Future Energy: Opportunities and Challenges

Part II. Energy Sources

Chapter 10. Geothermal Energy

Future Energy:
Opportunities and Challenges

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10
Geothermal Energy

The Main Points

- **At depths of around 30 feet, soil temperature is nearly constant year-round.**
- **At depths greater than around 400 feet, temperature increases with depth (1.0 to 1.7^{o}F per 100 feet).**
- **In some locations, hydrothermal sources exist. These sites have near-surface hot rock with adequate permeability to allow naturally occurring water to capture heat.**
- **Enhanced geothermal systems are those in which permeability is induced in hot, dry rock by fracturing and water is then injected.**
- **Enhanced geothermal systems are potentially a very large energy source, but the effort that would be needed to modify huge underground rock formations is also large.**
- **Geothermal heat pumps exploit the constant near-surface underground conditions as a heat source or heat sink as needed.**

10.1 Introduction

The interior of the earth is hot. Some of the heat is attributed to energy released in the initial formation of the planet. In addition, radioactivity of elements in the earth produces a huge amount of heat energy. Heat flow to the surface is impeded by the rather poor heat transfer characteristics of the materials that comprise the earth's interior. This trapped heat has raised the temperature of earth materials. In some locations, this hot material is near the surface, and occasionally lava reaches the surface in volcanic eruptions. In some locations, water that has seeped into the depths is heated and trapped, or returns to the surface as hot water or steam. This "free" energy is there for the taking.

In addition, hot dry rock lies beneath the earth's entire surface and is a potential future source of useful energy. Accessing this energy requires human intervention to modify sub-surface conditions and to introduce water for transporting energy to the surface.

The earth also provides an opportunity to increase the efficiency of heating and cooling with heat pumps. The near constant temperature that exists a few feet below the earth's surface is better suited than ambient air for use as a heat source or heat sink in heat pump applications.

At the time this chapter was written, increased interest and activity related to geothermal energy was apparent. Numerous publications appeared, most notably three reports, one by the Massachusetts of Technology,[1] one by the U.S. Geological Survey,[2] and one by the U.S. Department of Energy[3]. Information from these reports was used extensively in preparing this chapter.

10.2 Sub-Surface Conditions

The earth has a radius of approximately 4,000 miles. The interior consists of three main concentric regions. The innermost region, the core, extends from depths from 1,800 miles to 4,000 miles. The core itself consists of two regions: the solid inner core and the liquid outer core. The intermediate concentric region is a 1,800-mile-thick region called the mantle, also consisting of two regions. The temperature ranges from around 2,000°F at the top of the mantle to over 8,000°F in the core. The top part of the mantle is a hot liquid rock called magma. The thin topmost layer (around 15 to 45 miles thick under landmasses) is the crust on which we live (see Figure 10-1).

The high subterranean temperatures provide a driving force that causes a continuous flow of heat to the earth's surface. The total rate of heat flow to the surface from the earth's interior is estimated to be about 45 million megawatts[4] (around 1,300 Quads per year). This is a huge amount of power, but it is less than one-thousandth as large as the solar radiation power absorbed by the earth's surface (as shown in Chapter 5, this is about 174

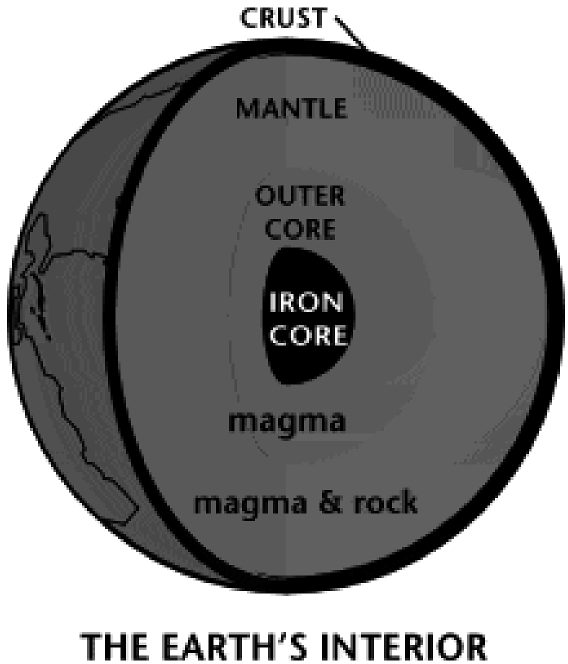

Figure 10-1. The Earth's Interior (courtesy of U.S. Dept. of Energy)

watts per square meter or 22 billion megawatts for the total earth surface). 45 million megawatts is approximately the thermal power that could be produced by 14,000 very large nuclear power plants. (Nevertheless, it is so small compared to incoming solar power that it plays an insignificant role in weather.)

The earth produces energy flow (power), and it contains stored energy in hot rocks. Exploitation of the earth's heat for practical purposes involves the extraction of a portion of the stored energy.

To a depth of 200 to 400 feet, atmospheric conditions and circulating ground water dominate temperatures. At greater depths, these effects become small compared to the effect of heat flow from the interior. The temperature of the earth below about 400 feet increases as depth increases. This increase is quantified by the geothermal gradient, defined as the temperature increase per unit increase in depth. The geothermal gradient is expressed as °C/km or °F/100 ft[5]. Geothermal gradient values range from about 17 to 30°C/km or 1.0 to 1.7°F/100 feet.

To extract energy from the stored subterranean heat, the heat must be transferred to a liquid or gas that can carry the energy to the surface. The ability of underground material to allow fluid passage is determined by its porosity and permeability, defined as follows:

- Porosity: The percentage of open spaces within rock.

- Permeability: The ability of pores in rock to permit the flow of liquids or gases under a pressure gradient. This ability depends on the connection between pores as needed to permit flow.

Access to rocks with adequate permeability is necessary for extracting geothermal energy. Adequate permeability occurs naturally in some rock formations and can be induced in others.

10.3 The Resource

In view of the amount of geothermal energy possibly within reach, it is important to assess the potential of geothermal energy to become a significant contributor to total energy supply. There are two types of geothermal energy systems: hydrothermal systems and enhanced geothermal systems. The necessary condition for either type of geothermal system is the presence of hot rocks with adequate permeability to permit the required flow of water.

Hydrothermal systems are those in which the necessary rock condition occurs naturally, and the necessary water is naturally present. Extracting the energy is basically a matter of drilling an extraction well. Enhanced geothermal systems (sometimes called engineered geothermal systems) are those in which subsurface rocks are modified by human intervention, and water is then introduced to be heated and brought to the surface.

The size of the geothermal resource that can be exploited for practical energy production remains a subject characterized by considerable uncertainty. For example, on page 10 of a 2003 U.S. Geological Survey (USGS) report[2], it is stated that "With current and foreseeable technologies, the hydrothermal environment is the only commercially exploitable form of geothermal energy for producing electricity." Then, only five years later, the USGS published a new assessment[5] that estimated that the potential for enhanced geothermal systems in the U.S. is 517,800 megawatts of electricity (equal to the power from over 500 large nuclear power plants). Another important publication by an MIT-led interdisciplinary panel[1] concluded that enhanced geothermal systems could provide 100,000 megawatts of competitive electricity within 50 years. The rapidly-changing assessments and the lack of agreement between highly-qualified teams underscore the difficulty and uncertainty associated with assessing the technical and economic potential of enhanced geothermal systems. Nevertheless, the important conclusion is that, while experts may disagree on the size of the usable geothermal resource, they agree that enhanced geothermal systems have the potential to contribute significantly to satisfying future energy needs.

Extracting geothermal energy requires drilling into the earth to reach the stored energy. A huge body of technology has been developed for drilling oil and gas wells. Even though this technology is not totally applicable to geothermal applications, it gives confidence that geothermal wells could reach depths of up to 6 miles as needed for extracting useful energy.

10.4 Hydrothermal Sources

As defined above, underground formations with adequate stored heat energy, adequate natural permeability, and adequate natural sources of water feeding the formation are called *hydrothermal sources*. These sites are generally located in regions where tectonic plates intersect. Motion of the plates creates fracture zones in the rock that allow water to enter and receive heat. The resulting hot water or steam can rise to the surface or be trapped underground by overhead rock.

Drilling into hydrothermal sources releases steam or hot water. These sources are the easiest geothermal sources to exploit. They account for all of the geothermal energy currently produced worldwide. The occurrence of this fortuitous combination of conditions for providing hydrothermal sources is not common, and all U.S. sites are in western states.

The steam or hot water is brought to the surface and used to power a turbine-generator to produce electricity or used directly for space heating. The water remaining can be released on the surface or, more commonly, pumped back into the hydrothermal reservoir.

10.5 Enhanced Geothermal Systems

Hot, dry rocks contain much more stored energy than hydrothermal sources, and they exist under all the earth's surface; however, they lack permeability and natural water supplies. To exploit this energy resource, it is necessary to create the necessary permeability and then to pump water (or other fluid) through the rock to extract the heat. Geothermal sources that are stimulated in this way are called enhanced geothermal systems.

The first step in creating an enhanced geothermal system is to drill one or more wells into the hot rock. Then high-pressure water, possibly containing chemicals to enhance fracturing, is injected. The purpose of doing this is to create many small passages that maintain intimate contact between the water and the surrounding rock. Large passages are undesirable because they would permit channeled water flow through the rock formation without the contact required to extract heat efficiently from the rock. The process is called hydrofracturing, and its viability has been demonstrated in the oil and gas industries. The oil and gas experience suggests the desirability of including proppants in the injected water. Proppants are small solid particles whose purpose is to keep passages open once they have been created by hydrofracturing.

After hydrofracturing is complete, water is introduced under pressure into the fractured zone through one or more injection wells. One or more production wells provide a lower pressure region to which the injected water flows. The temperature of the injected water increases as it passes through the fractured zone, producing steam or hot liquid water. Ideally, the fractured zone is surrounded by impermeable rock, thereby avoiding the loss of injected water. Water loss is an issue in determining the suitability of a location for an enhanced geothermal system, especially in regions where water is scarce.

Rock temperature increases with well depth, but well depth is limited by available drilling capability, especially for drilling in hot, deep environments. Facilities with extracted fluid temperatures of 250 to 300°F are mainly useful for space heating applications. Fluids from deeper wells with higher temperatures (currently up to around 700°F) are useful for producing electrical energy.

Energy extraction from hydrofractured rock will cool the rock over time, causing the energy extraction capacity to decrease. At some point, extraction would cease. Heat transfer from surrounding rocks would then slowly re-heat the rocks in the idle fracture zone, permitting resumption of energy extraction after decades of rest (possibly 100 years)[1].

The amount of useful energy available from an enhanced geothermal system depends on the fractured rock volume in contact with the water, the temperature drop induced by heat transfer from the rock to the water, and the efficiency of conversion of the extracted thermal energy into useful energy (typically electricity). The electrical energy production is given by

$$E = \rho V C \Delta T e \tag{10-1}$$

where

E	=	useful energy (BTU)
ρ	=	rock density (approximately 160 pounds per cubic foot)
V	=	fractured rock volume (cubic feet)
C	=	rock-specific heat capacity (approximately 0.24 BTU per pound per degree Fahrenheit)

ΔT	=	temperature drop in rock during duration of extraction period (degrees F)
e	=	efficiency of conversion from thermal energy in extracted fluid to electrical energy

Substituting values for density and specific heat capacity and expressing fractured rock volume in cubic miles gives:

$$V\Delta Te = 177E(\text{in Quads}) \tag{10-2}$$

The weight, W, of the rock that must be fractured is given by

$$W = E/C\Delta Te \tag{10-3}$$

Substituting the value for C, expressing E in Quads, and expressing W in millions of tons give:

$$W(\text{millions of tons}) = 2{,}100 \times E/(\Delta Te) \tag{10-4}$$

Finally, the average power is given by the energy extraction per unit time. Converting energy into megawatt-hours and introducing the duration of operation of the system, Y, gives

$$P = 190V\Delta Te/Y \tag{10-5}$$

Example 10.1
It is desired to obtain 1 Quad of energy from a rock formation by reducing the rock temperature by 100°F, with conversion to electricity occurring with an average efficiency of 0.15. The lifetime of the system is taken to be 20 years.

The volume of fractured rock required is:

$$V = 17/(100 \times 0.15) = 11.8 \text{ cubic miles.}$$

The weight of rock to be fractured is:

$$W = 2{,}100 \times 1/(100 \times 0.15) = 140 \text{ million tons.}$$

The average power is:

$$P = 190 \times 11.8 \times 100 \times .15/20 = 1{,}682 \text{ megawatts.}$$

This example illustrates the promise and the limitation of enhanced geothermal system energy. 1,682 megawatts is a lot of power (comparable to that of a very large nuclear power plant), but 140 million tons is a lot of rock to access and fracture.

The technology for enhanced geothermal systems is fully formulated, but as yet, it is unproven. The estimated energy available from enhanced geothermal sources is enormous; it provides energy with little or no pollution, and it avoids expenditures for foreign energy supplies. However, the practicality of creating suitably large underground fracture zones is yet to be demonstrated. To obtain a significant quantity of energy from enhanced geothermal energy would require the creation of thousands of cubic miles of fractured rock far below the earth's surface.

10.6 Geothermal Energy for Heat and Electricity

The ubiquity of potential enhanced geothermal energy sites creates the possibility of locating energy sources close to the locations where the energy would be consumed. This would reduce the costs and energy losses associated with long-distance electricity transmission or fuel transport.

Proximity of energy sources and energy consumers also increases the possibility of using hot water for space heating in buildings. Hot water pumped through insulated pipes could deliver heat to homes, businesses, and factories near a geothermal source. This technology has already been implemented in those locations where hydrothermal sources are close to energy consumers. Tapping the energy in enhanced geothermal sources would open the possibility for geothermal space heating in many more locations.

Electricity may be produced using geothermal energy as a source of steam to drive turbine-generators. Three types of geothermal power plants are envisioned. In locations where dry steam is available, power plants would use steam fed directly to a turbine. In locations where hot water or steam-water mixtures are available, a flash steam system could be used. In flash steam systems, the water or steam-water mixture is introduced into a lower pressure region where evaporation produces steam to be fed to a turbine. In locations where the geothermal fluid temperature is lower (200 to 300^{o}F), a binary cycle power plant would be used. In binary cycle power plants, heat is transferred to a second fluid with a lower boiling point than water, and the resulting vapor drives a turbine. These systems are illustrated in Figures 10-2 through 10-4. In all three types of geothermal power plants, the water drawn from the underground formation is pumped back into the formation.

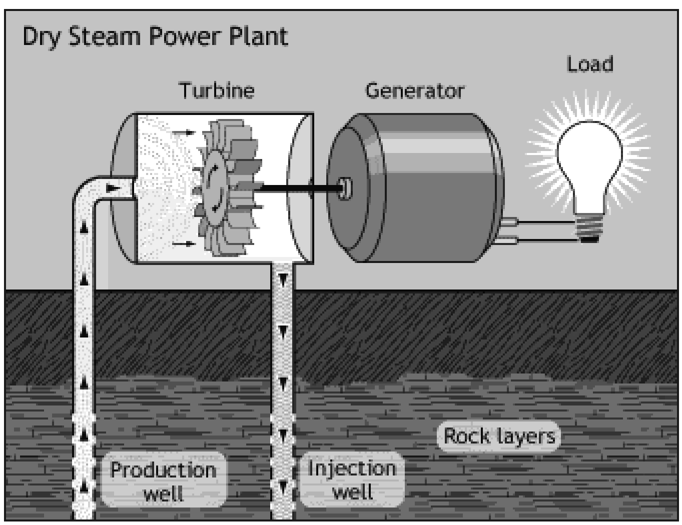

Figure 10-2. A Dry-Steam Geothermal Power Plant
(courtesy of U.S. Dept. of Energy)

The conversion of heat energy to electrical energy is limited by the thermodynamic efficiency of the process. As shown in Section 2.6, thermodynamic efficiency increases with increasing temperature of the working fluid. Because of the lower temperature of available working fluids, geothermal

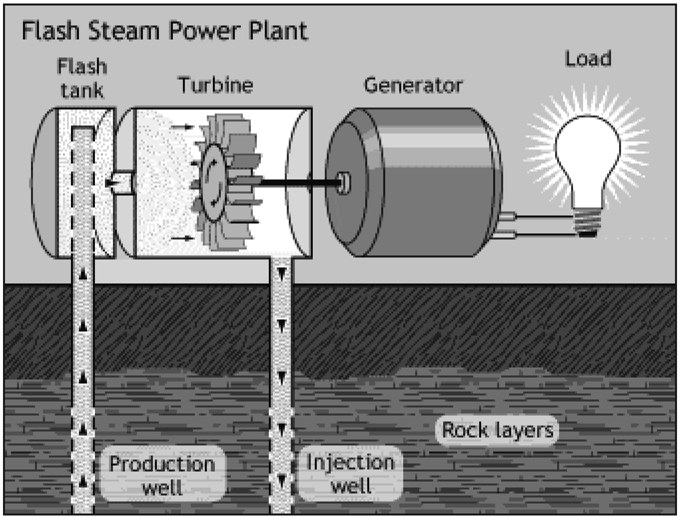

Figure 10-3. A Flash-Steam Geothermal Power Plant
(courtesy of U.S. Dept. of Energy)

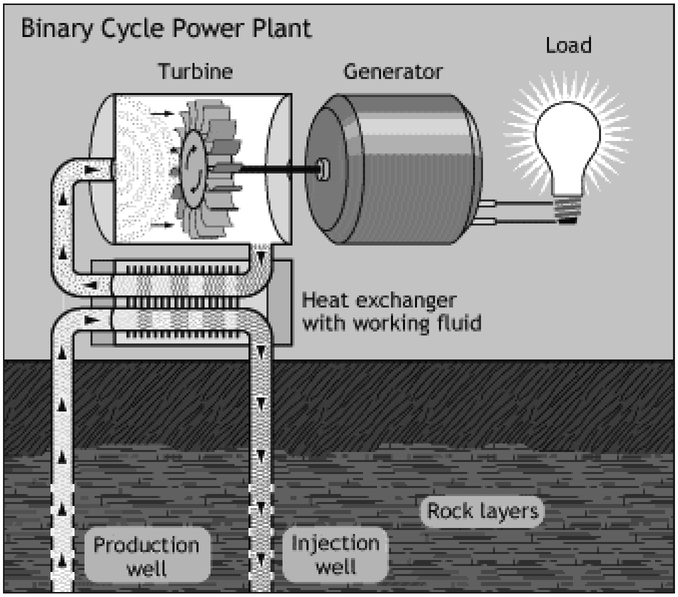

Figure 10-4. A Binary-Cycle Geothermal Power Plant
(courtesy of U.S. Dept. of Energy)

power plants have considerably lower thermodynamic efficiencies than fossil or nuclear plants. Typical efficiencies are 10 to 20 percent.

Thermal power plants such as geothermal plants must provide some sort of cooling to condense the vapor leaving the turbine. The most efficient cooling means is with water, in which heat is transferred to water in a lake, river, or ocean, or to water that extracts heat by vaporizing in a cooling tower. Where sufficient water is unavailable, ambient air may be used to condense turbine exhaust, but air cooling is much less efficient. Consequently, the availability of water for the power plant as well as water for the makeup of lost water from the fracture zone is a factor in determining whether a geothermal power plant would be practical in a particular location.

10.7 Environmental Effects

Geothermal energy is usually considered to be pollution-free. Some gases (including carbon dioxide) contained in the rock formation may be brought to the surface with the heat transfer fluid. However, the release of gases into the atmosphere is so small compared to fossil power plant releases that the emissions are considered insignificant.

Since the power plant on the surface is small compared to the size of the subsurface reservoir, the impact of geothermal energy production on surface land is small. The small surface footprint makes it feasible to locate facilities where large conventional power plants would be unacceptable.

The main concern about the environmental effects of geothermal power plants is the possible need for water for condensing turbine exhaust and for makeup of any losses of the water injected into the underground formation. There is also some concern about stimulating seismic activity by the massive alteration of rock characteristics required for enhanced geothermal systems.

10.8 Heat Pumps

The basic idea of a heat pump is to use mechanical energy to extract heat from a cooler region and deposit it in a warmer region (see Appendix K). The heat pump drives heat in the opposite direction that it would flow naturally. A familiar example is a typical home refrigerator. It employs a compressor that uses the mechanical energy from a motor. The refrigerator pumps heat from its cool interior into warmer room air. (Heat pump applications are discussed in Section 15.3.3.)

A heat pump enables a space of interest to be warmed or cooled. The space that accepts heat in a cooling application or provides heat in a heating application is called a reservoir. In conventional heat pump applications, the reservoir is ambient air. However, heat extraction is more efficient when the reservoir is warmer, and heat deposition is more efficient when the reservoir is cooler. Unfortunately, ambient air is coolest when heat is most needed (winter) and warmest when cooling is most needed (summer).

Heat pump performance is enhanced when the reservoir temperature is lower than ambient air temperature in summer and higher in winter. These are exactly the conditions found in soil, rock, and groundwater located near the surface and in bodies of water. Tubes carrying refrigerant can be immersed in these regions to extract or deposit heat energy according to seasonal requirements. Doing this increases the initial cost of a heat pump installation but reduces subsequent energy costs.

To work effectively, the heat transfer tubes must be in good thermal contact with their surroundings. This means that heat can move readily between the heat exchange region and surrounding regions by conduction and/or water movement. If this condition is not met, the heat exchange region will cool down during heat extraction or heat up during heat deposition, and thereby lose its ability to supply or absorb heat.

10.9 Conclusions

Geothermal energy can be obtained from three sources: hydrothermal systems that possess desirable attributes naturally, enhanced geothermal systems that require deep drilling, hydrofracturing of rock, and supplying water for energy extraction, and geothermal heat pumps that use near-surface earth or water in lakes or rivers as a heat source or heat sink. Widespread use of geothermal heat pumps could contribute significantly to America's energy future if they become commonplace.

It is very tempting to say that the answer to our future energy supply problems lies beneath our feet. The geothermal energy source should be pursued vigorously, but the technical and economic challenges must not be minimized.

References

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Exercises

10-1. Estimate the subterranean temperature at a depth of three miles.

10-2. How much thermal energy (BTUs and kilowatt-hours) is stored in a cubic mile of rock with a temperature of 600°F and recoverable by heat transfer to a medium at 100°F?

10-3. How many tons of rock must be accessed and fractured to extract one Quad of thermal energy by heat transfer to water that reduces the rock temperature by 400°F?

10-4. Use the Internet to discover the current state of enhanced (engineered) geothermal technology and application. Discuss your findings. Are you optimistic or pessimistic about the future potential of engineered geothermal systems? Explain your reasons.