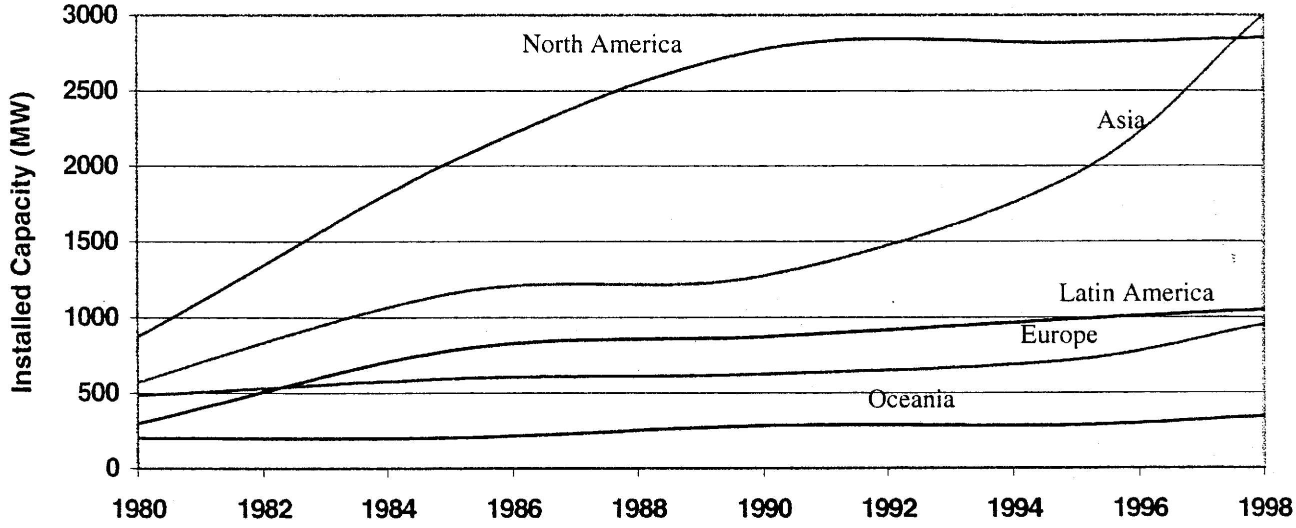

Figure 3.5 Growth of Installed Geothermal Capacity in the World since 1980.

Sources: Goodman (1980); Huttrer (1995); International Geothermal Association (1998).

3.3 The Geysers Geothermal Field

The Geysers is the largest and most productive vapor-dominated hydrothermal reservoir in the world. Figure 3.6 shows the annual geothermal electricity production and capacity at the site. Both of them grew substantially from 1974 to 1988 and were the primary contributor of the new generating capacity and geothermally produced electricity in the US. Since 1988, however, steam production has been decreasing at about 7-8% per year due to a reservoir pressure drop. Scientists believe the cause of the problem is that the water content of the reservoir is being extracted at a faster rate than natural recharge can replenish it. The good news is that only 5% of the thermal energy content of the reservoir rock has been consumed during thirty years of operations. Extensive experiments undertaken by Unocal, Calpine, Northern California Power Agency, Pacific Gas & Electric, and the U.S. Department of Energy indicated that water injection into the reservoir will halt pressure declines and enable the reservoir to produce steam for many more decades (Mock *et al,* 1997; Wright, 1998). Current research is focused on determining the best method for water injection.

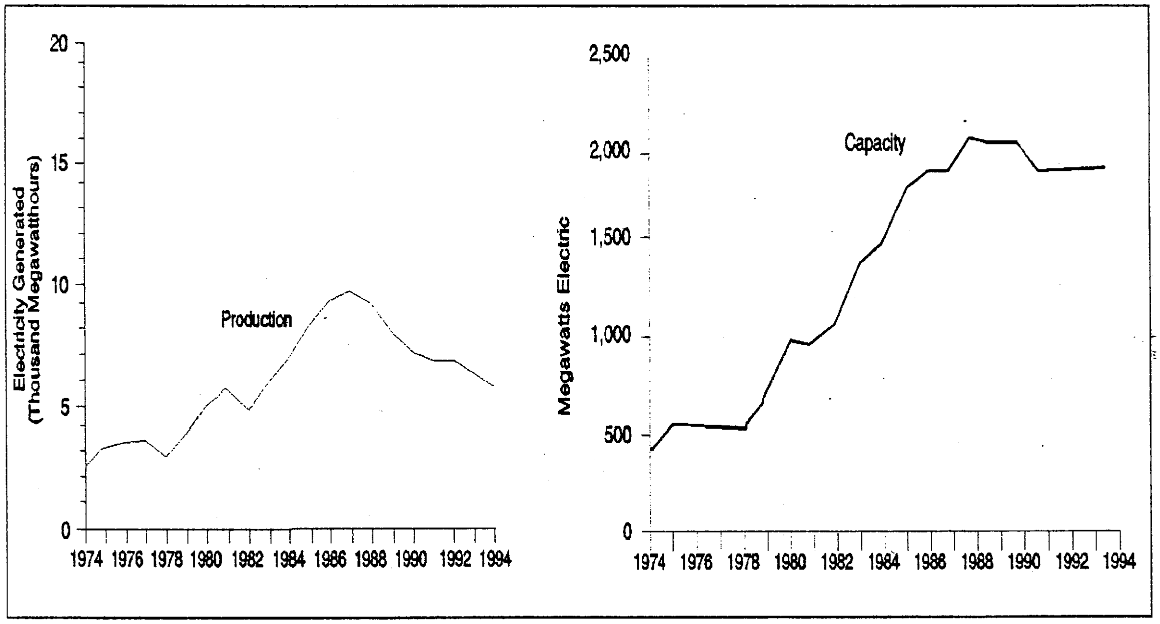

Figure 3.6 Annual Geothermal Electricity Production and Capacity at The Geysers.
Source: EIA, Form EIA-759, "Monthly Power Plant Report"

The major injection program is the Southeast Geysers Pipeline project, which involves the construction of a 51-centimeter diameter, 46-kilometer long pipeline with a capacity of 29.5 million liters per day. This pipeline will carry water from a wastewater treatment facility north of The Geysers for injection into the southeastern portion of the reservoir.

The problems at the Geysers have given rise to the issue of whether geothermal resources can provide energy in a sustainable way. In general, the reservoir is no longer economically useful for energy production when pressure and temperature drop below certain limits. However, water reinjection and proper monitoring of the reservoir performance can prolong the useful lifetime of a reservoir. Some scientists believe that hydrothermal systems that become depleted of naturally occurring fluid or steam may be treated as HDR systems, from which the heat can be recovered by artificial water injection (Cappetti, 1998; Duchane, 1996). Therefore, it is imperative for the growth of geothermal industry that we develop technologies to mine the heat from hot dry rock formations in a cost-effective way.

Chapter 4

Environmental Attributes of Geothermal Power Systems

4.1 Environmental Benefits

With industrialization and population growth, greenhouse gas emissions from human activities have consistently increased. Burning of coal, oil, and natural gas releases about six billion tons of carbon into the atmosphere each year worldwide (EPA, 1999). The result is that atmospheric levels of carbon dioxide, the most important contributor to greenhouse effect, have increased by 30%, methane concentrations have more than doubled, and nitrous oxide concentrations have risen by about 15%, since the beginning of the industrial revolution. These increases have enhanced the heat-trapping capability of the earth's atmosphere.

Scientists believe that today's emissions will be affecting the climate well into the 21st century. They expect that the average global surface temperature could rise 0.9-3.5°F by 2100, with significant regional variation. Evaporation will increase as the climate warms, which will increase average global precipitation. Soil moisture is likely to decline in some regions and increase in others, and intense rainstorms are likely to become more frequent. Increasing concentrations of greenhouse gases are likely to accelerate the rate of climate change.

Calculations of climate change for specific regions are much less reliable than global ones, and it is unclear whether regional climate will become more variable. Estimating future emissions is difficult, because it depends on demographic, economic, technological, policy, and institutional developments. Increasing concentrations of greenhouse gases are likely to accelerate the rate of climate change.

Because of the potential adverse impacts of global climate change, many countries in the world try to rebalance their energy portfolio in order to address these concerns. Geothermal power systems can play an important role as a mitigation technology, since they have the advantage of being a relatively low CO_2 emitter compared to fossil-fueled power generation.

Figure 4.1 gives a comparison of life cycle CO_2 emissions from renewables and fossil fuels. Emissions from wind, PV, and hydropower occur only during the manufacturing and/or plant construction stages. Emissions from all other technologies occur during all stages (manufacturing, construction, and operations). Carbon dioxide emissions from geothermal plants are significantly less than those arising from fossil-fueled plants. Typically, CO_2 emissions from a geothermal flash plant are only 5% of those emitted by a coal plant and 8% of those from a oil plant, per kWh (DiPippo, 1991). Binary plants have essentially no emissions since the organic fluid is continuously recirculated in a closed loop, and the spent geothermal fluid is injected back into the reservoir. HDR/EGS systems have also zero emissions because the water follows a closed loop.

Another advantage of geothermal power systems is that the entire fuel cycle, from resource extraction to electric transmission, is located at the site. The actual land use in geothermal operations is fairly small, unlike other fossil-fueled technologies, for which the total fuel cycle requires a substantially greater land use for mining, drilling, refining, re-processing operations, and waste disposal. Furthermore, other applications, such as crop growing or cattle grazing can co-exist in proximity to the wells, pipelines, and power plants of a geothermal field.

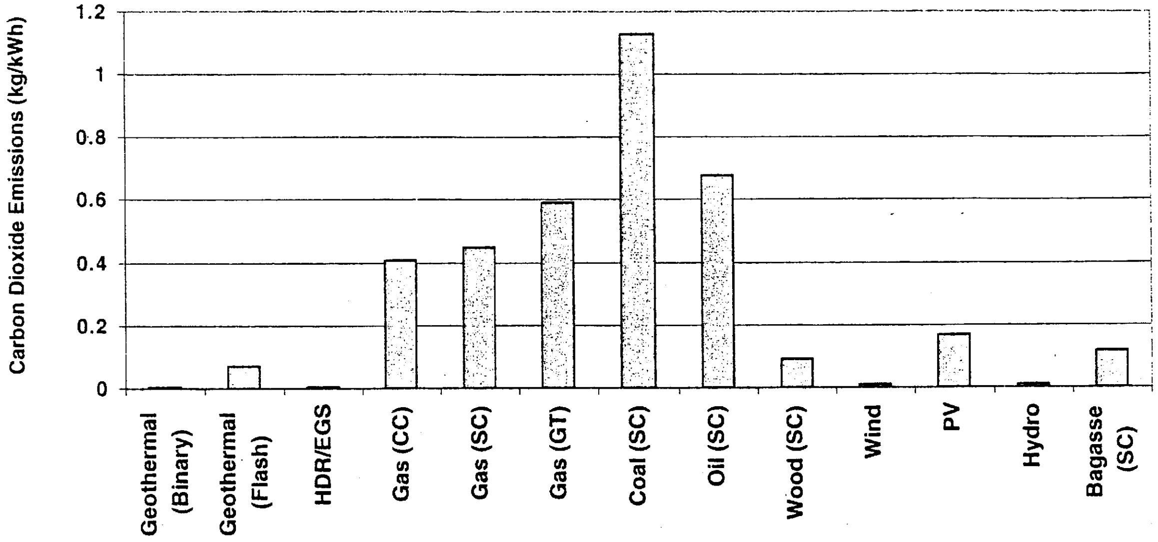

Figure 4.1 CO_2 emissions of various types of power plants
(CC: Combined Cycle, SC: Steam Cycle; GT: Gas Turbine; PV: Photovoltaics)
Source: DiPippo (1991, 1988); IEA (1998)

In general, geothermal plants have a small footprint and require less land per megawatt produced than other power systems, as Figure 4.2 shows. The value for geothermal plants includes the land usage for the wells and the power plant itself. Binary systems require more land than flash systems. This is due to the fact that binary systems have more equipment than flash plants do and, therefore, they require more power plant area. A description of the technical characteristics of geothermal power plants is given in Chapter 5. It should be noted that the values for wind systems and PVs are expressed in average MW_e instead of peak MW_e. The value for the coal plant includes 30 years of coal strip mining. For nuclear, the number expresses only land requirements for the power plant. If we take into account the total life cycle of coal and nuclear, including the fuel cycle, the numbers for these technologies would be much higher. Thus, one should be very careful when making comparisons of technologies that have the entire life cycle at a specific site with technologies with different lifecycle patterns.

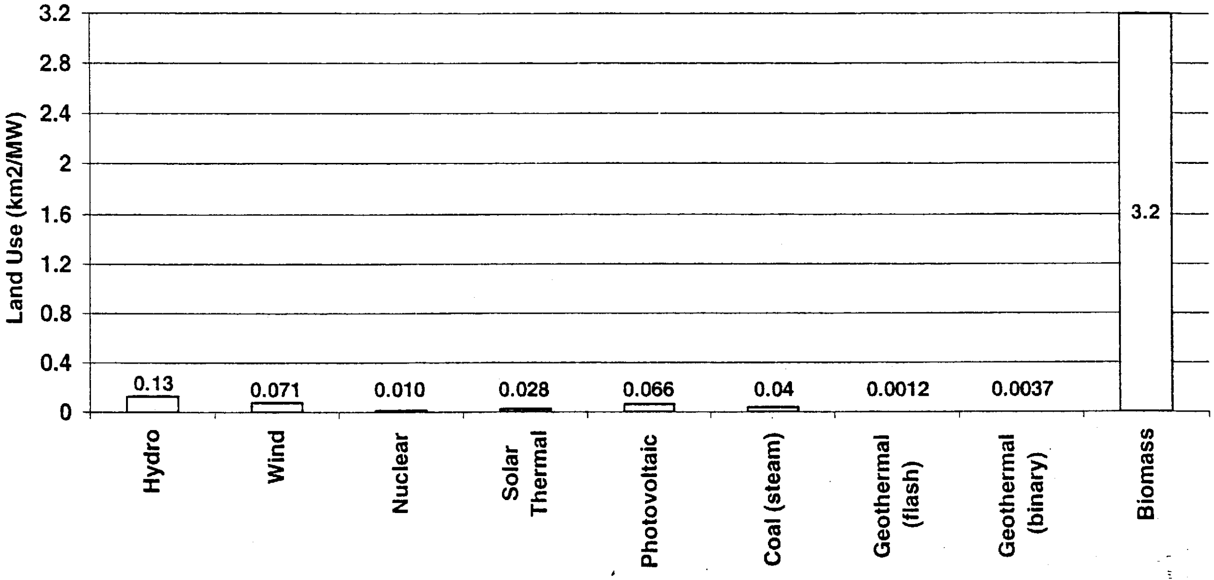

Figure 4.2 Land requirements per MW produced for various types of power plants

Source: Gipe (1995); EPRI (1997); DiPippo (1990); IEA(1998b)

4.2 Environmental Impacts

Hydrogen sulfide (H_2S)

Hydrogen sulfide (H_2S) is present in almost every high-temperature geofluid. At low concentrations (around 30 ppb) H_2S has a very annoying odor of "rotten egg", which can be detected by 20% of the population at a concentration of just 2 ppb by volume. At high concentration, it is toxic and corrosive. Through a series of chemical reactions H_2S is transformed into sulfuric acid, which is a source of acid rain. A concentration of 600,000 ppb of H_2S can prove fatal to humans after 30 minutes exposure. Nowadays, emissions-abatement technologies can achieve a reduction of total sulfur emissions from a geothermal plant over 90 percent to levels that are only about one percent of the sulfur emissions from a fossil-fuel-fired plant of similar capacity (Armstead 1983; DiPippo, 1991; Golob and Brus, 1993). In binary plants, the geothermal fluid is circulated in a closed loop and therefore, hydrogen sulfide emissions are not a problem.

Noise

Noise is an important factor during drilling, construction and production operations at a geothermal site. Noise pollution can reach the 120dBa, which is the pain threshold and is produced by high pressure venting steam during well-testing operations, by ground vibrations at uncontrolled wells, and by well drilling.

The noise of plant operations, under normal conditions, is practically indistinguishable from other background noises at about one kilometer distance (DiPippo, 1991). Measures to mitigate the noise problem include the installation of rock mufflers to reduce the velocity and consequently the noise of the venting steam, and the installation of suitable mufflers and silencers on machinery. Workers can be protected by wearing ear mufflers. Control rooms can be sound-proofed, so that the personnel is protected. In general, the noise in a geothermal power plant is not worse than in conventional thermal power plants (Armstead, 1983).

Water Use

Direct steam and flash plants have no need for cooling water, since the geosteam is condensed, cooled and re-circulated to the condenser. Binary plants, which don't have geosteam condensate, can use air-cooled condensers.

Ecological destruction

Industrial development on a geothermal site may disturb local ecosystems (e.g. by noise, dust and fumes) and result in soil erosion and ecosystem destruction. Proximity between hot springs and geothermal fields can lead to a reduction in the vigor of the former due to a decline in the reservoir pressure or even to a depletion of the springs by heat extraction from geothermal wells. For these reasons, industrial operations are usually limited or precluded where geothermal resources are situated in protected areas or areas of tourist attraction (e.g. national forests, volcanic parks, geysers, hot springs, spars, hot pools).

Water Pollution

Geofluids usually contain significant amounts of: (1) dissolved minerals, such as sodium, potassium, potassium chlorides, (2) carbonates, such as calcium, fluoride, magnesium, silicate, iodine, antimony, strontium, bicarbonate, sulfate, and (3) toxic substances, such as arsenic, boron, lithium, hydrogen sulfide, rubidium, lead, mercury and ammonia (Nicholson, 1992). If these geofluids are discharged in the environment, they can contaminate groundwater, or surface waters used for farming, aquaculture, or drinking supplies, and fish. (Armannsson and Kristmannsdottir, 1992). In addition, spent geothermal fluids have high temperatures and when discharged into lakes and rivers can cause adverse effects to aquatic ecosystems. Furthermore, discharging large volumes of spent brine can increase erosion in water ways and also lead to the precipitation of minerals. The impacts of spent geothermal fluids can be avoided by collecting and re-injecting them back into the reservoir, which is the common practice in the US.

Ground Subsidence

Ground subsidence is caused by the withdrawal of large quantities of geofluid from the reservoir at rates that exceed the replenishment inflow. The subsidence rate depends on the geological conditions of the field. So far, the major vapor-dominated fields in the world, i.e. the Larderello field in Italy, and The Geysers in California, have not experienced any subsidence incidents. The largest subsidence phenomenon has been observed at the Wairakei liquid-dominated field in New Zealand where the maximum vertical settlement exceeded 7.5 m and was continuing at a rate of 0.4 m per year (Thain and Stacey, 1984). The problem of subsidence can be mitigated by re-injecting fluid into the reservoir.

Seismicity

Many geothermal fields are located in regions that are prone to natural seismic activities. It is often believed that prolonged geothermal exploitation of a field and especially re-injection of fluid into the reservoir may increase the frequency of microseismic events. The danger of induced seismicity can be minimized by reducing injection and re-injection pressures.

Thermal Pollution

Geothermal plants produce large quantities of waste heat which can given rise to a great deal of vapors if rejected into the air. These vapors are absorbed by the atmosphere if the climate is dry, whereas, in humid climates, they result in local fog and sometimes in ice precipitation (Armstead, 1983). Geothermal plants reject two to three times more waste heat per unit of electricity generated than typical gas turbine, nuclear, coal and gas-turbine combined cycle plants (DiPippo, 1990, 1991). However, this is only at the plant site. If we take into account the whole life-cycle of a technology and calculate the heat dissipated during the mining, processing, transportation, and reprocessing operations then the case for geothermal is not that bad as it initially might looked like. Furthermore, thermal pollution can be abated by using re-injection techniques or using the heat for some other applications.

Depletion of groundwater

Groundwater can be depleted from a hydrothermal reservoir if the water content of the reservoir is extracted at a faster rate than natural recharge could replenish it. This was the case of The Geysers field in the USA. Water reinjection and proper monitoring of the reservoir performance can prolong the lifetime of a reservoir.

Overall, geothermal power systems are considered a benign, safe, essentially emissions-free and therefore clean and environmentally friendly technology compared with fossil-fueled systems. Their environmental impacts are locally contained to a small footprint and can be reduced by careful design, proper monitoring, and attention to quality control during drilling, construction, and operations. Furthermore, geothermal fields are available for other uses such as, forestry, farming, cattle grazing, and water management.

Chapter 5

Technical Challenges for Increasing Growth of Geothermal Power Generation

5.1 Resource Exploration

The development of a geothermal resource starts with exploration, in order to detect the existence of a reservoir. Exploration techniques and equipment, such as volcanological maps, gravity meters, seismic methods, chemical geothermometers, and sub-surface mapping, are used in order to assess physical, chemical and electrical properties of the rock. Then, exploratory drilling is used to establish the properties of the field. Once a promising site has been confirmed, the geometry and characteristics of the reservoir are modeled, changes in reservoir fluids and rocks are analyzed, long-term circulation is predicted by numerical simulation models and, finally the siting for productive drilling is determined.

However, exploratory drilling is a risky process because of the chance of hitting a "dry hole" or finding geothermal fluids that do not meet temperature or heat flow requirements for commercial exploitation of the field. Furthermore, exploration methods have been inadequate to provide a good understanding of the field characteristics. More R&D is necessary in order to improve the diagnostic methods to assess and map the structure of a geothermal reservoir.

Researchers believe that the development of new core hole evaluation technologies, such as the "slim-hole" technology, will significantly reduce the economic risk of exploratory drilling. It has been estimated that by drilling "slim", i.e. small diameter exploratory holes, the cost of exploration can drop by 40-60% (Finger, 1998). However, it is still necessary to drill a more expensive large diameter bore for reservoir testing and evaluation.

Methods and equipment suitable for conducting reservoir testing and evaluation during core drilling must be developed in order to take full advantage of the lower cost of core drilling. In addition, advanced computer models must be developed to simulate and predict with accuracy the behavior of a geothermal system.

5.2 Geothermal Drilling

Drilling technology used for the development of geothermal wells has been transferred from the petroleum industry. However, conventional oil and gas well equipment, instruments and methods fail to perform properly in the geothermal environment which is characterized by high temperatures, hard and abrasive rock formations, and corrosive fluids. This section discusses the challenges that the geothermal industry is facing in drilling and completion operations.

Geothermal wells are currently drilled using oil field rotary drilling. In conventional applications, the well bore is drilled by turning a bit which is attached to the drill pipe, as shown in Figure 5.1. The drill pipe is rotated by a mechanical drive at the surface, such as an diesel engine or an electric motor. The drill-pipe assembly is supported through a swivel hung from the drill rig, and weight on the bit is provided by drill collars. Drilling mud, which can also be pure water (or nearly so) and air, is pumped down the drill pipe and is recirculated up the annular space. Drilling muds are used for: (1) carrying rock cuttings to the surface, (2) cooling and lubricating the bit, (3) stabilizing the hole, and (4) preventing formation fluids from entering the hole.

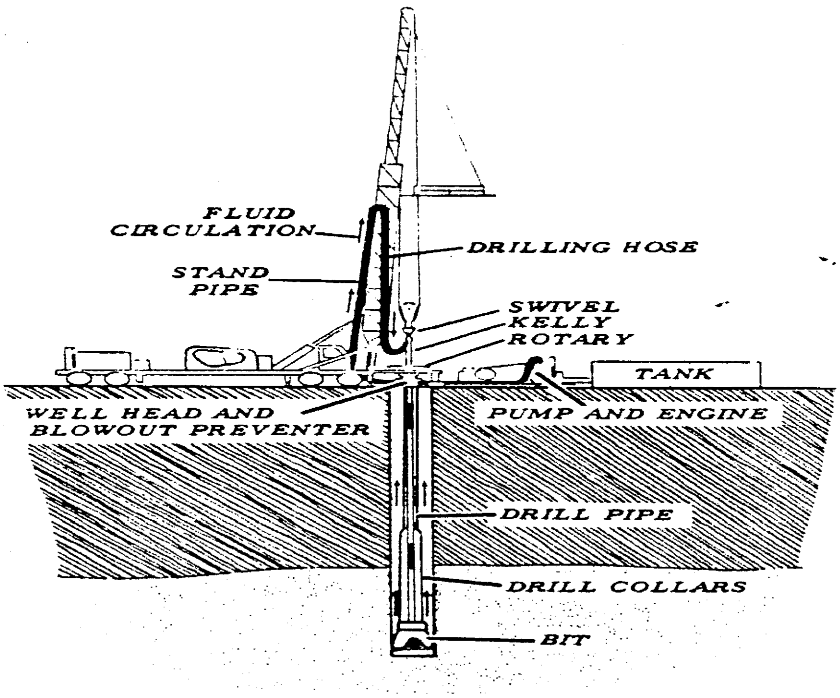

Figure 5.1 Geothermal drilling rig Source: Petroleum Extension Service

For temperatures of about 200°C, water-based drilling muds containing bentonite clay, barite, or other clay-based materials with special additives, such as chrome lignite/chrome ligno-sulphonate are used. For higher temperatures, oil-based muds are used. Both types of muds, however, undergo severe degradation of their properties at temperatures greater than 260°C. The lack of adequate high-temperature drilling fluids is a major problem for the geothermal industry. Therefore, improved drilling fluids must be developed in order to access geothermal resources beyond hydrothermal reservoirs that are located at shallow depths, i.e. at low temperatures and soft rock formations.

Many geothermal wells are drilled in granite, basalt, and other rocks which are much harder than the sendimentary rocks usually encountered in the oil industry. This results in rapid wear and short bit lifetime. Enhancements in drill bits are necessary so that they can withstand high geothermal temperatures as well as hard formations, and corrosive and erosive geofluids.

Once the well is drilled, several casing strings of different diameters are usually needed in order to stabilize the wellbore and prevent formation fluids from entering into the well. These strings are cemented into the well. However, the properties of casing cements degrade by high temperatures and the presence of highly corrosive geothermal fluids (Armstead, 1983).

Another very common problem encountered during drilling operations in geothermal wells is lost circulation. It is caused by the loss of drilling muds into the surrounding rock. Small losses can be compensated for with the injection of additional mud, but the cost of make-up fluids becomes prohibitive in case of significant losses. High circulation losses can add 20% - 30% to the total cost of a well (DOE/OGT, 1998), because of lost drilling time, stuck drill strings, loss of control of formation fluids, failure to carry rock cuttings to the surface, decreased borehole stability, and use of materials, specialized equipment, and services for lost circulation treatment.

Many other materials typically used in mechanical components, such as blowout preventers, packers, perforating guns, and downhole drilling motors, suffer degradation and failure on exposure to high-temperature corrosive environments.

Currently, advanced drilling techniques are being studied, but they have yet to be adequately demonstrated in the field. These novel techniques use four basic principles to communicate and remove rock: (1) melting and vaporization, (2) thermal spallation, (3) chemical reactions; and (4) mechanically-induced stresses.

Improvements in drilling technology and materials will not only result in more productive exploitation of geothermal resources but also in lower costs; therefore reducing the financial impact from these operations on the economics of geothermal projects.

With a sufficient R&D effort it should be possible by 2020, to reduce drilling costs by a factor of two over the current costs as a direct result of both evolutionary developments and the appearance of new breakthrough drilling technologies (Peterson, 1996). In addition, improvements in downhole data transmission systems will lead to drilling cost reductions.

Researchers at the Sandia National Laboratories have proposed the development of an advanced transmission system called Diagnostics-While-Drilling (DWD). The DWD system produces a real-time report on the status of drilling conditions as acquired from downhole sensors and carries surface control signals back downhole. The project is sponsored by DOE, and if proved successful, it will enhance drilling performance by improving the penetration rate of the bit, increasing the bit life, and diminishing tool failures, and consequently it will reduce drilling and completion costs (Finger *et al*, 1999).

5.3 Power Generation

The main types of geothermal energy conversion technologies are: direct steam, flash steam, and binary fluid cycle systems. Flash steam systems can be subdivided into single and double depending on the number of flash stages involved. The technologies employed for generating electricity are contingent on the characteristics of the geothermal resource as it is shown in table 5.1.

Table 5.1 Types of geothermal power generating systems

Geothermal resource	Power production system
Vapor-dominated ($T > 120^{o}C$)	Direct steam cycle
Liquid-dominated ($T > 150^{o}C$)	Flash steam cycle
Liquid-dominated ($90^{o}C < T < 150^{o}C$)	Binary fluid cycle

5.3.1 Direct Steam Systems

Direct steam systems use vapor-dominated resources for electricity generation. In theory, vapor extracted from the production well can be piped directly to a steam turbine for electrical power production (Figure 5.2). However, in practice, wellhead vapor streams first pass through separators to remove any particulate matter such as rock dust and moisture and through drain pots to remove any condensate formed during transmission, both of which can cause scaling and corrosion problems to the turbine and other parts of the equipment.

The factors that determine the choice of the turbine are: (1) the amount of non-condensable gases, hydrogen sulfide and carbon dioxide, in the steam, and (2) the environmental limitations on the geothermal field.

There are two turbine types, non-condensing and condensing. Non-condensing turbines exhaust directly to the atmosphere, whereas condensing turbines discharge the steam to a condenser (Hudson, 1988). The condensed steam is cooled in a cooling tower and used as cooling tower water for the condenser. Excess cooling water is reinjected into the reservoir to help maintain its pressure.

If the steam contains non-condensable gases in contents higher than 12% of its mass, the use of a non-condensing turbine is preferred because of the high power consumption required to extract them from the condenser. However, environmental concerns sometimes require the use of non-condensable gas extraction equipment.

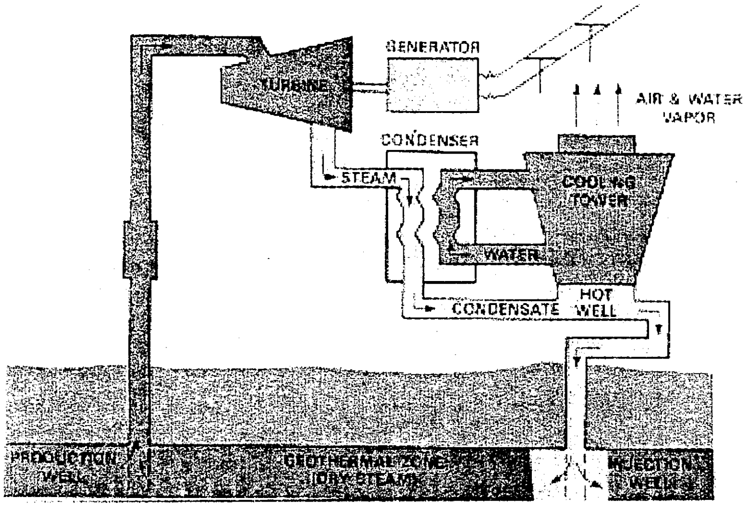

Figure 5.2 Direct-Steam System

5.3.2 Single- and Double-Flash Steam Systems

Flash steam systems use liquid-dominated resources comprising of high-pressure hot water or water-vapor mixture that are hot enough to flash. In a single-flash system, hot geofluid passes through a pressure-controlled separator, which operates at a pressure lower than that of the entering fluid, and flashes. The steam is then piped into a turbine for electricity generation. After expanding, it is directed into a condenser (Figure 5.3).

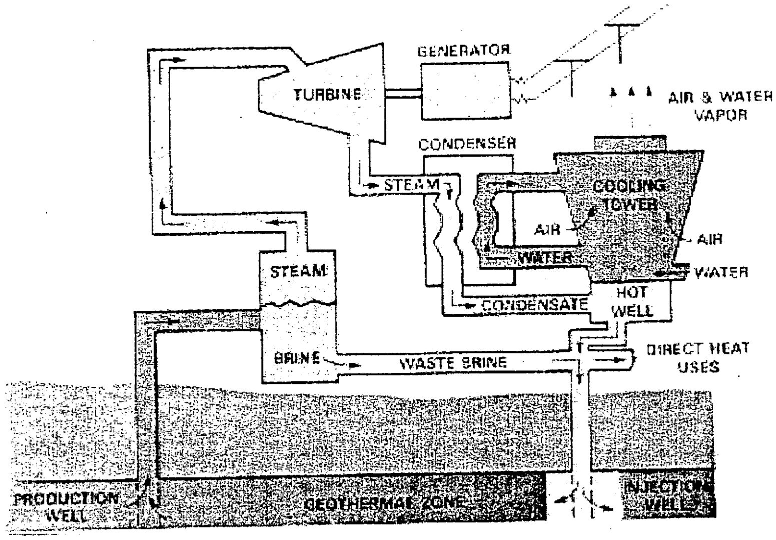

Figure 5.3 Single-Flash System

In a double-flash system, the remaining liquid from the first stage undergoes a second flash in a separator operating at a lower-pressure than the one in the first stage (Figure 5.4). The generated steam can enter either the low-pressure section of the same turbine or a second turbine.

In both the single- and double- flash systems, the condensed steam is cooled in a cooling tower and used as cooling water or is injected back into the reservoir. The residual unflashed liquid can be reinjected into the reservoir or be used for direct heat applications.

Depending on the temperature of geothermal fluid, double-flash systems produce 20-30% more power than single-flash systems for only a 5% increase in plant cost (Milora and Tester, 1976; Tester, 1982; Brown, 1996).

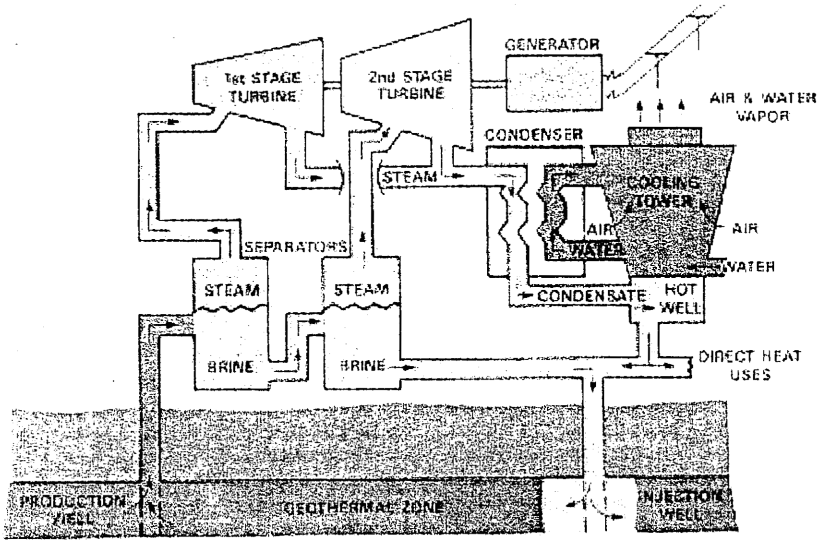

Figure 5.4 Double-Flash System

Although the flash process can be repeated for more than two stages for producing additional steam, the increase in efficiency must be weighed against the additional cost of turbines. Thus, the double-flash system is usually preferred from an economic point of view (Mock *et al.*, 1997).

5.3.3 Binary Systems

In typical applications, binary systems use liquid-dominated resources containing significant amounts of non-condensable gases or dissolved solids that are either not hot enough for efficient flash steam production or are too corrosive to use directly in a turbine.

A binary cycle, which is actually a closed-loop Ranking cycle, transfers heat from the geothermal fluid to a working fluid of very low boiling point, such as isobutane, propane, or Freons. The working fluid vaporizes and expands through a turbine. After expanding, it is condensed and pumped to the heat exchanger to begin a new cycle (Figure 5.5). The spent geothermal fluid is reinjected into the reservoir to assist in maintaining the reservoir pressure. Because binary systems are closed-loop systems, the possibility of releasing noncondensable gases or brine chemicals is low.

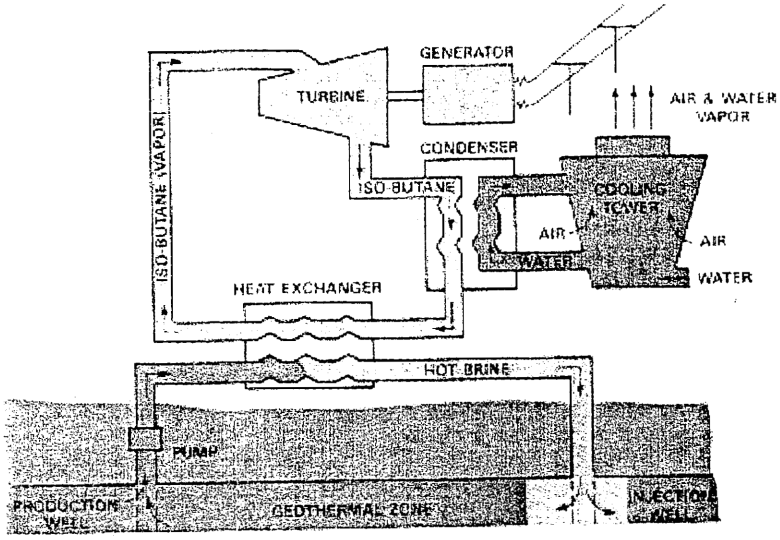

Figure 5.5 Binary System

5.4 Energy Conversion

A disadvantage of geothermal systems over conventional power systems is that they have much lower efficiencies, based on the Second law of thermodynamics. Even with high–temperature reservoirs, the efficiency of converting geothermal steam into electricity is typically around 10-15% compared to 30-50% achieved by conventional power generating technologies (DiPippo, 1991; Brower, 1992; Mock *et al*, 1997).

It is estimated that geothermal power-plant efficiencies can be improved at least 25% over the next ten years with a moderate investment in R&D (Wright, 1998; Mock *et al.*, 1997).

A new energy conversion system based on the "Kalina Cycle" is expected to increase the efficiency of closed-loop geothermal plants by 40% (GAO, 1994).

The Kalina Cycle uses a mixture of water and ammonia as the working fluid. Because the boiling of ammonia is much lower than that of water, the technology is able to drive a turbine at lower temperatures that those used in conventional steam turbine systems. By varying the ratio of water and ammonia at various points in the steam cycle, higher efficiencies can be achieved. A Kalina energy conversion system allows the geothermal fluid to remain condensed at high pressure throughout the process, so that it can be readily reinjected into the reservoir. Furthermore, it has the potential to produce electricity from geothermal resources that have lower temperatures than those currently used for power generation.

The Kalina Cycle is patented by Exergy Inc., a US company, and has been used for the first time at a commercial plant at Canoga Park in California, with an output of 3.2MWe. In Australia, Hot Rock Energy Pty Ltd, a consortium of private companies which manage the development of a commercial HDR system at the Hunter Valley, are considering the use of the Kalina Cycle for the geothermal power plant design (Hot Rock Energy Pty Ltd., 1997).

Chapter 6

Economic and Financial Challenges for Achieving Growth

6.1 Necessary conditions for geothermal site development

The successful development of a geothermal site requires the convergence of the following conditions:

- The presence of a good quality resource, as discussed in Chapter 2.
- The availability of sufficient financing.
- The existence of a secure long-term market for the energy produced.

The four key parties necessary for the construction of a geothermal plant are the user, the developer and the lender. The user is usually a public or private utility which signs a power purchase agreement (PPA) with the developer. This agreement guarantees that the utility will absorb a certain fraction of the capacity of the geothermal plant and sets the price for the electricity produced. The developer signs a construction contract with a contractor for the implementation of the project, and also enters into an agreement with the lender to obtain the necessary project financing. The existence of a PPA is often a precondition for the lender to grant the loan requested by the developer.

The aforementioned necessary conditions were satisfied in the western United States during the 1980's. In particular, the passage of the U.S. Public Utilities Regulatory Policies Act of 1978 (PURPA) mandated that electric utilities purchase power from qualifying facilities at the utilities' own avoided cost of production. This was implemented in California via the Interim Standard Offer 4 (ISO4) contracts, which provided for utilities to buy electricity generated by qualified facilities at a fixed prices for up to ten years, after which point energy prices were to revert to the short-run avoided cost of the utility. This practice encouraged the growth of the geothermal industry, as discussed in Chapter 2.

However, the last of the ISO4 contracts will expire by 2001 and this can have a significant impact on the US geothermal industry. Furthermore, the U.S. electricity market is in the midst of restructuring and deregulation, which may have important implications for geothermal energy development.

6.2 *Costs of a geothermal power system*

The principal cost components of a geothermal power system are:

- Field exploration costs
- Field development costs for drilling and fluid transmission
- Power plant construction costs

6.2.1 Field exploration costs

These are the costs of locating and evaluating the geothermal resource. They include the cost of hydrologic, geologic, and geophysical measurements or surveys to locate and characterize subsurface formation properties and *in situ* fluid quantity and quality. In addition, exploration costs usually include the cost of land lease or purchase, shallow exploratory drilling, and deep drilling to assess the quality of the reservoir. Their impact on the total capital cost is magnified because field exploration occurs several years before any power is generated. Furthermore, exploratory drilling is a risky process because of the chance of hitting a "dry hole" or finding geothermal fluids that do not meet temperature or heat flow requirements for commercial exploitation of the field. These two factors can discourage developers to invest in geothermal development. Improvements in exploratory drilling technology, such as slim holes, can significantly reduce the cost and risk of the field exploration phase.

6.2.2 Geothermal drilling costs

Geothermal drilling costs are a function of the type of the geothermal resource, the geology and lithology of the site, the depth, temperature, and pressure of the reservoir, and the chemical composition of the geothermal fluid. Because they are based on a number of variables that cannot be specified or calculated, drilling costs tend to vary over a wide range and are difficult to estimate accurately, particularly for new field development. In general, drilling costs are the largest contributor to the capital intensive character of a geothermal power system, as they can account up to 50% of the total capital cost (Milora and Tester, 1976; Finger *et al.*, 1999; Wright, 1998).

Figure 6.1 shows historical and projected drilling costs for hydrothermal, HDR, oil and gas, and ultra-deep wells (Tester and Herzog, 1994). The "problem burdened" line represents the estimated upper limit of drilling costs based on available cost data for first generation completed HDR wells. The "today's technology" cost line represents average well drilling costs for HDR systems using conventional rotary drilling technology. This line is midway between the "problem-burdened" and the "oil and gas average" line which is based on Joint Association Survey (JAS) data for completed oil and gas wells on-shore in the U.S. Novel drilling technologies can shift the cost versus depth relationship from its current exponential dependence to a more linear dependence. The "advanced conventional technology" and "linear drilling technology" lines represent two scenarios for projected improvements to drilling technology and therefore to drilling costs. Cost data for ultra-deep holes suggest that such improvements might be attainable, particularly if more robust drilling methods are developed to reduce wear and optimize penetration rates (Tester *et al.*, 1995).

For Hot Dry Rock systems, the cost of preparing artificial reservoirs should be taken into account when calculating the capital cost of a geothermal power plant. In most cases, this cost is high because it requires complicated fracturing methods for creating a network of fractures with appropriate flow control.

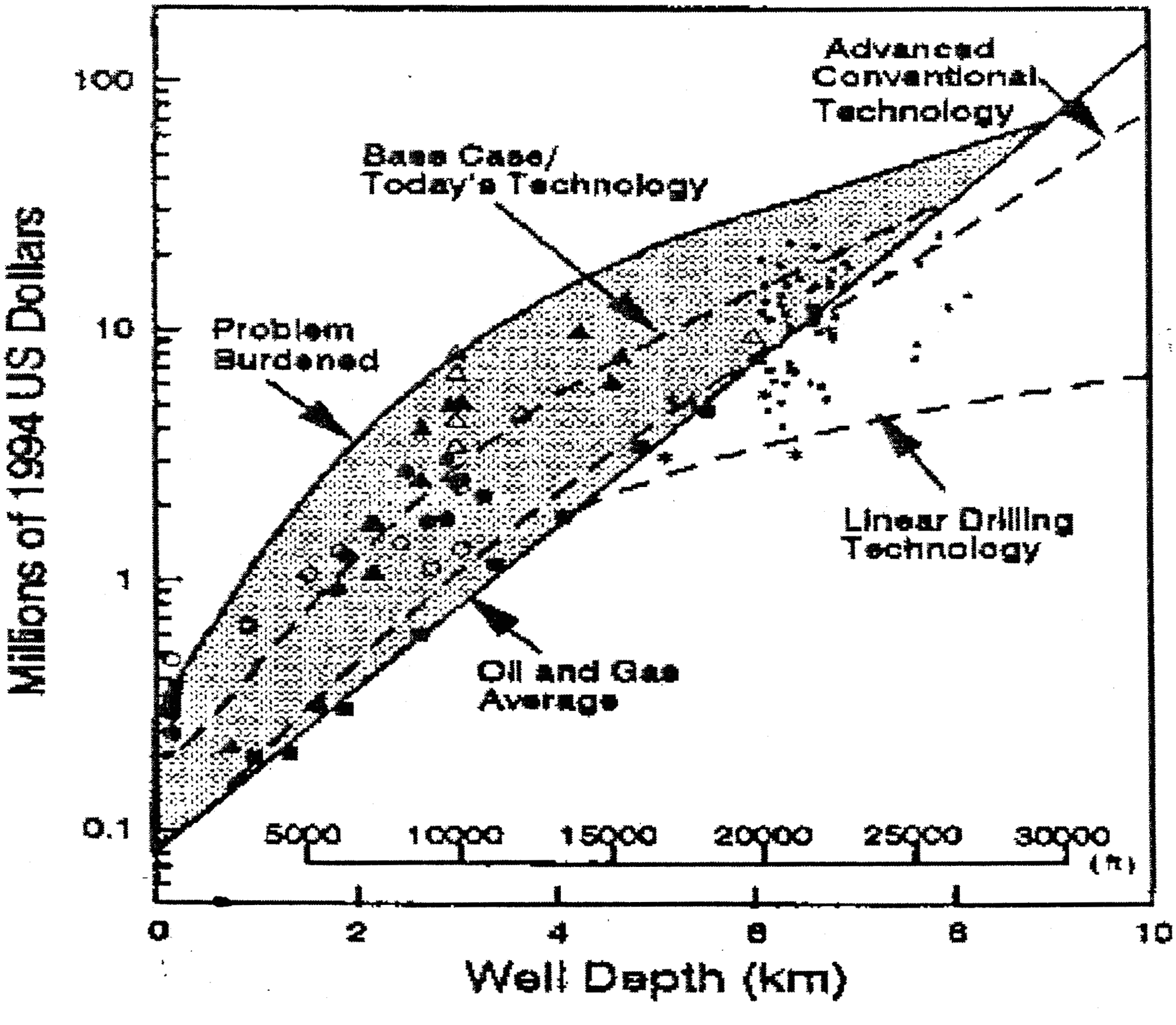

Figure 6.1 Drilling Costs Vs. Well Depth for different levels of technology.
(filled circles: hydrothermal actual; open circles: hydrothermal predicted; filled triangles: HDR actual; open triangles: HDR predicted; small filled squares: JAS ultra deep; large filled squares: JAS correlation; stars: SPE oil and gas)

Source: Tester and Herzog (1994)

6.2.3 Power plant construction costs

Power plant construction costs include the cost of building and installing the equipment of the power plant. They depend on the type of the geothermal resource, and the geothermal fluid temperature and composition. Their major components are the cost of heat exchange equipment, such as primary heat exchangers, condensers and cooling towers; the cost of pumps, such as downhole, fluid circulation and re-injection pumps; and the cost of turbines and generators. Figure 6.2 shows the cost of constructing the surface component of a geothermal system, i.e. the power plant. Drilling costs are not included. The costs of renewable technologies depend on site-specific factors and it is very difficult to estimate them accurately. A range of cost values is given for hydrothermal, HDR, and hydropower systems.

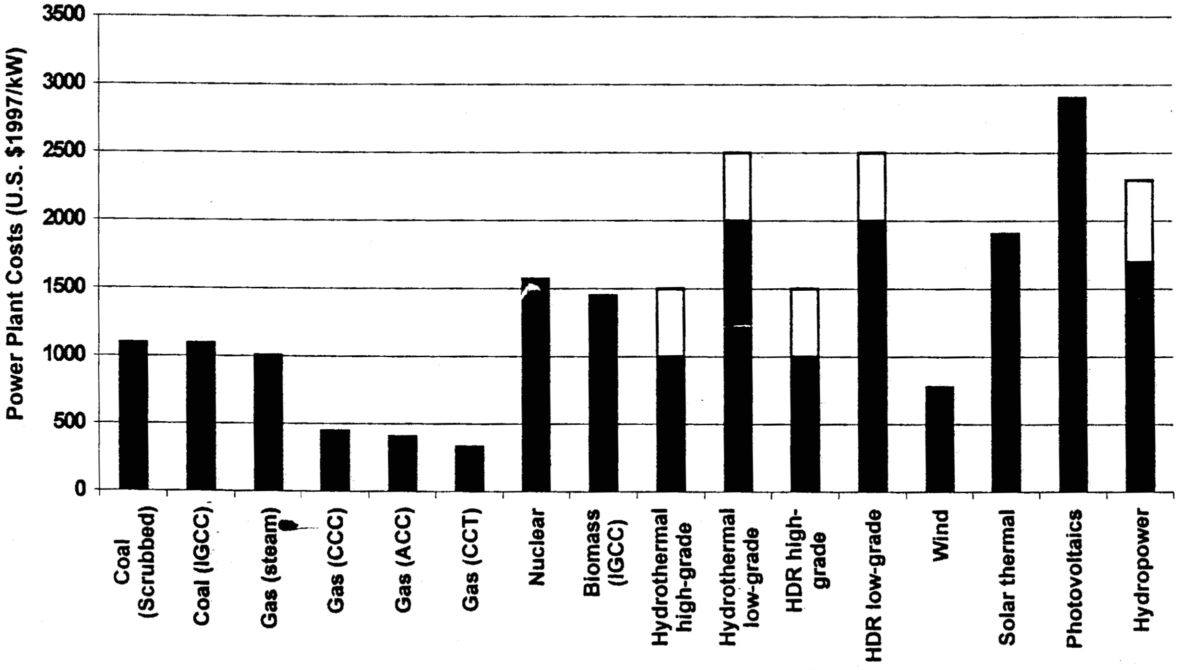

Figure 6.2 Cost of investment for different types of power plants

(IGCC: Integrated Gasification Combined Cycle, CCC: Conventional Combined Cycle, ACC: Advanced Combined Cycle; CCT: Conventional Combustion Turbine)

Source: See Table 6.1

Table 6.1 summarizes the cost characteristics of various power generating technologies. Geothermal systems have a high capital cost where all the fuel costs are included in the initial investment in drilling wells and connecting the fluid production and reinjection piping. These high front-end costs make geothermal power systems less economically attractive than other power plants with lower capital costs. [For example, the average capital cost for a new conventional combustion gas turbine is only $329/kW, making it the least expensive option to build.]

Table 6.1 Cost characteristics of different power systems[a]

Technology	Capacity Factor	Capital Cost ($/kW)	Annualized Capital Cost (¢/kWh)[b]	O&M (¢/kWh)	Fuel Cost or Annualized Well Drilling (¢/kWh)	Levelized Busbar Price (¢/kWh)
Coal (scrubbed)	**60%**	**1,093**	**3.1**	**0.4**	**0.7-4.5**	**4.2-8.0**
Coal (IGCC)	**65%**	**1,091**	**2.9**	**0.1**	**0.6-3.5**	**3.6-6.5**
Gas (steam)	**40%**	**1,004**	**4.3**	**0.1**	**1-2.9**	**5.4-7.3**
Gas (CCC)	**65%**	**445**	**1.2**	**0.1**	**0.7-2.1**	**2-3.4**
Gas (ACC)	**65%**	**405**	**1.1**	**0.1**	**0.6-2**	**1.8-3.2**
Gas (CCT)	**65%**	**329**	**0.9**	**0.1**	**1.1-3.2**	**2.1-4.2**
Hydropower	**45%**	**1,700-2,300**	**6.5-8.8**	**0.2**	**0**	**6.7-9.0**
Nuclear	**65%**	**1,570**	**4.1**	**0.1**	**0.8**	**5**
Biomass (IGCC)	**60%**	**1,448**	**4.1**	**0.6**	**1.6**	**6.3**
Hydrothermal						
High-grade	**75%**	**1,000-1,500**	**2.3-3.4**	**0.3**	**2-3**	**4.6-6.7**
Low-grade	**75%**	**2,000-2,500**	**4.6-5.7**	**0.4**	**4-10**	**9-16.1**
Hot Dry Rock						
High-grade	**75%**	**1,000-1,500**	**2.3-3.4**	**0.3**	**3-4**	**5.6-7.7**
Low-grade	**75%**	**2,000-2,500**	**4.6-5.7**	**0.4**	**20**	**25**
Wind	**30%**	**776**	**4.4**	**0.1**	**0**	**4.5**
Solar thermal	**40%**	**1907**	**8.2**	**0.2**	**0**	**8.4**
Photovoltaics	**26%**	**2903**[c]	**19.1**	**0.1**	**0**	**19.2**

a Values are given in 1997 U.S. dollars.
b Annual cost based on 15% fixed charge rate.
c The cost value is for a 5 MW_e capacity.

Sources: EIA (1998), DOE (1998), Mock *et al.* (1997)

This is particularly the case for independent power producers, which cannot raise capital as easily as large investor-owned or municipality-owned utilities. Also, as the electricity industry becomes more competitive, producers' risk aversion towards large investments will increase, since sales will no longer be guaranteed as they were during the regulated era. Only high-grade hydrothermal resources can compete with conventional power systems in today's electricity market. The economic projections for HDR systems assume reservoir productivities comparable to hydrothermal systems, which, however, have not been demonstrated on site. In general, the high degree of uncertainty that is embedded in the cost calculations of any technology that has not reached the stage of commercial feasibility gives little validity of such computational estimates.

Technologies such as wind turbines and solar photovoltaics have an intermittent nature, which means that they can generate electricity when the wind is blowing and the sun is shining, respectively. These technologies, typically, have a storage system which adds to the cost or have a hybrid operation, e.g. a solar parabolic trough with fossil fuel firing capability to provide thermal energy to a turbine when the sun is not shining. Therefore, these additional costs should be taken into account when comparing the economics of different technologies.

The cost of conventional fossil-fueled technologies depends heavily on the cost of the fuel they use. The low prices of both oil and natural gas in recent years have put geothermally produced power at a competitive disadvantage. However, one should keep in mind the large variability inherent in these prices. If higher oil and gas prices prevail over a period of time, the interest in the development of geothermal resources is expected to increase.

6.3 Capacity Factor

The amount of power generated depends on the capacity factor, i.e. the amount of power produced relative to the maximum possible output. Because fixed costs are constant, the average fixed unit cost (total fixed cost divided by the level of output) increases as the rate of output decreases. This increases the unit cost of electricity generation. In contrast, the unit cost of generation is not affected by the variable cost component, since the total variable cost decreases in proportion to the reduced generation.

As the capacity factor drops, the unit cost of geothermal electricity increases at a higher rate compared to fuel-based technologies (i.e. technologies which have predominantly variable costs) such as coal-fired, gas turbine or diesel engine plants. As a result, from an economic standpoint, geothermal plants need to be operated at a high capacity factor (base load). Typical capacity factors for geothermal plants range from 60% to 85% (EIA, 1997, 1998). However, the average capacity factor for geothermal plants in the U.S. was 55% in 1998. Table 6.2 illustrates the trends of annual net geothermal generation, capacity and capacity factor in the U.S. from 1988 to 1998.

There are two major reasons for the production decline and the low capacity factors in the US. The first one is economics. Low gas prices have reduced the fuel cost component of a gas-fired plant and technological advances in gas turbines have improved their efficiencies in such degree that have render the marginal cost of operations and maintenance for a steam or combined-cycle gas-fired power plant very small compared to geothermal plants.

Table 6.2 Trends in geothermal power generation in the USA

Year	Net Power Generation Million kWh	Installed Capacity MW	Capacity Factor
1989	14,596	2846.6	59%
1990	15,599	2774.6	64%
1991	15,860	2787.6	65%
1992	16,422	2758.7	68%
1993	17,025	2816.7	69%
1994	16,757	2816.7	68%
1995	14,359	2816.7	58%
1996	15,126	n/a	n/a
1997	14,306	n/a	n/a
1998	13,851	2850	55%

Source: EIA, " Electric Power Annual" (1998)

Therefore, power producers prefer to put on-line their gas-fired capacity to generate baseload electricity. For instance, in 1995, a representative long-term geothermal electricity contract provided for firm capacity payments that were about 3 times higher than avoided costs of the Pacific Gas & Electric Company (PG&E) for capacity, whereas the respective payments for the associated energy were 8-10 times higher. As a result, PG&E and its steam suppliers at The Geysers had to renegotiate their contracts in August 1995, so as to lower the price of generation from those steam supplies above the 40% of annual field capacity for which PG&E had take-or pay commitments.

The second reason has to do with the pressure drop at The Geysers field, as was described in Chapter 3. As it became apparent that The Geysers could be depleted, many producers realized that hydrothermal resources must be properly managed rather than "mined for steam", and they curtailed their production schedules. A change in thinking has occurred, with developers aiming to optimize resource exploitation over a 30-year horizon, instead of maximizing the short-term output.

Chapter 7

U.S. DOE Strategic Plan for Geothermal Systems

This chapter will discuss the strategic plan for the Geothermal Energy Program of the U.S. Department of Energy, with particular emphasis on the components of the plan pertaining to Enhanced Geothermal Systems (EGS).

7.1 Strategic goals of the DOE geothermal program

The mission of the Office of Geothermal Technologies of the U.S. Department of Energy is to work in partnership with U.S. industry to establish geothermal energy as a sustainable, environmentally sound, economically competitive contributor to the U.S. and world energy supply. In order to fulfill its mission, it has identified the following five strategic goals (DOE/OGT, 1998):

1. *Electric Power Generation.*

Supply the electrical power needs of 7 million U.S. homes from geothermal energy by the year 2010.

2. *Direct Use Applications and Geothermal Heat Pumps.*

Expand direct uses of geothermal resources and applications of geothermal heat pumps to provide the heating, cooling, and hot water needs of 7 million homes by the year 2010.

3. *International Geothermal Development.*

Meet the energy needs of 100 million people in developing countries by using U.S. geothermal technology to install at least 10000 MW by the year 2010.

4. *Science and Technology.*

Accelerate the development of U.S. geothermal science and technology to ensure that the U.S. continues to lead the world.

5. *Future geothermal resources.*

By the year 2010, develop new technology to meet 10% of U.S. non-transportation energy needs in subsequent years.

7.2 EGS R&D initiative

7.2.1 Motivation and background

A key component in the strategy to achieve the last goal (goal #5) of the strategy plan is DOE's EGS R&D initiative. DOE has coined the term *Enhanced Geothermal Systems* (EGS) to describe geothermal systems which require some form of enhancement to render them commercially viable for development or continued exploitation (McLarty, 1999; Sass and Robertson-Tait, 1998).

EGS differ from currently developed hydrothermal systems in that permeability and porosity may be too low for commercial exploitation and/or the reservoir may be fluid-deficient (either naturally or from production over many years). Enhanced Geothermal Systems fall into three main categories:

a) Marginal areas of hydrothermal systems, where the reservoir is hot, but the permeability is too low for exploitation by conventional means.
b) Permeable but fluid-deficient reservoirs with considerable residual heat.
c) Hot dry rock (HDR) reservoirs, which are not associated with an existing hydrothermal system but consist of hot, low permeability rock.

It should be noted that two major changes in the perception of geothermal resources have occurred in recent years and these are manifested in the EGS R&D initiative:

- First, it has been realized that the geothermal resources contained in subsurface rocks are much more extensive than the resource accessible via naturally occurring hot water or steam. As an example, the production from The Geysers geothermal field has declined by approximately half due to the decline of the geofluid content of the reservoir after 30 years of exploitation. On the other hand, only about 5% of the heat content of the reservoir rock has been extracted. The situation at the Geysers has been described extensively in section 3.3.
- Second, research and experience has shown that developing a project relying upon artificially created permeability alone (e.g. Fenton Hill, N.M) is overly ambitious at present both for technical and economic reasons. Field experience at Fenton Hill has shown that the reservoir is characterized by sealed natural fractures that result in very low matrix permeability. Thus, Fenton Hill is an example of a reservoir that has the temperature gradient required for cost-effective heat mining, but does not have the flow rates required to extract the heat in a commercially viable way. It also revealed that the key problem in achieving reservoir productivities comparable to commercial hydrothermal systems is lowering flow impedance which results from the low permeability of HDR formations as we have already discussed in previous sections of this chapter.

7.2.2 The EGS strategic plan

The EGS program strategic goal is that, by 2010, EGS technical barriers will be largely overcome, and EGS resources will have been identified and evaluated with the potential of supplying 10% of the nation's electricity. The program has specified several milestones as guidelines in achieving its mission:

Milestone 1:

By 1999, have in place a well-organized, functioning program, with strong industry participation, that represents a smooth transition from the findings of DOE's twenty-year HDR R&D program to a program designed to achieve commercial success across a much wider range of types of valuable geothermal resources.

- **Objective 1.1:** Transfer management of the EGS R&D sub-program from a laboratory-based to an industry-based R&D program management organization.
- **Objective 1.2:** Involve U.S. industry to a much higher degree in the development and commercialization of this technology.
- **Objective 1.3:** Transfer the data knowledge developed by the Fenton Hill HDR project and related research to the U.S. geothermal industry, other DOE National Laboratories and other EGS stakeholders.
- **Objective 1.4:** Establish improved communication and coordination of R&D efforts with the HDR/EGS experimental teams in other countries.
- **Objective 1.5:** Develop improved R&D planning and management strategies, tactics, and tools.

Milestone 2:

By 2000, implement research and development and field experiments to begin overcoming the technical barriers to EGS development.

- **Objective 2.1:** Identify and evaluate the technical barriers.
- **Objective 2.2:** Evaluate available technology.
- **Objective 2.3:** Suggest specific R&D to overcome shortcomings.
- **Objective 2.4:** Begin field experiments in 1999.

Milestone 3:

By 2003, identify and focus development efforts on the most promising methodologies and technologies to mitigate barriers and increase EGS energy recovery.

- **Objective 3.1:** Develop predictive and modeling capability of fracturing and other simulation techniques from rock mechanics.
- **Objective 3.2:** Improve technology to understand and define fracture network.
- **Objective 3.3:** Develop numerical modeling techniques to predict fluid flow and heat transfer in fracture networks.
- **Objective 3.4:** Quantify project economics and assess resource potential.
- **Objective 3.5:** Develop EGS site criteria and identify sites that fit those criteria.

Milestone 4:

By 2004, select five prospective EGS sites and initiate projects in cooperation with industry to apply EGS methodologies and demonstrate increased energy recovery.

- **Objective 4.1:** Match sites with EGS technologies.
- **Objective 4.2:** Enlist industry participation in cooperative projects.
- **Objective 4.3:** Design, perform, and evaluate the projects.

Milestone 5:

By 2008, complete development and begin operating a cost-shared, comprehensive, pilot-scale, demonstration project at an EGS site.

- **Objective 5.1:** Select best technologies and a highly appropriate site.
- **Objective 5.2:** Design, build, and operate the project.
- **Objective 5.3:** Increase political, non-profit organization, and public support-base for EGS research, development and demonstration to help ensure adequate R&D funding.

Milestone 6:

By 2010, analyze results of pilot and make conclusions about technical and economic feasibility.

- **Objective 6.1:** Analyze results.
- **Objective 6.2:** Reach conclusions about technical and economic feasibility.
- **Objective 6.3:** Widely disseminate the results and conclusions.

7.3 Commentary of the EGS strategic plan

Formulating an EGS geothermal plan, the DOE is trying to refocus its efforts to develop technology for a broad range of geothermal resources. However, it is not clear whether it is sufficient to address successfully the pressing problems geothermal systems are facing.

- En route to the first milestone, in October 1997, the DOE selected a team of private contractors, Princeton Economic Research, Inc. and GeothermEx, Inc. (PERI/GX), to manage the EGS R&D Initiative. The team has helped institute a small industry advisory group, called the EGS National Coordinating Committee (NCC).

Unfortunately, this committee does not involve any representatives from the academic community, which could provide complementary skills and expertise.

- Two of the most important technical barriers to EGS development require significant progress in drilling and reservoir technology. R&D in these areas is coordinated by the Geothermal Drilling Organization and the Geothermal Reservoir Initiative respectively. Therefore, it is essential to establish close cooperation and exchange of information with these offices, to avoid duplication of efforts and ensure that progress in one of these areas can quickly be implemented in the others.

- As part of the EGS R&D, it is proposed that the EGS-Hydrothermal Dual-Use approach will be used as a main criterion for deciding what specific research projects to fund. In other words, for the near-term, research should target hot, low permeability zones within or near the margins of commercially developed hydrothermal systems. However, it is unclear whether R&D conducted at the margins of hydrothermal resources is transferable to HDR. Research at Fenton Hill has revealed that the key problem in achieving HDR reservoir productivities comparable to commercial hydrothermal systems is lowering flow impedance which results from the low permeability of HDR formations, as we have already discussed in chapter 1. Thus, specific care must be taken, so that the available funding is indeed used in a way beneficial to both hydrothermal and HDR development. The different characteristics of the resources included under the umbrella of EGS must be well understood to determine whether research on the high-end portion of the spectrum of EGS (marginal hydrothermal systems) is applicable to the low-end portion (HDR).

- The current EGS plan correctly acknowledges the importance of political and public support for securing R&D funding. However, R&D funding cannot by itself deploy geothermal systems to a competitive electricity market. The DOE should assist in efforts to generate public and political support for policy measures. Such policy measures will be recommended in Chapter 8.

- The plan does not provide any specifics as to how to attract potential cost-sharing partners from among the power generation industry. This may prove to be difficult to achieve, given that these companies usually engage in power production from several sources, which may be more profitable than geothermal, e.g. natural gas. Recently, some producers (Unocal, CalEnergy) have divested their geothermal assets, while others plan to do so in the near future (e.g. PG&E).

In conclusion, although the strategic plan addresses some near-term R&D opportunities for the development of Enhanced Geothermal Systems, clearly, a much more innovative, longer-term, and bolder strategy should be followed to enable the U.S. geothermal industry become competitive both domestically and internationally. DOE should assume more prominent leadership position in this endeavor and should spearhead the effort to secure sufficient R&D funding. In particular, DOE should ensure that HDR development continue and not yield to the temptation of concentrating only on hydrothermal-related R&D to satisfy the desires of the geothermal power producers. At present, geothermal energy is not recognized as a viable energy option by most majority of people. DOE should take a lead in lobbying efforts to ensure public and political support.

Chapter 8

Conclusions and Recommendations

CONCLUSIONS

This thesis has provided an evaluation for the potential growth of geothermal power systems. While it may be difficult to predict the future, it is clear that, as scientific evidence about the adverse impacts of greenhouse gases and, especially, CO_2 is accumulating, the need for clean power generation will grow. Geothermal power systems can become an important electricity supply option, as they are an environmentally friendly and safe technology, and, unlike most renewables, can provide baseload power.

The main focus of this thesis was on two distinct categories of geothermal resources: Hydrothermal and Hot Dry Rock. The hydrothermal resource base is estimated at about 130,000 quads and HDR at about $1.05*10^8$ quads. Taking into consideration that the current annual energy consumption is 350 quads and is expected to reach 612 quads in 2020, the available heat content of hydrothermal and HDR is sufficient to supply the world's energy needs for hundreds of years.

Currently, these two types of geothermal resources have reached different levels of development and deployment. Hydrothermal power systems have found commercial applications in areas with high-grade hydrothermal resources, whereas HDR systems are still in an experimental stage. Being at different stages of research, development and deployment, hydrothermal and HDR power systems encounter significantly different obstacles in penetrating the electricity market.

- Hydrothermal Systems:

The predominant barriers to widespread adoption of hydrothermal systems are economic, such as difficulty in attracting capital, high up-front capital requirements, high cost of electricity production, and competition from fossil-fueled power systems.

- HDR Systems:

Although the scientific concept of heat mining from low permeability hot rock formations has been proved on site, research efforts have not succeeded so far in creating a commercially feasible HDR system. The major barriers HDR systems face are associated with high drilling costs stemming from lack of appropriate drilling materials and methods, and with great uncertainties resulting from poor understanding of the reservoir behavior, the thermal productivity and the lifetime of the system.

This thesis makes recommendations on policies and measures to reduce the barriers that hydrothermal and HDR systems encounter. The goal of these recommendations is to address the economic barriers making possible for hydrothermal systems to contribute to electric power generation in the short-term and to advance HDR systems so that they can contribute substantially in the long-term.

RECOMMEDATIONS

- **Measures to address the economic impediments:**

1) Full cost pricing

Financial measures to incorporate social and environmental costs into energy prices would clearly favor geothermal systems, as they are an environmentally benign technology. Mechanisms for including the cost could involve a carbon tax on fuels or emissions, or a system of tradable permits. Furthermore, conventional power technologies are subsidized in many energy markets in the world. Removal of these subsidies could improve the economic attractiveness of geothermal systems.

2) Green markets

The creation of green markets, whereby customers voluntarily pay a premium for their electricity if it is produced from environmentally friendly sources, could create a stream of private finance for geothermal energy projects. Possible actions to increase the consumers' demand for geothermal energy and their willingness to pay a premium include the provision of public education material to explain the benefits of geothermal energy, and development of electricity labeling on consumers' electric bill so that they can see which sources of power generation their payment supported.

3) Renewable-energy Portfolio Standard

Imposing a renewable-energy portfolio standard (RPS) that requires that a minimum quantity of all power generation be produced by renewables can give an incentive for geothermal energy production. In the U.S. the terms of RPS vary among States, but the minimum requirement starts at 2.5% in the year 2000 and climbs incrementally to 20% in 2020. The requirement can be placed on either the power producers or the distribution companies. In addition, the RPS can provide assurance to geothermal developers by guaranteeing markets for their power.

4) Guaranteed loans and tax incentives

In order to promote geothermal development, it is very important for a government to establish long-term confidence in the market. Measures include the setting of guidelines for utilities and regulators regarding charging structures for new grid connections, guaranteed purchase schemes, such as government procurement, premium prices and buy-back rates, and provision of fiscal incentives in the form of low- or zero-interest loans or investment grants as a means to overcome barriers associated with the high capital investment. Furthermore, insurance programs to insure developers against early depletion of geothermal reservoirs should be considered.

In the 1970's, the U.S. government introduced the "Geothermal Loan Guarantee Program" with the objective to assist the private sector in accelerating the development of geothermal projects. The program covered about 75% of the fixed capital cost with the private sector providing the remaining 25%. The program was not a great success for three reasons: (1) the geothermal technology was not mature enough thirty years ago, (2) the private sector considered the 25% risk to be too high in many cases, and (3) the program covered only fixed costs, and as a result it did not eliminate the risk of resource depletion or extended power plant outages that could create significant problems to the investors (Tester, 1982). Today, however, due to technological achievements and the accumulated knowledge from past experience such a program could provide a very good stimulation mechanism for geothermal development.

Other economic incentives equivalent to capital subsidies are tax exemptions, tax reductions, credits and deferrals.

5) Lobbying

A successful lobbying strategy is critical to the promotion of geothermal systems. The size of the geothermal constituency is small relative to other renewable alternatives, such as wind and solar power. Thus, as many of the proposed measures to promote renewables are not resource-specific, the geothermal community may face difficulties in benefiting from them. The geothermal community should take action in order to increase its base of support. This can be achieved by educating the general public, the media, and public officers about the amenities of geothermal energy. Information mechanisms may include organizing workshops, direct presentations, publishing of articles in major journals and newspapers. Furthermore, the wide acceptance of geothermal power systems will be advanced by the demonstration of the feasibility of electric power production from geothermal resources in various parts of the country.

- **Measures to address the technical impediments:**

The prospects of HDR development will grow once we achieve to develop a commercially feasible HDR system. The main form of action for addressing the technical obstacles is through Research and Development (R&D). Regarding HDR R&D, efforts should be two-fold, emphasizing the development of novel exploration and drilling technologies, as well as energy conversion and utilization technologies. More specifically, R&D programs should focus on the development of: (1) improved drilling and excavation technologies and materials that can handle high temperatures and hard rock formations and reduce drilling costs, (2) advanced reservoir diagnostics, rock fracturing, reservoir stimulation and modeling techniques to gain a better understanding of the behavior of an HDR reservoir, and to reduce field development costs, and (3) enhanced energy conversion cycle designs to improve the performance of the power plant. A critical step for the development of HDR systems is that technological improvements need to be proved on site in order to obtain actual experience. The private sector should be involved in the selection of demonstration sites since they will ultimately be the users of the technology.

DOE's EGS strategic plan addresses these issues in the context of EGS and dual-use approach. However, care should be taken that results stemming from this R&D effort are transferable and beneficial to HDR development.

A combination of economic incentives and well-designed R&D programs is necessary to lead a consistent overall effort to promote the commercial viability of geothermal power systems. As the technological parameters improve and the economic barriers are surmounted the number of geothermal sites that will be good candidates for commercial exploitation will increase, and this will lead geothermal industry to a sustainable growth.

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