GEOTHERMAL POWER

Electric power was first produced from geothermal energy in 1904 when a 560 W generator was placed in operation at the Larderello steam field in the Tuscany region of Italy. It was not until 1960 that geothermal power was first generated in the United States (at The Geysers, California) (1). Since then, geothermal power capacity has expanded worldwide to over 6925 MW (of which 2850 MW is installed in the United States). Although geothermal energy represents an extremely large worldwide resource, its exploitation has been slow. Its commercial viability depends upon a number of factors: technical, economic, legal, and environmental. There is a special need for technological improvement: (1) in the geosciences to help locate and characterize geothermal resources, (2) in hard-rock drilling to reduce geothermal drilling costs, which are currently up to three times oil and gas drilling costs, and (3) in energy conversion systems to decrease the cost of producing electricity by reducing power plant capital costs as well as reducing the costs of operations and maintenance.

THE NATURE OF GEOTHERMAL RESOURCES

Geothermal energy is the generic term for the heat energy of the earth, which is contained in magma, underground rocks, and fluids. Volcanoes, geysers, fumaroles, and mineral springs represent surface manifestations of this ubiquitous source of energy, whose origin lies in (1) the decay of natural radioactive elements in the crust of the earth, (2) the residual

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

heat of planetary formation (from the kinetic and potential energy of material accreted by the early earth), and (3) the heat generated by the friction of tectonic plates grinding against one another.

At certain locations, the earth's crust thins or cracks, and magma rises close to the surface, occasionally penetrating to create hot molten fissures or volcanoes. In other cases, it comes close to the surface, transferring heat by conduction to rocks or underground bodies of water. The geysers and hot springs observed at Yellowstone National Park are graphic examples of manifestations of near-surface hot spots. It is such hot spots that represent attractive targets for the commercial generation of electricity.

Geothermal resources can be classified based upon their intrinsic properties as hydrothermal, geopressured, hot dry rock, or magma. *Hydrothermal* resources consist of naturally occurring steam or hot water carried upward by convective circulation. The porosity of the underlying reservoir rocks determines the total amount of fluid available; their permeability determines the rate at which fluid can be produced. These resources are found from several hundred to 4300 m beneath the earth's surface with temperatures up to 400°C. Hydrothermal resources are the easiest geothermal resource to access and the only resource currently exploited commercially.

The other three geothermal resources will require advanced technology before becoming commercial. *Geopressured* resources consist of hot pressurized brines containing dissolved natural gas, lying at depths ranging from 3600 m to over 6000 m, and characterized by temperatures of 50° to 260°C, pressures 50 MPa to 140 MPa, salinities of 20,000 to 300,000 parts per million, and gas content of 0.7 m^3 to 3 m^3 of methane per barrel of brine (2). The unique advantage of geopressured resources is that they contain three forms of energy—thermal, chemical, and hydraulic—which can be converted individually or in combination to generate electricity. *Hot dry rock* resources consist of hot, relatively water-free rocks at depths of 2400 m to 9000 m, with temperatures up to 350°C. These hot rocks have few pore spaces or fractures; hence, they contain little water and little or no interconnected permeability. Heat can be extracted from the rocks by creating artificial fractures connecting two wells, injecting water through one well and recovering the hot fluid through the second well, extracting the heat therefrom for the generation of electricity (3). *Magma* resources are molten or partially molten rock within the upper 10,000 m of the earth's crust with temperatures as high as 1300°C. Magma comes close to the earth's surface primarily at the edges of the major tectonic plates that float on the molten underlying mantle. As the tectonic plates move apart from one another (producing rift zones or spreading centers) or subduct one under the other, magma rises close to the surface. Occasionally, as in the creation of the Hawaiian Island chain, a geological "hot spot" continuously extrudes magma as a tectonic plate slowly moves over it.

Individually, or together, these geothermal resources represent a major source of energy for the world. The US Geological Survey defines geothermal resources as (1) the "accessible resource base," which includes all geothermal resources shallow enough to be reached by production drilling in the foreseeable future regardless of near-term economic viability, and (2) the "resource," which includes only those geothermal resources that can be extracted from the accessible resource base at a production cost competitive with other forms of energy at a foreseeable time and under reasonable assumptions of continuing technological improvement (4). Estimates of US geothermal resources are shown in Table 1. For comparison, the total consumption of energy in the United States in 1995 was approximately 85×10^{18} J.

Table 1. Estimated US Geothermal Resources

Type	Accessible Resource Base (10^{18} J)	Resource (10^{18} J)
Hydrothermal ($T \geq 90°C$)	9,600	2,400
Geopressured		
Thermal energy	107,000	270–2800
Methane energy	63,000	158–1640
Total	170,000	430–4440
Hot dry rock	450,000	(Uncertain)
Magma	500,000	(Uncertain)

Source: US Geological Survey Circular 790.

Geothermal resources, as shown in Fig. 1, are not distributed uniformly. In the United States, hydrothermal reservoirs are located primarily in the West, where relatively recent geologic activity has occurred (creating shallow and accessible high-temperature sites). Hydrothermal electricity production currently is based in California, Nevada, Utah, and Hawaii. A large geopressured resource exists along the Texas/Louisiana Gulf Coast. Although advanced technology using hot dry rock could extend development of geothermal resources across the entire United States, early developments will most naturally occur in the tectonically active West, Alaska, and Hawaii. The geographic distribution of potential magma resources is purely speculative at this time, but the best prospects lie in the western part of the United States.

APPLICATIONS OF GEOTHERMAL ENERGY

Production of Geothermal Power

Two separate steps are required in the development of geothermal power. The first step, developing the geothermal field to provide thermal energy and fluids to the power plant, can be lengthy and expensive. It consists of exploration to locate a suitable reservoir, testing to determine its size and quality (temperature, pressure, enthalpy, salinity), and flow tests to determine its impedance (resistance to flow) and to optimize the location of production wells. The second step—after the adequacy of the reservoir has been established—is the construction of the power plant suitably connected through distribution lines to both production and injection wells, as shown in Fig. 2. Depending on the state of the geothermal resource (liquid or steam) and on its temperature and pressure, one of three conversion technologies is generally used. In the case of *dry steam,* as at The Geysers and Larderello, the steam is treated to remove any entrained particulate matter, and then passed directly into a conventional steam turbine. After the steam is condensed, the condensate provides makeup water for the cooling tower or is reinjected into the ground.

For *high-temperature liquids* (above 200°C), flash steam technology is generally utilized (5). In flash systems, the liquid's pressure is dropped as it reaches the surface, allowing a

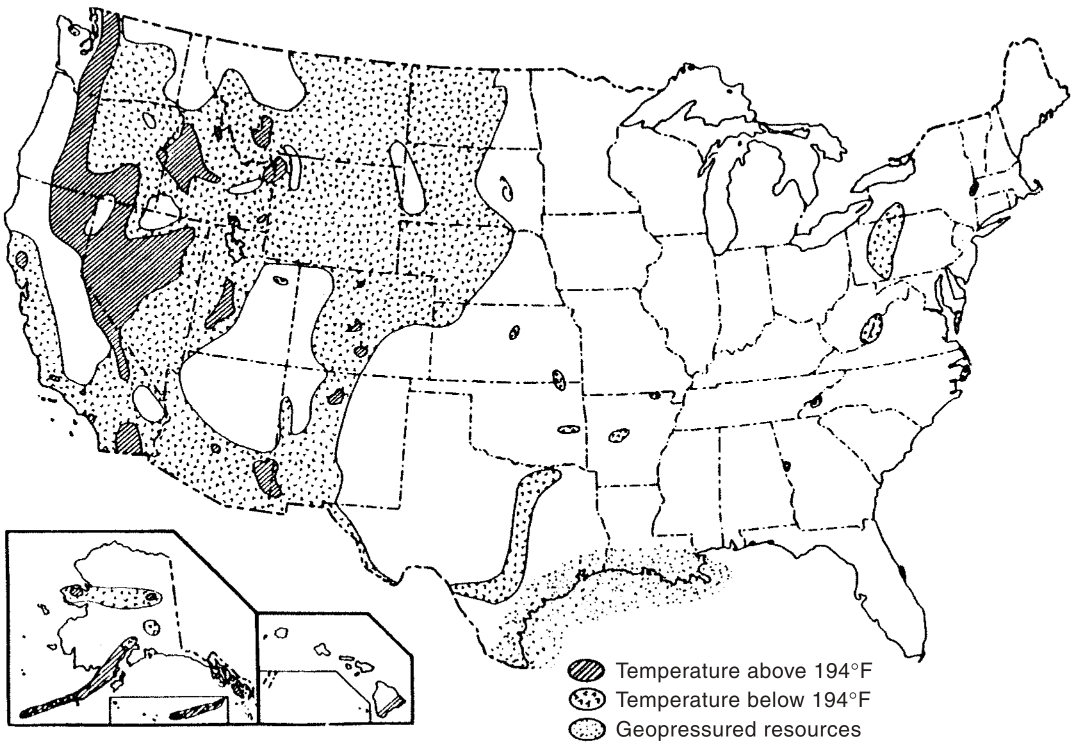

Figure 1. US high-temperature geothermal resources are located primarily in the West, Alaska, and Hawaii. (From US Geological Survey.)

portion of the fluid to flash into steam, which is used to drive a conventional steam turbine, as shown in Fig. 3(a). For *moderate-temperature* liquids (150° to 200°C), binary technology is more efficient (6). In binary systems, as shown in Fig. 3(b), the heat from the geothermal fluid is used to vaporize a secondary working fluid (such as isobutane or isopentane), which is then used to drive a vapor turbine analogous to a steam turbine but smaller in size for the same output power.

Commercial electricity was first produced in the United States in 1960 from superheated steam at The Geysers. By 1975 the installed capacity at The Geysers reached 500 MW, and by the late 1980s it peaked at 2000 MW. Flash plants and binary plants were first installed in the early 1980s in several reservoirs in the Imperial Valley of California. Currently the US geothermal industry has over 2800 MW of installed capacity, and produces some 17×10^9 kWh of electric-

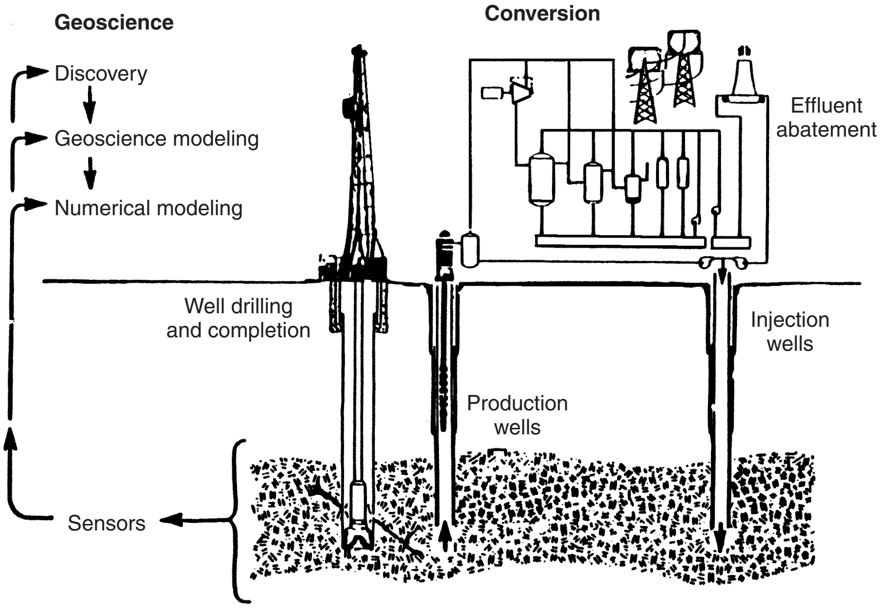

Figure 2. Geothermal power projects are developed in two phases: (1) the discovery, validation, and development of a geothermal field and (2) the construction of a power plant designed to convert efficiently the geothermal heat into electricity.

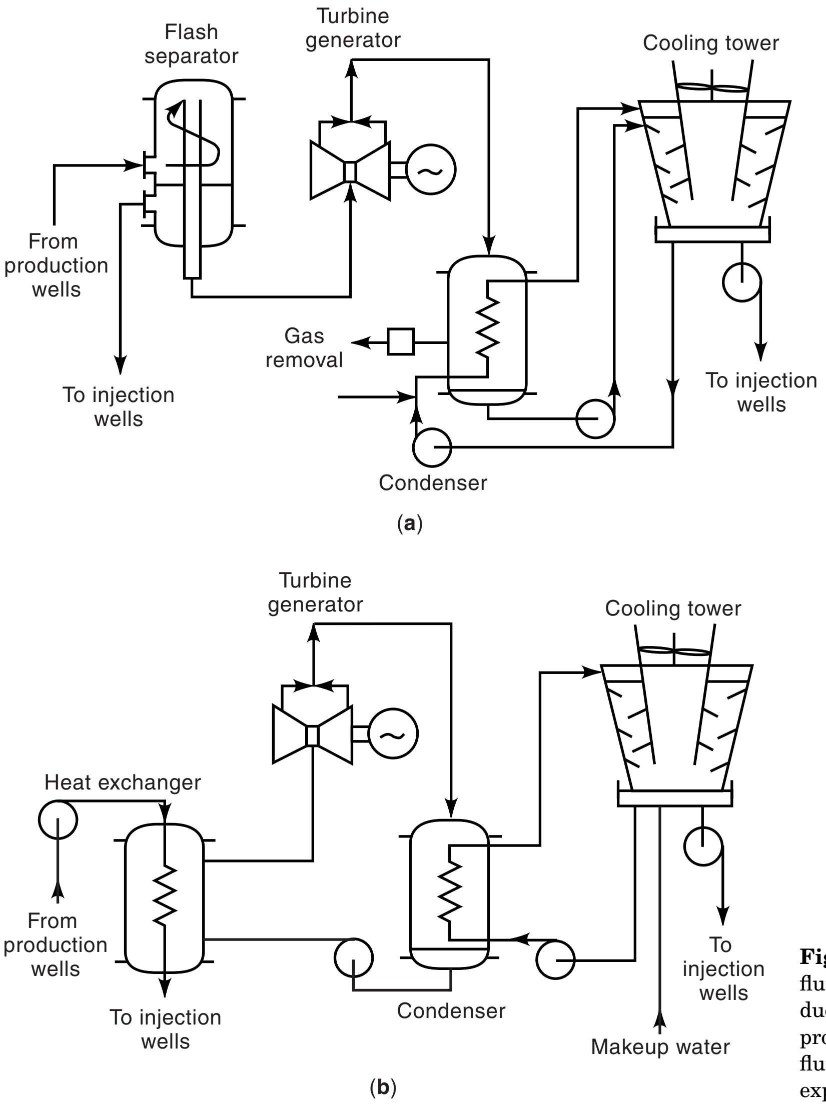

Figure 3. (a) In a single-flash system, the high-pressure fluid passes into a separator where reduced pressure produces steam which rotates a conventional turbogenerator to produce electricity. (b) In a binary system, the geothermal fluid transfers heat to a secondary fluid which vaporizes, and expands through a turbogenerator to produce electricity.

ity annually (7). Geothermal energy is the second largest grid-connected renewable electricity source in America—exceeded only by hydropower. Table 2 compares estimated costs of baseload electricity in the United States for fossil, nuclear, and geothermal resources.

Geothermal power plants have a number of desirable properties making them attractive to developers, especially in rapidly growing nations lacking hard currencies for fossil fuels. They are modular and can be installed in increments from less than one to over 50 MW. They can be designed to provide either baseload or peaking power and offer short construction times: as short as 6 months for plants in the range of 0.5 MW to 10 MW, and less than 2 years for clusters of plants totaling 250 MW or more (8). Many developing countries are located in areas of active geologic processes—areas generally containing high-grade geothermal resources. It has been estimated that as much as 78,000 MW of geothermal electrical power from hydrothermal resources are available for development in known resource areas in some 50 developing countries (9).

Currently total worldwide installed capacity is 6925 MW as shown in Table 3. The most rapid growth of geothermal power is taking place in the Philippines and in Indonesia, where projects under construction or planned will bring 2400 MW of new power on line by the year 2000 (10). New projects are also under consideration in Central America, South America, and East Africa. These developments reflect the steady growth of geothermal power worldwide which has increased at a robust rate of 8.5% per year since the early 1920s (11).

Geothermal Heat Pumps

The earth maintains a relatively constant temperature at shallow depths below 1.5 m, warmer on average than the air above it in winter, cooler in summer. The term *geothermal heat pumps* is generic for all heat pumps which utilize the earth's thermal capacity as an energy source (for heating) or energy sink (for cooling). The earth's thermal capacity can be utilized either directly or indirectly (for example, by using groundwater as an intermediary heat transfer agent).

Geothermal heat pumps are more energy efficient than air-source heat pumps, central air-conditioners, and gas furnaces. The heat pump itself operates on the same principle as the

Table 2. Estimated Costs for New Baseload Capacity

Resource Type	Installed and Annual Plant Cost ($/kW)	Installed and Annual Plant Cost (¢/kWh)	O&M Costs (¢/kWh)	Fuel Costs[a] (¢/kWh)	Breakeven Busbar Price (¢/kWh)
Oil	800	2.0	0.3	1.7–3.4	4.0–5.7
Gas	600	1.5	0.3	0.8–2.3	2.6–4.1
Coal	1200	3.0	0.3	0.6–4.0	3.9–7.3
Nuclear	3200	7.8	0.4	1.0	9.2
Hydrothermal (high-grade)	1000–1500	2.4–3.6	0.3	2–3	4.7–6.9
Hydrothermal (low-grade)	2000–2500	5.1–6.3	0.4	4–10	9.5–16.7
Hot dry rock (high-grade)	1000–1500	2.4–3.6	0.3	3–4	5.7–7.9
Hot dry rock (low-grade)	2000–2500	5.1–6.3	0.4	20	25.5–26.7

[a] Geothermal "fuel" costs represent the cost of drilling additional wells when needed. The cost ranges for fossil energy are dependent on market fuel prices: oil ($10–$20/bbl), gas ($1–$3/MBTU), coal ($15–$100/ton).

Source: J. E. Mock, J. W. Tester, and P. W. Wright, Geothermal energy from the earth, *Annual Reviews of Energy and the Environment,* V. 22, Palo Alto, CA: Annual Reviews, Inc., 1997.

home refrigerator, which is actually a one-way heat pump. Because electricity is used only to transfer heat, not to generate it, the geothermal heat pump delivers three to four times more energy than it consumes. In a typical installation a loop of plastic pipe is placed in a vertical drill hole up to 120 m deep, and the hole is backfilled with clay. A water–antifreeze solution is circulated through the loop, then through the heat pump. There is no consumption of groundwater, nor is there any contact between the solution in the plastic pipe and the earth or groundwater. An alternative installation is often used in which a loop of plastic pipe is placed below the frost zone in a horizontal trench and backfilled with soil (12).

Table 3. Geothermal Electrical Plants: Country and World Total Installed Capacity (MW)

Nation	Existing Capacity	Year-2000 Capacity
Argentina	0.7	0.7
Australia	0.2	0.2
China	28.8	81.0
Costa Rica	57.0	170.0
El Salvador	105.0	165.0
France	4.2	4.2
Guatemala	0	240.0
Iceland	49.4	49.4
Indonesia	309.8	1957.0
Italy	631.7	856.0
Japan	50.4	600.0
Kenya	45.0	45.0
Mexico	753.0	960.0
New Zealand	286.0	440.0
Nicaragua	35.0	35.0
Philippines	1227.0	1976.0
Portugal	6.4	6.4
Russia	11.0	110.0
Thailand	0.3	0.3
Turkey	20.6	125.0
United States	2849.9	3395.0
World total	6925.0	11216.2

Source: Geothermal Energy Association, *International Geothermal Electric Power Plants* (Davis, CA, 1991); L. McLarty, DynCorp EENSP, Inc. (Alexandria, VA, August 1995); G. W. Huttrer, International Geothermal Association, *Proceedings of the World Geothermal Congress* (Florence, Italy, 1995).

In addition to providing the home or building owner with lower heating and cooling costs, several significant advantages also accrue to the local utilities. GHPs are ideal demand management tools, reducing summer cooling peak loads by 1 kW to 2 kW and winter heating peak loads by 4 kW to 8 kW for the typical residence (13). These impressive load-leveling capabilities and energy savings permit utilities to manage their operations more efficiently (both diurnally and seasonally) and postpone the construction of new generating capacity.

Direct Thermal Use

There are many energy uses which do not require high-grade energy sources such as electricity, but can be satisfied with low- to moderate-temperature sources of heat. Low-temperature geothermal resources have found significant use in a wide variety of commercial applications ranging from 10°C for soil warming (for agriculture) and ice melting, to 200°C for cement drying. Historically, geothermal heat was first used in the United States by small resorts and district (or home) heating systems. By the mid-1990s, geothermal heat was used in a wide variety of applications, providing over 14×10^{15} J annually (14). Industrial applications now include: pulp and paper processing (200°C), dehydration of vegetables (130°C), heap leach mining operations to extract precious metals (110°C), enhanced oil recovery (90°C), and mushroom growing (60°C). Geothermal fluids are also finding increasing use in aquaculture (to raise catfish, tilapia, sturgeon, lobster, shrimp, and tropical fish) and greenhouse operations (to raise many commercial crops such as flowers, house plants, vegetables, and tree seedlings). Geothermal energy serves as the heat source for 23 district heating systems in the United States including the nation's oldest in Boise, Idaho, and the nation's largest in San Bernardino, California (15).

Environmental Considerations

The exploitation of geothermal energy has a net positive impact on the environment. Modern geothermal power plants have extremely low levels of SO_x, NO_x, CO_2, and particulate emissions. Sulfur oxides and nitrogen oxides average only a few percent of those from fossil fuel alternatives. Geothermal energy use also reduces markedly the emissions of greenhouse gases. The current generation of geothermal power plants emits only 0.14 kg of carbon (in the form of CO_2) per megawatt-hour of electricity generated, compared to 128 kg/MWh for natural gas plants, 190 kg/MWh for a plant operating on No. 6 fuel oil, and 226 kg/MWh for a plant using bituminous coal (16). Air-cooled, closed-loop geothermal power plants, which employ 100% injection of all geothermal fluids and gases, have essentially zero air emissions. The direct use of geothermal heat in many cases displaces electrical heat, reducing demand for electricity with its associated pollutants. In the same vein, geothermal heat pumps (which produce no pollution) reduce the demand for electricity.

GEOTHERMAL POWER DEVELOPMENT

Hydrothermal resources share with nonconcentrated solar and ocean thermal systems the disadvantage of low resource temperatures, which limits the efficiency of electric conversion processes. Whereas fossil energy and nuclear plants operate at efficiencies of 35% to 50%, geothermal plants perform typically at efficiencies as low as 10% to 20%. Improved technologies are needed to decrease the overall cost of conversion of geothermal energy to electrical power, and to reduce the substantial costs associated with geothermal exploration and field development.

Locating a Geothermal Field

The first step in geothermal power development is exploration, which includes (1) locating suitable reservoirs and (2) siting wells for the production of geothermal fluids. Even within well-explored fields such as The Geysers, the drilling success rate is only 80%, whereas for wildcat drilling in relatively unknown areas, the success rate is as low as 10% to 20% (17). The key problem is not in finding a source of heat, but in finding both adequate permeability and fluids that are recoverable in amounts sufficient to supply a commercial-size power plant. In any geothermal exploration program, an adequate understanding must be developed of the regional and local geology. Geologic mapping is the important first step, conducted by field geologists who (1) identify and locate the various rock units in the area (sedimentary, plutonic, volcanic); (2) map the structural elements of the geology (faults, fractures, folds); (3) search for evidence of geothermal activity from such obvious indicators as thermal springs, geysers, and fumaroles, to such subtle indicators as hydrothermal alteration of rocks, or ancient spring deposits of sinter or travertine; (4) collect samples of rocks and minerals for microscopic examination, radioactive age dating, and geochemical analysis; and (5) collect samples of fluids from wells and springs for geochemical studies (17). Based on these results, promising areas are identified for more detailed geochemical and geophysical investigations.

In geothermal *geochemistry,* the chemistry of the geothermal fluids is investigated as well as the chemistry of the rocks in which the geothermal resource exists. The simplest chemical parameters used to characterize geothermal fluids are total dissolved solids (TDS) and pH, which can be measured in the field by using a conductivity meter and a pH meter. The amount and nature of dissolved chemical species are functions of temperature and the local geology. Many of the high-temperature resources in the western United States contain 6,000 mg/L to 10,000 mg/L TDS, whereas some resources in the Imperial Valley of California are saturated with salts at 300,000 mg/L. The pH of geothermal resources ranges from moderately alkaline (8.5) to moderately acidic (5.5) (17).

Geophysical exploration makes use of physical measurements: (1) to detect a resource directly, (2) to provide indirect evidence of its existence and location, and/or (3) to determine and map its physical and chemical characteristics. Such physical parameters as the distribution of temperature over the surface of the earth and at depth, the electrical, magnetic, or density properties of the ground, and the manner in which seismic waves are propagated in the earth all respond in characteristic ways to the presence of a geothermal resource. Geophysical surveys are valuable to help locate resources that have no evident surface expression, to site production and injection wells, and to monitor production from and injection into a reservoir.

Selecting a Geothermal Power Plant

Geothermal power plants operate on the same Rankine cycle used by fossil and nuclear plants; however, hydrothermal conversion systems are constrained to a relatively small operating range of temperatures. Most commercial hydrothermal systems operate with fluid temperatures of 250°C or less—with heat rejection at ambient temperatures around 35°C, leaving a temperature differential of only 215°C for operating the power cycle. Consequently, a high premium is placed on designing all parts of the geothermal system to operate at peak efficiency.

Thermodynamic Considerations: Cycle and Utilization Efficiencies. The second law of thermodynamics imposes an upper limit on the production of electricity from low-temperature resources and provides a basis for defining *utilization efficiency,* η_u:

$$\eta_u = \frac{W_{net}}{\Delta B} = \frac{W_{net}}{m \cdot \overline{\Delta B}}$$

where W_{net} represents the net useful work from an actual system; ΔB (thermodynamic availability) represents the maximum amount of work which theoretically could be extracted in a reversible process in which a condensed geofluid is cooled from its well-head temperature, T_w, to ambient temperature, T_o; m is the mass fluid flow rate; and $\overline{\Delta B}$ is availability per unit mass (18). ΔB can be calculated from

$$\Delta B = (\Delta H - T_0 \Delta S)|_{T_0}^{T_w}$$

where ΔH is the enthalpy difference and ΔS the entropy difference between the two states. Thus, η_u is a direct measure of the effectiveness of resource utilization; for a fixed T_w, higher values of η_u correspond to lower required flow rates (m) for a given power output (W_{net}). This efficiency concept is especially useful in comparing flash- and binary-cycle performance for the same resource.

If the utilization efficiency is low, then the resource is being utilized wastefully, and an unduly large investment in wells is required. On the other hand, as we approach utilization of the full potential of the geothermal resource, total well costs decrease, but the required investment in highly efficient power conversion equipment is high. The economic optimum occurs when η_u takes on some intermediate value; for example, at The Geysers, $\eta_u = 0.55$ is typical with $T_o = 26.7°C$ (19).

An alternative approach is achieved by defining a *cycle efficiency,* η_{cycle}, which represents the ratio of the net work, W_{net}, to the amount of heat actually transferred from the geothermal fluid, Q_H. As the cycle efficiency decreases, the amount of heat rejected to the environment increases. For ambient temperatures of 25°C with a geothermal heat source of 100°C, cycle efficiency is less than 10%. As the source temperature increases to 150°C, $\eta_{cycle} \approx 12.5\%$; at 200°C, $\approx 17.5\%$; and at 250°C, $\approx 20\%$. Because power conversion efficiencies are low, the amount of heat transferred may be 5 to 15 times greater than the power produced, requiring large heat exchangers at significant cost. For example, a 50 MW geothermal plant with a 12% cycle efficiency requires about 30,000 m^2 (325,000 ft^2) of heat-exchanger surface area.

In general, to obtain efficient utilization of a geothermal power plant it is necessary that (1) most of the heat be extracted from the geothermal fluid before disposal, (2) temperature differences across heat transfer surfaces be minimized, (3) turbines and pumps be designed for optimum performance, and (4) heat be rejected at the lowest possible ambient temperature, T_o (19). For example, for a 200°C geothermal resource, a decrease in condensing temperature from 50° to 25°C increases the potentially available work by more than 40%.

Design of Geothermal Power Plants. Commercial geothermal power plants range in size from 0.5 MW to 180 MW (8). The specific design of each plant depends primarily on the physical and chemical state of the geothermal fluid, and to a lesser extent on the local ambient temperatures. Seasonal and diurnal variations of dry bulb temperatures can also affect cycle performance. Power conversion technologies in current commercial operation include dry-steam, flash-steam, binary plants, and steam/binary combined cycle plants.

Dry Steam Plants. Dry steam resources are very rare; only two dry-steam fields are being utilized commercially—one at Larderello, Italy, the other at The Geysers, CA. For a typical 50 MW plant at The Geysers, 10 to 20 production wells are drilled about 1000 m apart to provide sufficient steam for the turbogenerators. Gathering lines are constructed to deliver steam from the wells to cyclone separators which remove entrained particles and water droplets. The steam then passes through the turbines to the condensers and to steam ejectors, which remove noncondensable gases. The condensate from the condensers is used to replace water evaporated in the cooling tower; any excess condensate is pumped to injection wells, which helps to maintain reservoir pressure, replace lost fluid, prevent land subsidence, and dispose of wastes. Gaseous emanations from the condensers, primarily CO_2, may require chemical treatment to remove contaminants such as hydrogen sulfide and traces of methane, arsenic, and boron (5).

By the late 1980s, The Geysers had become a mature steam field, characterized by a general pressure decline and a gradual decrease (7% to 8% per year) in steam production. Measures were taken to reduce the decline in production including (20): cooperative steam field management among the individual field owners, power plant improvements to utilize low pressure steam more efficiently, and fluid injection, for example, by the Southeast Geysers Effluent Pipeline Project—the world's first wastewater-to-electricity system. A 29 mi., 20 in. diameter pipeline has been designed and constructed to carry 7.8 million gallons a day of Lake County, CA wastewater for injection to depths of approximately 2430 m (8000 ft.) at The Geysers to produce a total of 70 MW of power from six existing geothermal power plants (21).

Flash Steam Plants. In the western United States many geothermal reservoirs are found that produce hot water at temperatures above 170°C and pressures above 10 atm, making them economically attractive for flash-steam plants. As shown in Fig. 3(a), flash systems consist basically of one or two large tanks, wherein part of the geothermal fluid vaporizes (flashes) into steam at pressures less than reservoir pressure. The steam, typically 18% to 25% of the fluid from the reservoir, is sent to the turbogenerator. The remaining water (75% to 82% by weight of the initial fluid) is disposed of in injection wells (8). For some fields in the Salton Sea area (but not at most US flash plants) the high-temperature brines contain substantial amounts of dissolved silica, which, if not treated, precipitates upon equipment walls in the form of hard scale. Ameliorating measures available include: (1) increasing the brine exit temperature above that optimal for power production, (2) using a "crystallizer–clarifier" system in conjunction with the first flash tank to precipitate and remove silica crystals, or (3) using a "pH-modification" system which injects small quantities of an acid (H_2SO_4 or HCl) upstream of the first flash tank to help keep the silica in solution (22).

Flash-stream plants can be designed using either condensing or noncondensing cycles. Single-flash, noncondensing plants with steam exhausted to the atmosphere through a diffuser–silencer do not optimize the use of the resource, but are simple to operate and can be installed at minimum cost. Geothermal resources having very high noncondensable gas content may make condensing cycles impractical or uneconomical and thus favor the use of such noncondensing systems (23). The addition of a condenser can double the output of a flash plant, at the expense of increasing its cost and complexity. With low-temperature resources, up to half of the power developed by the turbine comes from the expansion of the steam below atmospheric pressure (23).

A dual-flash cycle represents a simple extension of the single-flash cycle, making use of the energy remaining in the separated brine from the first flash tank. By flashing this brine in a low-pressure separator, additional steam is generated which can increase total power by as much as 50%.

Binary Plants. For geothermal resources with temperatures below 170°C, the most efficient and economical plant is one employing a secondary working fluid in a binary cycle. Temperatures as low as 100°C and as high as 200°C are suited to binary operation, depending on the availability of cooling water, range of ambient temperatures, and cost of wells (5). In this system, shown in Fig. 3(b), the geothermal brine flows through the tubes of a shell-and-tube heat exchanger, vaporizing the binary fluid, which expands through a turbogenerator, generating electricity. The binary fluid is then cooled in a water-cooled condenser and sent to a storage tank. The heated water from the condenser is pumped to a conventional cooling tower. In spite of its greater complexity and capital cost, the binary system may be preferred in some cases to the flash system—even for high-temperature resources—because of its higher efficiency and environmental acceptability.

A geothermal combined cycle power plant, commercialized by ORMAT, efficiently extracts the energy contained in the typical mixture of steam and brine flowing from geothermal wells. In this system the geothermal fluid flows directly into a steam separator with the separated high-pressure steam used to drive a back-pressure turbine. Low-pressure steam, which exits the back-pressure turbine, flows into the vaporizer of an organic cycle binary system wherein its heat of condensation is added to the thermal energy of the separated brine to vaporize an organic fluid, which is used to drive a binary turbine.

System Application. Geothermal power plants are generally baseload systems, but may sometimes be used in a load-following mode. Current contractual *capacity factors* for most geothermal plants are on the order of 80%. However, actual capacity factors for some operating plants approach 100% (24). System capacity factor is defined based on nameplate rating:

$$\text{Capacity factor} = \frac{\text{kWh output per year}}{\text{(Nameplate kW)(8760 hours per year)}}$$

System *availability factors* (the percentage of a year in which the system is capable of delivering its rated power) are also very high, typically 95% or better (8). The capacity and availability factors of geothermal power systems tend to be higher than other baseload systems primarily because of the intrinsic simplicity of geothermal plants.

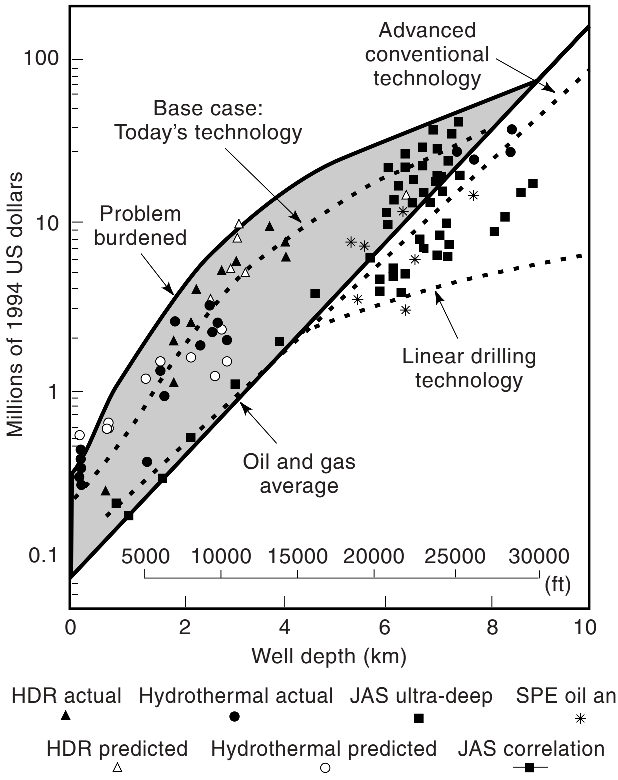

Figure 4. Drilling costs for oil/gas/geothermal wells increase exponentially with depth. Geothermal wells can cost up to three times more than oil/gas wells drilled to the same depth.

Advances in Geothermal Technology

Drilling Technology. Drilling to depths of several thousand feet is required at all stages of geothermal development: exploration, production, and reinjection. Geothermal wells are difficult and expensive to drill since geothermal reservoirs are typically found in hard, abrasive, high-temperature, fractured rock formations. Unique problems arise in drilling through fractured formations, such as the loss of drilling fluids, leading to wellbore instability, stuck drill pipe, inadequate casing cementing, and increased costs—accounting for 10% to 20% of the costs of a typical geothermal well. Figure 4 shows that drilling costs increase exponentially with depth and that geothermal wells cost, on average, two to three times more than oil and gas wells at similar depths (25). Costs per typical geothermal wells range from $1 to $3 million. Drilling and well completion costs generally represent 35% to 50% of the total cost of a geothermal power project; and being accrued early in the life of the project, their financial impact is particularly significant (26). Three mutually supporting approaches appear promising to reduce drilling costs: (1) well emplacement optimization, (2) drilling components development, and (3) smart systems development. Under well emplacement optimization, one approach is to maximize well production—that is, to aim for large wells capable of producing 20 MW each, instead of the more typical 5 MW per well. [The most productive of the Unocal Salton Sea wells supplies enough brine to produce 45 MW, a world record (27).] Multileg completion and side tracking wells are also methods of improving well productivity. The successful directional drilling of four or five wells from the same drill pad, rather than drilling at several different locations, minimizes pipeline, site, and access costs. During exploration, there are significant advantages to drilling small wells—so-called slimholes. Geothermal exploration has traditionally entailed the drilling of large-diameter (30 cm) wellbores for production testing to prove a new resource. A newer cost-effective method is to drill small-diameter (10 cm) wells to obtain the required reservoir data. Slimhole drilling is up to 40% cheaper because the drilling rigs, crews, and drilling fluid requirements are smaller and because site preparation and road construction in remote areas is significantly reduced (for example, by using helicopter-portable drill rigs) (28).

As part of component developments, Sandia National Laboratory has collaborated with General Electric and drill-bit manufacturers in applying human-made diamonds to drilling bits. Field tests in the shales and sandstones of geothermal wells in the Imperial Valley of California demonstrated bit lives and penetration rates two to ten times those achievable with conventional roller cone bits; however, tests in hard, abrasive, highly fractured rock formations were less successful, leading to further advances in polycrystalline diamond compact (PDC) bits, impregnated diamond bits, and thermally stable polycrystalline (TSP) bits (29). Other significant technical advances include the development of: high-temperature drilling muds, high-temperature elastomers for downhole drilling motors, high-temperature cements, CO_2-resistant cements, high-temperature logging instruments, lost-circulation materials, and acoustic technology to transmit downhole data to the surface in real time (30).

The National Research Council concluded in a 1994 study that revolutionary advances (cost reductions up to 50%) are now within reach through the development of smart drilling systems—that is systems capable of sensing and adapting to conditions around and ahead of the drill bit in real time with minimal operator intervention (31). Rapid innovation in microelectronics and other fields of computer science and miniaturization technology holds great promise for significant improvements. The National Advanced Drilling and Excavation Technologies (NADET) Program was established by the US Department of Energy in collaboration with industry with the goal of reducing drilling costs for deep geothermal wells by at least 50% within the next two decades (32).

Energy Conversion Technology. Although geothermal energy conversion technologies are mature—with dry steam plants in operation for over 30 years, flash steam plants since the early 1980s, and binary plants in commercial operation since the mid 1980s—substantial room for improvement still exists. During the period 1986 to 1992, Ormat Inc. reduced binary system costs by approximately 30%, largely through equipment design improvements that decreased manufacturing costs (33). Flash system costs were reduced in the same time period by 20%; the most cost-effective improvement was made by Unocal in their Salton Sea flash plants by replacing the older crystallizer–clarifier technology (at about $17 million per 40 MW plant) with newer pH-modification technology for silicate scaling control (at only a few million dollars per plant) (8,20). These successes result from the continuing research efforts of the geothermal industry to improve geothermal power conversion systems.

Geothermal power plant costs are projected to continue to decline (1) as the number of operating personnel, instruments, controls, and safety systems are reduced as experience is gained and (2) as improved conversion cycle designs are utilized which produce more electricity per pound of geothermal fluid through the addition of (a) topping cycles (with the ORMAT Biphase rotary separator or Rotoflow turbines) that extract extra power from high-temperature fluids, (b) hybrid cycles that extract extra power from moderate temperature fluids (e.g., by using the proposed Kalina cycle or the ORMAT combined cycle), (c) bottoming cycles that extract extra power from low-temperature fluids (e.g., by using the vacuum-flash cycle), and (d) cycles combining combustion turbines with binary systems to extract power from the lowest temperature geothermal reservoirs (34).

Synchronous speed turbines offer significant advantages for geothermal binary systems. Commercial binary turbines are high-speed, radial inflow turbines, which require a speed reduction gear box between the turbine and the generator. Synchronous speed turbines rotate at the same speed as the generator (being coupled directly to it), thereby avoiding the energy losses and cost of the gear box. Synchronous turbines reduce capital costs by 17% while increasing brine utilization by 3% (34).

Other technological improvements include the use of mixed working fluids for binary plants (generally mixtures of butanes, pentanes, and hexanes), and the use of metastable, supersaturated turbine expansion cycles, capable of producing up to 10% more power (35). Isobutane, commonly used in binary systems, has a retrograde dew point curve on a temperature–entropy diagram; thus, in contrast to steam, isobutane vapor tends to become drier (more superheated) as it expands. In a test conducted on a 3.5 MW binary unit at Mammoth, CA, supersaturated turbine expansion showed an improvement in power output of up to 35% (36).

Geothermal turbines are conventional in concept; however, a number of special-purpose power generation devices have been investigated. For example, "total flow turbines" such as the Biphase turbine have been designed to extract efficiently both hydraulic and thermal energy from the two-phase flow (of steam and water) from wet geothermal wells. In the Biphase machine, pressurized brine (or a water/steam mixture) impinges tangentially on a rotary-separator wheel which is set spinning by frictional drag. Impulse steam blades, attached to the rotary wheel, extract additional kinetic energy from the high-velocity steam. Tests of an experimental Biphase turbine at Roosevelt Hot Springs, UT, reported an increase in power (up to 20% depending upon flow conditions) compared to a single-flash steam turbine (37). An advanced system, diagrammed in Fig. 5, is designed to increase production at a plant in Cerro Prieto, Mexico from 7,410 kW to 10,760 kW, a potential gain of 45% (37). The Biphase turbine can also operate as a bottoming unit using the hot water from steam separators or can be used as a stand-alone wellhead generator to serve remote communities.

Flash plants can be made more cost-effective by using more efficiently the lower-temperature fluid flowing from the first flash tank. One of the more promising cycles is the Kaline cycle, invented and developed by Exergy, Inc., which replaces hydrocarbon working fluids with an ammonia–water mixture, and uses a number of high-temperature and low-temperature heat exchangers, as shown in Fig. 6, to improve thermodynamic efficiency. Exergy, Inc. speculates that their Kalina system can reduce capital costs by 35% to 40%, increase brine utilization by 20% to 30%, and reduce the overall cost of power by 30% to 35% (27).

Many of these cycle improvements produce a synergistic effect. Although they add components and cost to the system, the ultimate result is a lower cost per kilowatt-hour, since the increased efficiency requires less geothermal fluid per kilowatt-hour, which in turn reduces (1) the size (and cost) of those parts of the plant through which the fluids flow and (2) the number of wells needed to be drilled and maintained.

Small Geothermal Power Plants

Small geothermal power plants, a few megawatts or smaller in size, can enhance the reliability and backup aspects of off-grid or end-of-grid powering at remote locations—such as on the many isolated Indonesian islands or in remote villages in the Rift Valley of East Africa. They are also valuable as "ice-breaker" plants installed during the early development of new fields, providing both (1) the power needed for field development activities and (2) an early source of revenue to help offset front-end costs.

Small geothermal plants are readily transportable: For 100 kW to 300 kW systems, the entire plant including the cooling system can be built on a single skid fitting into a standard transoceanic shipping container. These small plants are designed to be self-starting, with only semiskilled labor needed to monitor plant operation on a part-time basis. Completely unattended operation is possible with plant performance monitored and controlled remotely through a satellite link

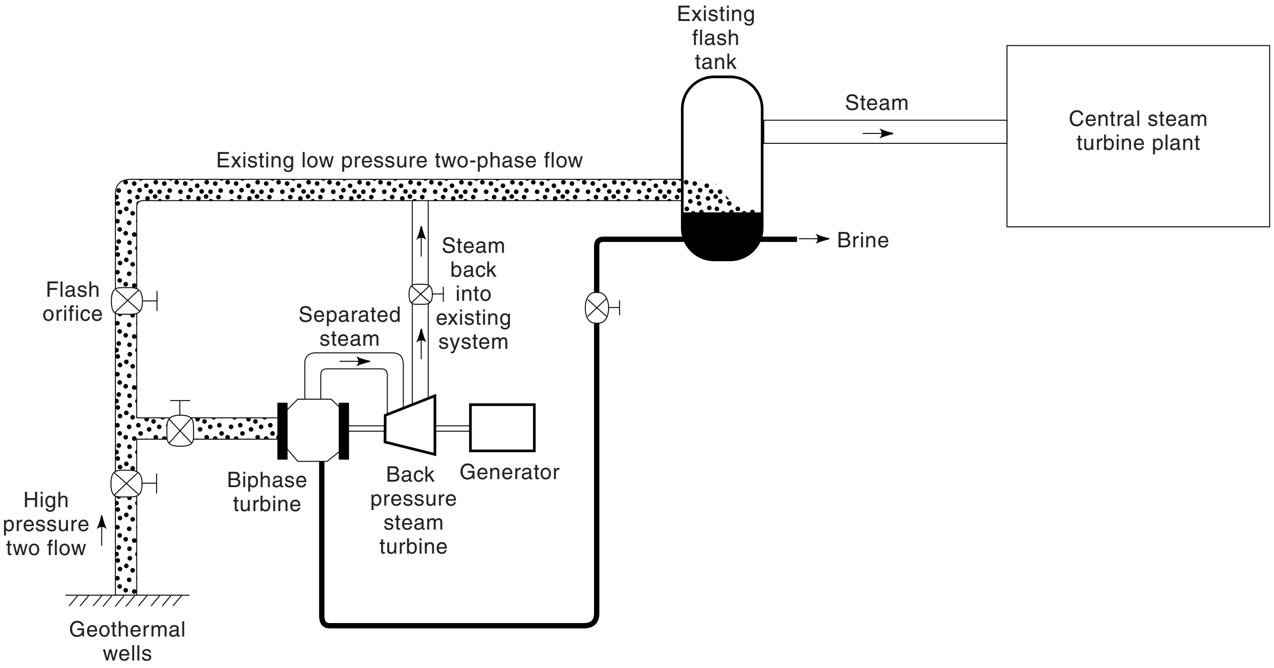

Figure 5. Schematic of a Biphase turbine system designed to increase power up to 45% at a geothermal well at Cerro Prieto, Mexico.

(38). These systems are environmentally friendly, releasing no greenhouse gases or other pollutants to the atmosphere. Power plants such as these have been installed by ORMAT in Thailand.

The demand for electric capacity per person at off-grid sites ranges from 0.2 kW in less-developed areas to greater than 1.0 kW in developed areas. Thus, a 100 kW geothermal plant can serve communities of 100 to 500 persons; a 1000 kW plant, 1000 to 5000 persons. The estimated cost of power for a 300 kW system on a 120°C reservoir is approximately 10.5 ¢/kWh, and it drops to 4.7 ¢/kWh for a 1000 kW plant on a 140°C reservoir (38). These costs compare quite favorably with alternatives such as diesel generators (46 ¢/kWh to 103 ¢/kWh) and solar photovoltaic systems with adequate battery storage (75 ¢/kWh to 100 ¢/kWh) (38).

FUTURE DEVELOPMENTS

Research efforts aimed at the increased use of geothermal energy are proceeding along two broad paths. The first path as discussed above is the improvement of today's hydrothermal technology—especially drilling and conversion technology—to reduce costs, thus making geothermal more competitive with conventional forms of energy. The second path is advanced research on geopressured, hot dry rock, and magma resources, whose successful exploitation will greatly expand the geographic availability of geothermal energy and, in view of the large size of these resources, provide a virtually inexhaustible supply of energy.

Advanced Technology

Geopressured. Geopressured resources are not yet commercially viable, primarily because of today's low price of natural gas. However, as conventional sources of natural gas are depleted and prices rise and as production costs of geopressured resources are reduced, these resources will become competitive. Geopressured resources represent one of the largest US sources of unconventional natural gas—with estimates of more than 63,000 × 10^{18} J (63,000 trillion cubic feet) just

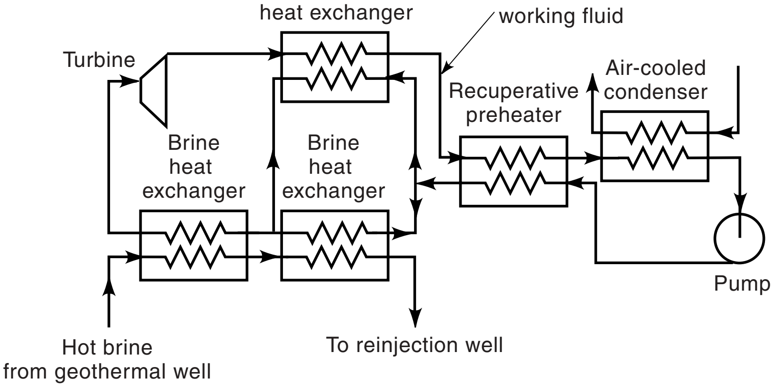

Figure 6. Schematic of Kalina cycle system, which utilizes ammonia–water working fluids and cascaded recuperative heat exchangers to increase power conversion efficiency.

in the coastal region of Texas and Louisiana (39). Other potential geopressured basins of the United States identified by the USGS include: Mississippi salt basin, Appalachian basin, Anadarko-Ardmore basin, north Louisiana salt basin, Delaware basin, Unita basin, Santa Barbara Channel/Los Angeles/Ventura/Tanner Banks basin, and Gray's Harbor to Hoh Head basin area in Oregon and Washington. It has been estimated that an additional $46{,}000 \times 10^{18}$ J of thermal energy exists in the upper 10 km in these basins, with a similar amount of energy contained in dissolved natural gas (39).

Research carried out under the sponsorship of the US Department of Energy has demonstrated that geopressured wells can be flowed at rates of 40,000 barrels per day, and the brine reinjected underground at depths of 1500 m to 2500 m without causing subsidence or associated seismic activity. Two large sandstone aquifers—at Pleasant Bayou in Texas and at Gladys McCall in Louisiana—each estimated to contain in excess of five billion barrels of geopressured brines—were tested and characterized (2). A 1 MW hybrid power system was constructed in 1990 at the Pleasant Bayou site in which gas was burned in an engine to generate electricity directly. The exhaust heat from the engine was then combined with heat from the brine to generate additional electricity using a binary cycle. Heat from the gas engine, available at a high temperature, improved markedly the efficiency of the binary part of the hybrid cycle. This demonstration showed that hybrid systems can yield 30% more power than stand-alone geothermal and fossil fuel power plants operating on the same resources (40).

Hot Dry Rock. Estimates of the useful US hot dry rock resource exceed 500,000 quads (4). In 1970, scientists at the Los Alamos National Laboratory conceived the idea of extracting heat from this large resource by creating an artificial reservoir through hydraulic fracturing of competent hot rock having low porosity and low permeability. This reservoir would be interconnected to a heat exchanger at the surface through a pair of wells (a production well and an injection well) forming a closed convective circulation loop. The basic HDR concept was subsequently expanded to encompass the heat mining of all geothermal resources requiring artificial measures beyond current technology to achieve commercial heat extraction.

The world's first HDR system was created in 1977 at Fenton Hill, NM. The system was constructed by drilling a well to 3000 m into granitic rock at 185°C; hydraulic fractures were produced at 2600 m depth; and after redrilling the production well to intersect the fractures, hydraulic communication was achieved. Pressurized water was circulated through the fractures bringing heat to the surface at temperatures up to 140°C, with a thermal energy output of 5 MW, some of which was used to operate a 60 kW binary-cycle, electrical generator (41). Based on the successful operation of this system, a larger, deeper (4390 m) system was constructed in the early 1980s at Fenton Hill with maximum rock temperatures of 327°C and a thermal output of 10 MW.

Although HDR technology has tremendous potential, its commercialization will depend on resolving several technical uncertainties, such as reservoir productivity and lifetime, water loss rates, flow impedance, and corrosion and scaling severity. The most critical technical obstacle is centered on the formation and connection of the fractured network to the injection and production well system in order to provide low impedance across sufficiently large rock volumes with acceptable water losses. Economic analyses show that the performance of HDR systems can be improved markedly by having more than one production well—preferably two or three. Other concepts have been advanced; for example, a patent (42) was issued to Shulman (Geothermal Power Co., Inc.) on a completely enclosed system (eliminating the need for a fractured reservoir) with the working fluid passing through continuous metallic pipe installed from the surface, through the hot rock zone, and back to the surface where the heated fluid is processed to recover the thermal energy. Economic analyses indicate the advantage of several injection wells connected to a manifold at the surface permitting rotation of the descending liquid among the pipe loops (as individual loops cool) for continuous operations. Because of the low thermal conductivity of hard rock, this system will have lower heat exchange rates than the more conventional system using a large fractured reservoir. However, such closed systems may be necessary in regions of highly fractured hot rock where large water losses would be unacceptable, and they may also prove to be advantageous for small power plants and/or for direct use.

Cost of energy from HDR resources are highly speculative and highly dependent on the characteristics of the source—especially its thermal gradient, that is, the rate at which the temperature increases with depth, measured in degrees centigrade per kilometer of depth. The worldwide average thermal gradient is about 25°C/km. Approximately 16% of the land area in the Untied States can be categorized as a thermal area—that is, an area with a significant fraction containing regions with gradients of 60°C/km to 80°C/km. Gradients are important for HDR economics because the higher the gradient, the shallower a well to reach a given temperature, greatly reducing well costs. An economic analysis has estimated that for thermal gradients of 80°C/km with today's technology, busbar electricity costs would be on the order of 5 ¢/kWh to 6 ¢/kWh; for gradients of 50°C/km, 8 ¢/kWh to 9 ¢/kWh; and for gradients of 30°C/km, 16 ¢/kWh to 18 ¢/kWh (25).

HDR research programs have also been established in Japan (at Hijiori), in Great Britain (at Rosemanowes), and in France (at Soultz) under the auspices of Germany and France, in union with the European Community, subsequently joined by Great Britain and the United States. Under this program, a consortium of European industrial firms has undertaken a $300 M effort aimed specifically at the development of HDR in areas of low thermal gradient (41).

The US HDR research program is aimed at developing technology to enable industrial HDR projects to generate power at less than 9.5 ¢/kWh early in the twenty-first century (43). Specific research areas include: (1) drilling—to develop better technology for creating fractures and for completing and logging wells, to develop means of locating accurately the intersection of fractures with the wellbores, and to reduce the cost of drilling deep wells in hard, hot rock; (2) reservoir definition—to improve instrumentation to locate, measure, and control fracture propagation in HDR reservoirs; (3) reservoir evaluation—to develop technology to monitor changes in reservoir volume and temperature and to study reservoir drawdown characteristics; (4) system optimization—to evaluate and model the performance of HDR reservoirs in order to develop improved cost estimates for electricity production and to evaluate the efficiency of various power plant designs.

HDR systems can both generate baseload electricity and be used in load-following modes. An experiment at Fenton Hill in 1995 demonstrated that a HDR reservoir is capable of a significant, rapid increase in thermal power output on demand. It is estimated that the thermal output could be increased up to 65% for four hours each day without requiring additional wells or a larger reservoir (43). The price premium for peaking power paid by utilities would more than cover the additional capital expense required to increase the power plant capacity, ultimately improving overall economics by approximately 10%.

Magma. The idea of extracting energy directly from magma emerged as an energy alternative during the early 1970s when it was realized that molten magma reservoirs within 10 km of the earth's surface in the continental United States contain up to half a million quads of energy (0.5×10^{24} J).

Large magma bodies insulated within the earth's crust have a very slow cooling rate, retaining significant amounts of heat for hundreds of thousands of years. Geophysical data indicate that large magma chambers exist in various parts of the world, including Kamchatka, Iceland, Sicily, Japan, the Azores, Alaska, and the western United States (44). Several calderas in the United States are known to be large enough and young enough to retain significant residual magma: the Yellowstone caldera in northwestern Wyoming (formed about 600,000 years ago), the Valles caldera in north-central New Mexico (formed about 1,100,000 years ago), and the Long Valley caldera in east-central California (formed about 730,000 years ago) (45). The size of these magma bodies may be as large as 1000 km^3 with temperatures as high as 1300°C. It is estimated that 2 km^3 of magma could provide the energy required to operate a 1000 MW power plant for 30 years—an energy output of approximately 10^{18} J, equivalent to 172 million barrels of oil (46).

The US government initiated a research program in 1974 which successfully demonstrated the scientific feasibility of this novel concept. The program was then extended to investigate engineering feasibility. Several significant findings emerged from this research: (1) Drilling into ultrahigh-temperature lava—using high-velocity water jets in advance of the drill bits to freeze the magma and maintain a stable borehole—was successfully demonstrated at the Kilauea Iki lava lake in Hawaii. (2) Energy extraction through the production of dry steam was also demonstrated in the Hawaiian experiment. (3) Engineering materials needed for drilling into magma and suitable for long-term energy extraction were evaluated in reconstituted magma environments at 850°C, showing that nickel-based superalloys have excellent chemical resistance and strength in this hostile environment. (4) It was also shown that many of the problems associated with ultrahigh temperatures (including accelerated drill bit wear, drilling fluid degradation, drillstring corrosion, and wellbore instability) can be eliminated or mitigated by using insulated drillpipe in conjunction with surface mud coolers to keep drilling fluids cool (47).

Two proposed methods of extracting energy from magma were analyzed (48): (1) a closed heat exchanger system consisting of two concentric pipes inserted into the magma, with fluid circulated down the annulus and up the inner pipe, extracting heat without the working fluid ever contacting the magma, and (2) an open heat exchanger system also consisting of two concentric pipe strings down to the magma chamber but with only the inner pipe penetrating the magma. Fluid is circulated down the inner string and returned through the fractured crust (formed around the inner pipe by the rapid freezing of the adjacent magma) and then up the annulus to the surface. Engineering analyses indicate that the amount of energy which can be extracted from a single magma well is 3 MW to 5 MW for the closed system and 25 MW to 45 MW for the open system—showing the clear superiority of the latter (47). Economic analyses conducted at Sandia estimate that for a magma reservoir at 5500 m depth the cost of power using the open system would be in the neighborhood of 8 ¢/kWh to 10 ¢/kWh (49). A second independent cost analysis developed for the California Energy Commission estimates that a 50 MW power plant could produce magma power for 5.6 ¢/kWh. Such estimates are clearly speculative; however, they do indicate the likelihood that energy can ultimately be extracted economically from the world's abundant magma resources (3).

Global Climate Improvements: CO_2 Reduction

Various geothermal options, including electricity production, direct heat application, and heat pump utilization, can be important components in a global strategy to transition to reduced fossil energy dependency, if and when needed. The production of carbon dioxide from the burning of fossil fuels is currently perceived as a serious threat to climate stability. The United Nations Conference on Environment and Development was held in Rio de Janeiro in 1992 to "achieve . . . stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (50). Follow-up conferences were held in Berlin in 1995, Geneva in 1996, and New York in 1997 to reaffirm this commitment.

Reduction of Demand for Fossil Fuels. The most significant greenhouse gas, in terms of both quantity and growth potential, is carbon dioxide, and its principal source originates in fossil fuel emissions from energy production, residential and commercial energy use, manufacturing, and transportation. In response to the Rio Conference, the United States promulgated a Climate Change Action Plan (CCAP) in 1993 aimed at returning US greenhouse gas emissions by the year 2000 to 1990 levels (50). These emissions were projected to grow by 7% by 2000 without the CCAP—from 1462 million metric tons of carbon equivalent (MMTCE) to 1568 MMTCE, an increase of 106 MMTCE. Under the CCAP, the private and public sectors established collaborative efforts to accelerate market acceptance of renewable energy technologies. A consortium of geothermal developers and utilities was created to cost-share exploration and drilling activities to expand known hydrothermal reserves. The substitution of geothermal energy for fossil fuels can markedly reduce CO_2 emissions. The annual pollutants per 1000 MW effective electric plant capacity are 2.609 MMTCE for a typical coal-fired plant, compared to 0.001 MMTCE for a geothermal flash steam plant. Thus, the substitution of each 1000 MW of geothermal power for an equivalent coal-fired plant reduces the greenhouse gas burden by 2.6 MMTCE (51).

The use of geothermal heat pumps (GHPs) reduces the amount of electricity needed to satisfy the nation's heating and cooling requirements, thus reducing the nation's CO_2 burden. GHPs can be categorized as ground-coupled, groundwater, and hybrid. In the first type, a closed loop of pipe is buried horizontally beneath the frost zone (or vertically 30 m to 120 m deep). The second type, used in the United States since the 1930s and until recently the most popular, delivers groundwater to a heat exchanger installed in the heat pump loop, then discharges the groundwater on the surface or into an injection well. The third type, the hybrid system, is used primarily in commercial buildings. Due to the high cost of meeting peak cooling loads, hybrids typically incorporate a cooling tower allowing the engineer-designer to (1) size the ground loops for heating loads and (2) use the tower to help meet the larger peak cooling loads.

Over two-thirds of the United State's electricity is used in buildings. Space heating and cooling, along with water heating, account for over 40% of the electric power used by residential and commercial buildings. GHPs have the potential to reduce electric energy consumption and related emissions by 20% to 40%. A Geothermal Heat Pump Consortium (GHPC) was formed in 1994 to accelerate the development and rapid commercialization of GHPs by promoting research to reduce drilling costs for the emplacement of subsurface heat-exchange loops and by developing training programs for engineers and installers. The GHPC goal is to increase the annual installation of geothermal heat pumps from 40,000 to 400,000 by the year 2000, reducing greenhouse gas emissions by 1.5 MMTCE annually (52,53).

Displacement of Fossil Fuels: Hydrogen Production. Automobiles account for approximately one-half of the oil consumed in the United States while producing more than half of urban pollution and one-quarter of that nation's greenhouse gases. Many metropolitan areas in the United States, such as Los Angeles, fail to meet the Environmental Protection Agency's air-quality standards. Elsewhere in the world, in cities such as Mexico City, Tokyo, Jakarta, and Sao Paulo, air pollution is even more severe. Many of these cities have initiated comprehensive studies to understand better the nature of the problem and to develop technically viable, politically acceptable, cost-effective solutions. Generally, government solutions embrace both regulatory controls (such as limiting the number of vehicles, rationing fuel, and enacting driverless days) and technical advances for pollution abatement (such as improved fuels, catalytic converters, and electric vehicles). A major US research program, the Partnership for a New Generation of Vehicles, was initiated in 1993 by the automobile industry and the government to create by 2004 cars which would meet stringent clean-air standards and have markedly improved energy efficiencies (equivalent to 80 mi. per gallon) (54). One of the promising approaches is the development of electric-drive vehicles, which include not only cars powered by batteries, but also vehicles that generate electricity onboard by the use of fuel cells. The ideal fuel for these cells, from both a technical and environmental perspective, is hydrogen, which, when burned, produces only water vapor.

The electrolytic production of hydrogen—the most environmentally benign process for generating it—currently amounts to less than 1% of the hydrogen market, because of the high cost of electricity. However, the cost of electrolytic hydrogen can be reduced using high-temperature electrolysis with efficiencies greater than 80%. Jonsson (55) explored the feasibility of using geothermal steam as a heat source for a high-temperature electrolyzer and found that geothermal-heated steam at 200°C can reduce the specific electricity requirements by 30% compared to conventional electrolytic processes. Furthermore, the capacity of geothermal fields, most efficiently used for base-load electric power, can be increased to above peak-load demand and the integrated excess capacity used in the production of hydrogen. The lower incremental cost of the excess power along with appropriate credits for air pollution abatement, reduction of greenhouse gases, and mitigation of other market externalities can help lower the cost of hydrogen produced from geothermal energy to competitive levels (56).

Geothermal's Growing Global Role

Geothermal resources are large and widely distributed, especially in many of the rapidly developing countries of the world, including the Philippines, Indonesia, and nations in East Africa, Central and South America. Geothermal power globally has grown steadily since the early 1920s at a rate of more than 8.5% per year, reaching 7000 MW installed capacity in 1997, and projected to exceed 11,000 MW by the year 2000. Geothermal power already makes a significant contribution on a regional basis; for example, over 7% of California's electricity is produced from geothermal energy.

Geothermal power plants offer numerous advantages: they are simple, safe, and modular (1 MW to 50 MW); have short construction periods (one year for a 50 MW plant); and are capable of providing base, load-following, or peaking capacity. Moreover, geothermal plants provide significant societal benefits: they reduce the demand for imported oil along with the concomitant national defense and balance-of-payments problems, and offer benign environmental attributes (negligible emissions of CO_2, NO_x, SO_x, and particulates, and modest land and water use). These features are fully compatible with the sustainable growth of global energy supplies, making geothermal energy an attractive option.

The robust growth in geothermal power has been based almost exclusively on the use of high-temperature hydrothermal resources. If geothermal power is to become more universally available with a significant impact on global energy supplies, then low-temperature resources (and advanced concepts including hot dry rock, geopressured, and magma) must be pursued vigorously to make them economically competitive. This will require an aggressive research program to reduce field development and energy conversion costs.

Low-temperature resources provide an economical source of energy for GHPs and for direct use in domestic, industrial, agriculture, aquaculture, and district heating applications. The installation of GHPs in the United States has been growing rapidly at a rate exceeding 15% per year. GHPs offer users an inexpensive means of space heating and cooling, along with domestic hot water, while offering utilities the benefits of reduced peak demands for power, and the deferred need for new plant capacity.

Research programs designed to increase understanding and improve technology for heat mining in the severe environment of hot dry rock and magma resources are underway in Europe, Japan, and the United States. If successful, these efforts will make abundant geothermal energy universally available to humankind.

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JOHN E. MOCK
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