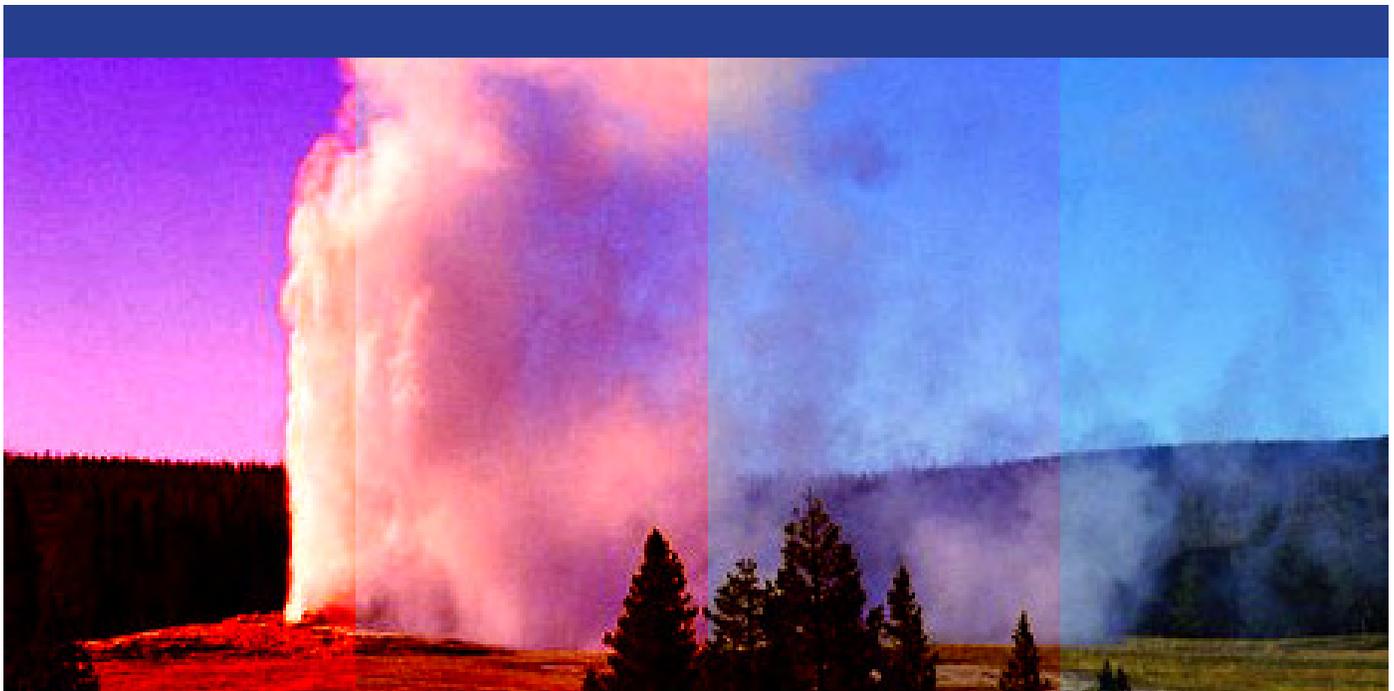


Geothermal Power:

**Issues, Technologies, and Opportunities for Research, Development,
Demonstration, and Deployment**

February 2010



An EPR Technology Innovation White Paper





Executive Summary

Geothermal energy supplies electricity, space conditioning, and water heating services with a long track record of reliable, cost-competitive operation. Geothermal resources are abundant, widely available, and renewable and may be harnessed at scales ranging from central-station power plants to residential heating systems.

On a global basis, heating represents the most common use, but U.S. Energy Information Administration (EIA) data shown in Figure 1 demonstrate that more than 90% of the geothermal energy consumed in the United States is applied for power generation. (EIA, July 2009) Geothermal plants remain a noticeable contributor to the nation’s energy supply portfolio, even though very little capacity has been added since a boom in the 1980s led to overdevelopment of the Geysers field in northern California, a localized decline in hydrothermal steam pressure, and a worldwide slowdown. Since the turn of the century, overseas deployment has accelerated, existing U.S. fields have accommodated incremental capacity additions, development activity has spread to other areas of the country, public investment in advanced geothermal technology has increased, and the long-term outlook has brightened.

This white paper focuses on research, development, demonstration, and deployment (RDD&D) issues relating to U.S. use of geothermal energy for electricity generation, consistent with serving consumer demand at low cost in a clean, reliable, and sustainable manner. It also addresses the potential of geothermal heat pumps as an electricity-based space conditioning and water heating technology.

Unlike variable-output renewables such as wind and solar, geothermal plants are dispatchable and capable of base-load operation. Relative to biomass generation, geothermal offers essentially zero fuel cost plus unquestioned status as a greenhouse gas mitigation option. It thus represents a promising technology for satisfying renewable portfolio standard (RPS) requirements and responding to climate change and security concerns. According to EPRI analyses, geothermal exploration, pre-development, capital, and operating and maintenance costs remain high. This makes incremental capacity additions at existing U.S. fields the most economical, lowest-risk approach to near-term deployment, and it puts a premium on technologies for reducing costs and improving productivity at current and new plants. RDD&D progress promises breakthroughs that could improve competitiveness and catalyze extensive deployment in coming decades.

U.S. Geothermal Energy Consumption by Sector, 2003-2007

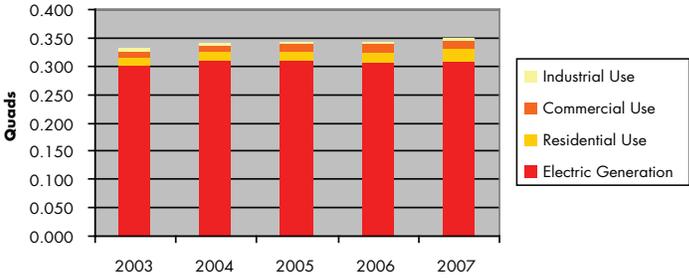


Figure 1 – Power generation represents the predominant use of geothermal energy in the United States, whereas other countries employ it largely for heating applications. (Data Source: EIA, July 2009)

To help expand the role of geothermal technologies in meeting energy needs, EPRI is addressing key issues and opportunities and collaborating with utilities, power producers, national laboratories, manufacturers, and other stakeholders to identify RDD&D priorities for the immediate, mid, and longer terms. (EPRI & ACORE, 2009)

Overview & Status

Geothermal energy literally is the “heat of the Earth.” Surface heating caused by solar radiation penetrates only about 30 feet (10 m) underground, after which temperatures and pressures steadily increase with depth. Radioactive decay of various isotopes in the Earth’s mantle and core represents the primary source of the underground heat that is tapped for energy production. Additional contributors include residual heat from the formation of the Earth billions of years ago, heat created by gravitational forces pulling more dense materials toward the center of the Earth, and latent heat from the solidifying of molten rock in the Earth’s core. (Anuta, 2006)

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This white paper was prepared by Chris Powicki of Water Energy & Ecology Information Services and Elizabeth Hooper of Hooper Design under the direction of EPRI’s Stan Rosinski, Travis Coleman and Luis Cerezo. (Cover photos: NREL)

The global geothermal resource is vast. An early EPRI study concluded that the amount of heat contained in just the first 2 miles (3 km) of the Earth's crust below the continents could supply enough energy to meet the world's consumption requirements for approximately 100,000 years. (EPRI, 1978) However, like other renewables, only a small fraction of available energy is potentially harvestable. The promise of and approach to geothermal energy capture depend largely on heat content (enthalpy), which is a function of temperature, pressure, and volume. Low-enthalpy resources have a temperature below 212°F (100°C). They are ubiquitous but suitable only for direct use at present. Electricity generation is possible for moderate- and higher-enthalpy resources; the power production potential generally increases with temperature.

The overwhelming majority of existing geothermal power plants draw energy from reservoirs of gaseous or liquid water in permeable rock at depths ranging from less than 1,000 feet (300 m) to more than 7,000 feet (2,000 m). These hydrothermal reservoirs, which are subdivided into vapor- and liquid-dominated resources depending on whether primarily steam or liquid water is present, are the result of heat transfer from geologically active high-temperature belts to aquifers. Production wells are used to bring the fluids to the surface, where their heat energy is converted to electricity through a steam turbine-generator train. Fluids at high temperatures and pressures are used directly or flashed from water into steam, after which they are condensed and returned underground via separate injection wells to avoid reservoir depletion. Moderate-enthalpy resources are generally run through a binary heat exchange cycle to vaporize a working fluid before reinjection. To date, most geothermal plants have been sited in areas with high subsurface temperatures, high rock permeability, and a naturally occurring water-steam resource. The confluence of these three factors is rare, generally occurring in isolated locations within geologically active regions, such as the "Ring of Fire" bounding the Pacific Ocean.

Two other types of geothermal resources are suitable for power generation. Geopressed deposits of heated brine containing dissolved methane are found in conjunction with oil and gas reserves. They are limited in availability and economical for electricity production only in combination with existing fossil fuel extraction infrastructure. Hot dry rock (HDR) resources are found in areas offering sufficient heat for power generation but lacking an in situ water-steam supply. They are the most abundant and widely distributed geothermal source, but transforming their heat energy into electricity poses substantial engineering challenges. Enhanced geothermal system (EGS) technology—while not yet in the commercial stage of development—involves subsurface fracturing of impermeable rock, followed by the pumping of surface water or groundwater into the fractured area to create an artificial reservoir. Advanced concepts also are being pursued for power generation from HDR resources. (See box, p. 11)

Figure 3 displays worldwide installed capacity and energy production for all geothermal technologies. Globally, direct-use heating applications supply the majority of energy, while electric generating capacity exceeds 10,000 megawatts (MW). In the United States, more than 90% of geothermal production is from power plants. These plants, with aggregate capacity of more than 3,100 MW, accounted for 5% of the nation's total renewable energy and almost 13% of non-hydro renewable generation in 2008. (EIA, July 2009)

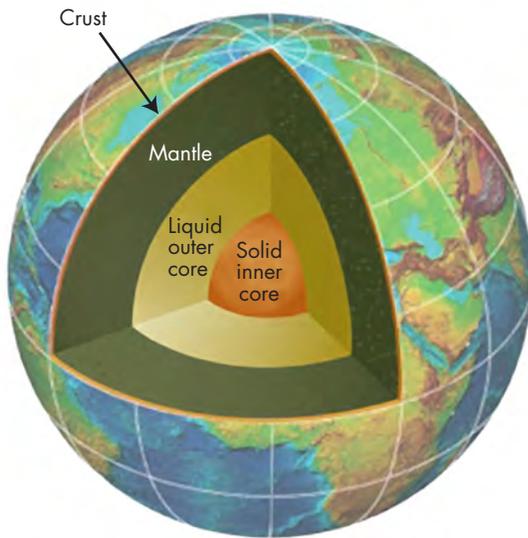


Figure 2 – Geothermal power plants tap heat that originates from deep inside the Earth. (Credit: Lawrence Livermore National Laboratory)

Direct use of geothermal energy has been practiced for millennia and continues today. Hot springs and steam vents at the Earth's surface—and heated groundwater at shallow depths—are tapped for diverse applications, including space conditioning, district heating, and process heating. Geothermal heat pumps, a recently developed technology, are widely used for residential and commercial buildings and offer significant growth potential in the United States. A relatively shallow borehole or well, or horizontal loops of piping buried below the frost line, capitalize on the relatively constant temperatures of groundwater and soil to extract energy for heating and cooling as seasonal demands require. (See box, p. 5)

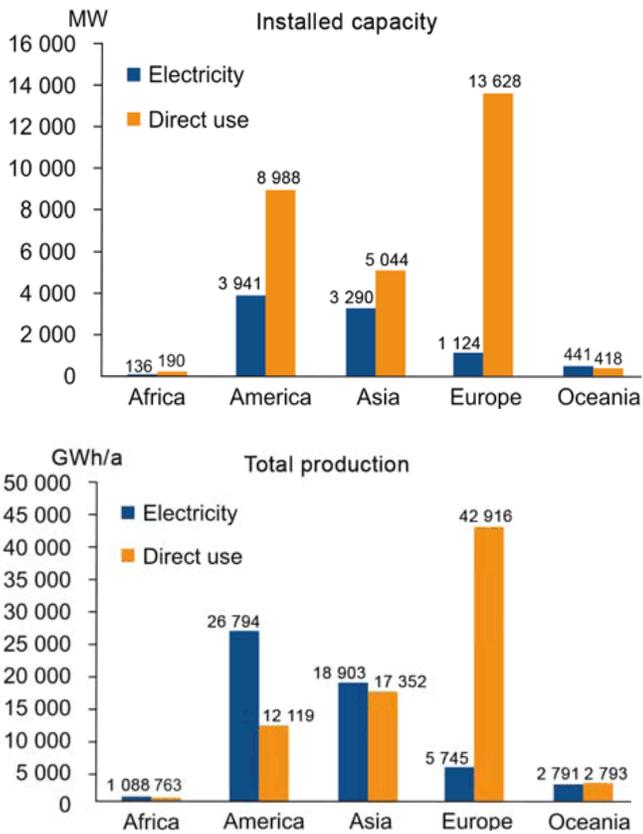


Figure 3 – Most geothermal energy is used directly for heating applications, while the United States is the world leader in electric generating capacity and production. (Source: World Energy Council, Survey of Energy Resources 2007)

The first geothermal power plant was built in Larderello, Italy, a site and country that continue to host sizeable generating capacity. Other major producing countries include Indonesia, the Philippines, Mexico, Japan, Iceland, and New Zealand. With more than 2,600 MW installed, California alone boasts more geothermal capacity than any country outside the United States, and more than half of this amount is located at the Geysers field north of San Francisco. Idaho, Nevada, Utah, and Hawaii also host utility-scale plants.

Based on decades of practical experience, geothermal power plants drawing upon high-enthalpy hydrothermal resources are considered to be a well-established commercial technology. (EPRI & DOE, 1996) Binary-cycle systems employing resources at the higher end of the moderate-enthalpy range are commercially available but not yet considered mature. Technologies optimized for resources at the lower end of the moderate-enthalpy range and for HDR applications are in much earlier stages of development. (EPRI, 2009a)

Existing geothermal power plants range in size from about 0.25 to 180 MWe. Many achieve annual capacity factors of 0.85 to 0.90 or higher, but relatively high maintenance costs are common due to challenging subsurface conditions and the corrosive and erosive nature of hydrothermal fluids. Increasing the competitiveness of existing plants is critical through advanced operations and maintenance (O&M) practices that reduce costs and improve availability and productivity.

Among renewable generation options, geothermal power offers the important advantage of being dispatchable to serve load: Energy production is not affected by daily or seasonal resource supply fluctuations; baseload operation is common, while ramp rates of 5 MW/hour are typical in load-following mode. These characteristics avoid many of the grid integration challenges associated with variable-output sources like wind and solar energy. Unlike biomass and fossil generation capacity, geothermal plants are not required to secure, purchase, and handle fuel, at least in a conventional sense. However, hydrothermal plants rely on underground reservoirs of gaseous or liquid water as a fuel, necessitating careful resource management to avoid depletion, as occurred at the Geysers field. Either conventional wet cooling systems—which require a surface water supply—or air cooling technologies typically are used to condense steam from the turbine exhaust and allow for reinjection of the hydrothermal fluid. At the Geysers and other sites, water from other sources is being injected underground to sustain energy production levels.



Figure 4 – The Steamboat Hills geothermal field in Nevada hosts both conventional hydrothermal capacity and binary-cycle power plants. (Credit: NREL)

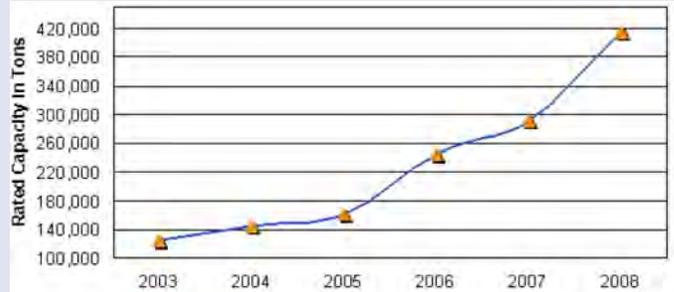
Steam plumes represent the most visible by-product of geothermal power plant operations (Figure 4). Releases of conventional air pollutants, greenhouse gases, and other chemicals generally are low to nonexistent and are controlled where necessary using existing technologies. Seismic activity induced by extraction and injection of un-

Harnessing Geothermal Energy for Space Conditioning, Electrification & Emission Reduction

Geothermal heat pump (GHP) technology exploits the nearly constant temperature of soil and groundwater near the Earth's surface to provide highly efficient space heating, space cooling, and water heating services.

At least 70% percent of the energy used by GHPs is derived from the ground. Electricity provides the remainder to run compressors and air handlers, but GHPs require much less power than air-source heat pumps, resistance heaters, and standard air conditioners. From a utility perspective, GHPs present load growth and demand-side management opportunities. (EPRI, 2008)

U.S. deployment is expanding rapidly, albeit from a small base, and market potential is enormous: GHPs have less than a 1% share of the more than 3 million unitary heating, ventilation, and air conditioning (HVAC) units shipped every year, but they typically offer the lowest life-cycle cost of any HVAC system. Further, they reduce exposure to volatile fuel prices, are eligible for renewable energy and energy efficiency incentives, require little maintenance, and produce no on-site emissions.



Growth in U.S. Geothermal Heat Pump Sales (Credit: EIA)

On the downside, the up-front costs and space requirements associated with ground loop piping make conventional GHPs not suitable for many applications. To address this barrier, EPRI is investigating use of centralized underground piping networks, owned by the electricity provider, to supply energy—in the form of water warmer or cooler than the ambient air—to heat and cool multiple homes or commercial buildings. This innovative ownership model would allow developers to provide consumers with state-of-the-art GHP systems at little or no additional cost. It also would allow utilities to expand their asset base and improve load shapes while delivering energy efficiency services.

derground fluids is a frequently cited concern, but most hydrothermal plants are located in regions where earthquakes already are common, which prevents buildup of the stresses required to create damaging events. In addition, most production and injection wells reach depths generally shallower than those associated with seismic activity.

The uncontrolled expansion at the Geysers in the 1980s, as well as the availability of lower-cost options for capacity expansion, contributed to a worldwide slowdown in geothermal energy development lasting more than a decade. In the past 5 years, activity has begun accelerating both globally and in the United States (Figure 5). As of October 2009, the Geothermal Energy Association (GEA) reports that between 4,000 and 6,500 MW were in various stages of confirmed development across the country, suggesting that U.S. capacity could more than double within the next 5 years. The majority of activity lies at sites and in states with existing plants, but projects also are being pursued in New Mexico, Colorado, Oregon, Alaska, Florida, and Arizona. (Jennejon/GEA, 2009)

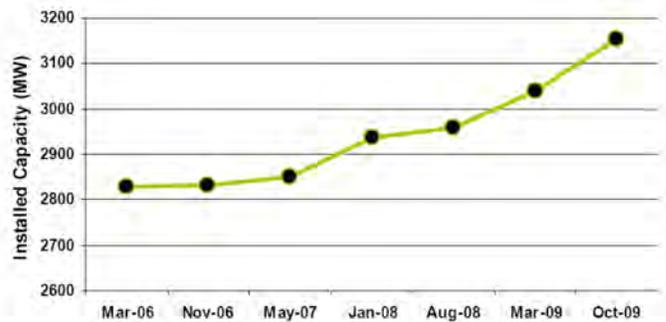


Figure 5 – After about 15 years of little to no growth in the United States, total installed electric generation capacity is starting to climb and could double within the next 5 years. (Credit: Jennejon/GEA, 2009)

Existing and anticipated energy and climate policies—including RPS requirements, tax and financing incentives, and carbon pricing—represent key drivers of current development activity. According to EPRI analysis, they are expected to become increasingly critical over time, particularly as geothermal technologies advance. In a recent modeling study, projected U.S. geothermal capacity in



2030 ranged between about 20,000 and 30,000 MW, depending on climate policy and other assumptions. (EPRI, 2009b) A 2006 analysis by Massachusetts Institute of Technology (MIT) concluded that technology progress—largely in EGS applications—could lead to the deployment of 100,000 MWe or more of cost-effective baseload capacity and a 10% share of the U.S. power generation market by 2050. More recent studies by the U.S. Department of Energy (DOE) have identified critical RDD&D issues and defined a technology roadmap for achieving these long-term goals. (DOE, 2008, 2009)

The factors most cited as limits to near-term growth are the high costs and risks associated with resource exploration and site development and the extended timelines associated with project permitting. Transmission access also is a concern due to the remote nature of many undeveloped sites. According to EPRI's analyses, incremental capacity additions at existing sites are thus the lowest-cost, lowest-risk option for near-term expansion of geothermal power, but the ability to serve baseload duty also makes project development in new areas attractive for RPS compliance because high capital costs (relative to wind) are balanced by low levelized cost of electricity.

To grow the role of geothermal energy in meeting needs for electricity across all time scales, advances are required in resource assessment and characterization, drilling technology, reservoir engineering and management, advanced energy conversion cycles and configurations, and O&M technology. In addition, successful large-scale EGS demonstration projects are needed to help unlock the potential of HDR resources. Substantial RDD&D investment, supportive policy and incentive frameworks, and public acceptance also are required to fuel an expanded role for geothermal power.

Resource Availability & Exploration

Survey (USGS), the nation's hydrothermal resource base in just the first 3 km beneath the Earth's surface could supply from 120,000 and 175,000 MW of generating capacity with a per-plant operating lifetime of 30 years. (USGS, 1978) To date, only a very small fraction of this resource has been tapped, even though most U.S. plants use production wells shallower than 3 km. Further, the capability now exists to access geothermal resources at depths of up to 10 km underground.

For HDR resources, temperatures generally reach commercial usefulness at depths of 3 km or more. They exist where geothermal gradients—the vertical profile of changing temperature—are significantly above average ($>50^{\circ}\text{C}/\text{km}$). The USGS estimates that acces-

sible HDR resources could supply enough energy to satisfy current U.S. consumption for tens of thousands of years. U.S. geopressured resources are found for the most part in the Texas-Louisiana coastal region near the Gulf of Mexico. (Southwest Research Institute, 1983) The resource base is relatively small, but the tens of thousands of operating and abandoned oil and gas wells here and in other areas of the United States represent opportunities for distributed geothermal power generation.

Generally, geothermal resources are classified based on temperature, which varies as a function of depth underground, rock type, depth to crust, and other characteristics. Figure 6 displays the U.S. resource at a depth of 6 km according to a traditional classification: non-electrical grade, $0\text{--}100^{\circ}\text{C}$ ($0\text{--}212^{\circ}\text{F}$); low, $100\text{--}150^{\circ}\text{C}$ ($212\text{--}300^{\circ}\text{F}$); moderate, $150\text{--}200^{\circ}\text{C}$ ($300\text{--}400^{\circ}\text{F}$); and high, $>200^{\circ}\text{C}$ ($>400^{\circ}\text{F}$). It suggests that much of the western United States harbors high-quality resources for hydrothermal generation and almost the entire country is suitable for EGS applications. On a practical basis, however, power plants are built in specific locations, and parameters beyond subsurface temperature—including depth, pressure, fluid phase, permeability, fluid flow rate, rock type, seismicity, and water/steam quality—have significant impacts on resource productivity.

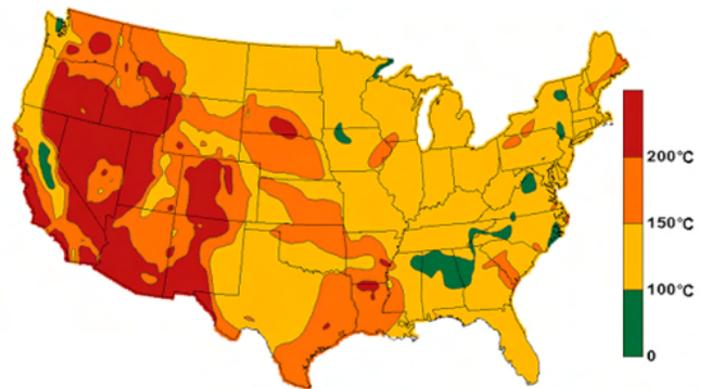


Figure 6 – Based on temperature at 6 km depth, the U.S. geothermal resource base suitable for electricity production using existing and emerging technologies appears to span almost the entire country. (Credit: DOE Geothermal Technologies Program)

Figure 7 provides a finer-grained U.S. geothermal map based on surface heat flow, which is strongly correlated to hydrothermal resource quality. (Wisian *et al*, 1999) Geological features are another important indicator. For example, porous rocks between impermeable sedimentary layers may harbor hot sedimentary aquifer (HSA) resources, the pattern of productive wells in a hydrothermal field may follow a fault line, or the limit of a production zone may be

marked by a change in rock type at a fault. Improved databases and maps represent a starting point for detailed geological and geophysical characterization studies. A variety of analytical techniques are available to support geothermal exploration, most adapted from the oil and gas industries. They measure different parameters, vary in resolution and cost, and work better at different depths. Typically, they are used in combination to improve reliability and provide as much detail of the underground resource as possible.

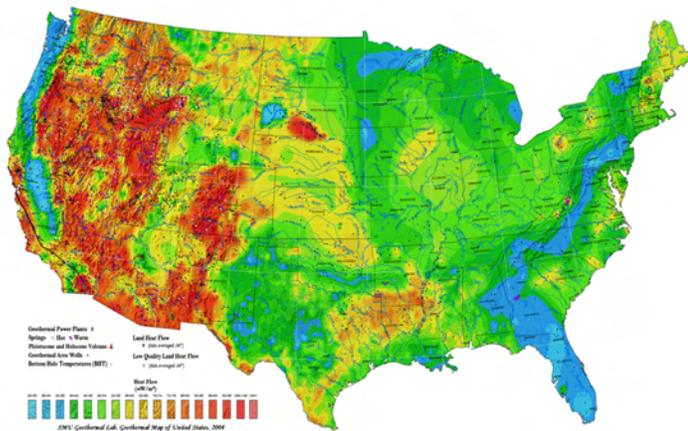


Figure 7 – Detailed resource characterizations accounting for surface heat flow and other critical parameters are required for a more accurate assessment of the site-specific geothermal energy development potential. (Credit: Blackwell & Richards, 2004)

Over the past two decades, however, the success rate for geothermal exploration—in terms of leading to electricity generation—has not improved. Some critical parameters are extremely variable but not yet characterized at the level of detail required by project developers. This is particularly true for HDR resources because they are located further underground and because the characteristics that determine resource quality and development potential for EGS applications are not well understood.

RDD&D Opportunities

The ability to direct exploration and follow-on verification activities toward higher-grade resources is critical because subsurface drilling is both costly and risky. Effective, nonintrusive capabilities are required for improved mapping, characterization, and analysis of geothermal resources, which will allow for more efficient and effective prospecting. Specific RDD&D needs are listed below:

- Comprehensive databases and fine-grained models to accurately and cost-effectively locate and characterize sites with recoverable and sustainable resources

- Fundamental knowledge of the influence of geological and geophysical parameters on HDR resource quality and development potential
- Advanced geological and geophysical analysis methods and “no drill” prospecting tools to identify and define resource boundaries, fracture zones, thermal gradients, fluid characteristics, permeability, etc.

Resource Verification & Delivery

After preliminary geological and geophysical analyses lead to the identification of a potentially promising site for hydrothermal project development, one or more narrow-bore exploratory wells are drilled to support resource confirmation and, if successful, further analysis using down-hole analytical methods. Critical parameters and boundaries are measured and delineated in detail to support reservoir modeling and site-specific assessment of generation economics, informing investment decisions. Ultimately, commercial-diameter production wells must be drilled to deliver the fuel—hot liquid or gaseous water—required to support deployment of geothermal capacity. In productive areas, a well field often is created by digging multiple slant wells from a single location. (*Reservoir management techniques are addressed in detail in the “Operations, Maintenance & Environmental Control” on page 13.*)

Figure 8 illustrates the additional complexities involved in identifying a potentially promising HDR resource and in developing a project using EGS technology. Subsequent to subsurface characterization via exploratory drilling, an artificial reservoir is created by drilling holes into a hot rock formation and pumping high-pressure water through an injection well. This hydraulic fracturing approach, commonly employed for boosting production from oil and gas fields, is used to increase the formation’s permeability and allow for enhanced fluid flow and heat transfer. Permeability is a function of the degree of fracture in the rock and the porosity of the rock matrix. High-permeability reservoirs offer higher flow rates and therefore improved abilities to deliver hot fluid. Once the artificial reservoir meets performance requirements, surface water may be pumped into the fractured zone, where it is heated and then delivered to the surface via a production well.

Often referred to as bores or bore holes, geothermal production wells are similar to those drilled for oil and gas exploration and extraction, and the same technology, equipment, and techniques generally are employed. However, geothermal wells generally are much wider to

expand fluid flow and production rates. They may be classified as follows: shallow, <3,500 m; mid-range, 3,500-5,500 m; and deep, 5,500-10,000 m. Shallow wells are typically employed for hydrothermal plants, while deep wells may prove typical for HDR resources.

carbon dioxide (CO₂) rather than water for hydraulic stimulation may prove more effective. Supercritical fluids have the unique ability to diffuse through solids like a gas while retaining the properties of a liquid. Studies suggest that injecting supercritical CO₂ to fracture underground formations, create an artificial reservoir, and serve as a hydrothermal fluid may yield heat extraction rates from HDR resources 50% greater than those achievable with water. In addition to reducing the costs and improving the productivity of geothermal power plants, this approach could allow storage of CO₂ captured from fossil generating facilities.

EGS Development Sequence

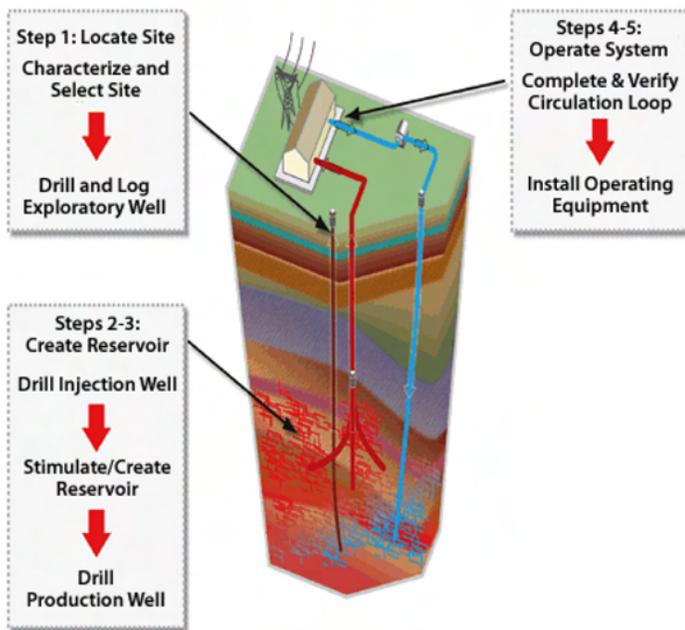


Figure 8 – To access heat energy stored in hot rock formations lacking a natural water source, an artificial reservoir is created using EGS technology. (Credit: DOE)

A few meters in the vertical or horizontal direction may make a substantial difference in well productivity, highlighting the importance of subsurface characterization and the complexities and risks associated with resource verification and delivery. Well costs, which increase rapidly with depth, account for 40% or more of the total capital costs for hydrothermal plants, while deep wells could account for much higher percentages. Emerging technologies for oil and gas exploration that have yet to be demonstrated in geothermal applications have the potential to significantly reduce these costs.

Small-scale demonstrations in several countries have established the technical feasibility of EGS technology. (See box, p. 11) Uncertainties regarding the resistance of rock formations to fracture, the resistance of engineered reservoirs to hydrothermal flow, the potential for thermal drawdown over time, water losses, and other factors are major obstacles to commercial development. Using supercritical

RDD&D Opportunities

New technologies for drilling geothermal wells—which, due to their wider bore, may currently cost up to 30% or more than oil and gas wells of the same depth—offer significant potential to increase the competitiveness of geothermal power plants. Improved knowledge of factors controlling the efficacy of hydraulic fracturing for creating artificial reservoirs in HDR formations is needed to reduce the costs and risks of EGS deployment. Specific RDD&D needs are listed below:

- Innovative “down-hole” instrumentation and new modeling tools to define resource characteristics, analyze development potential, and optimize production system design
- Horizontal, deep-hole, and smart drilling technologies and techniques adapted from the fossil fuel extraction industry to reduce the costs and risks of geothermal exploration and development
- Advanced bits, fluids, and abrasives and novel casing designs to improve drilling rates, reduce wear and failure rates, and increase well integrity and reliability
- Geothermal-specific drilling technology for producing wider bores and dealing with corrosive brines, high temperatures, and other harsh conditions
- Hydraulic stimulation, fracture detection, fracture permeability, reservoir validation, and long-term monitoring studies to support siting, demonstration, and deployment of EGS technology under varying geological conditions
- Supercritical fluid systems to stimulate creation of artificial reservoirs, improve thermal extraction efficiency from HDR resources, and sequester CO₂.

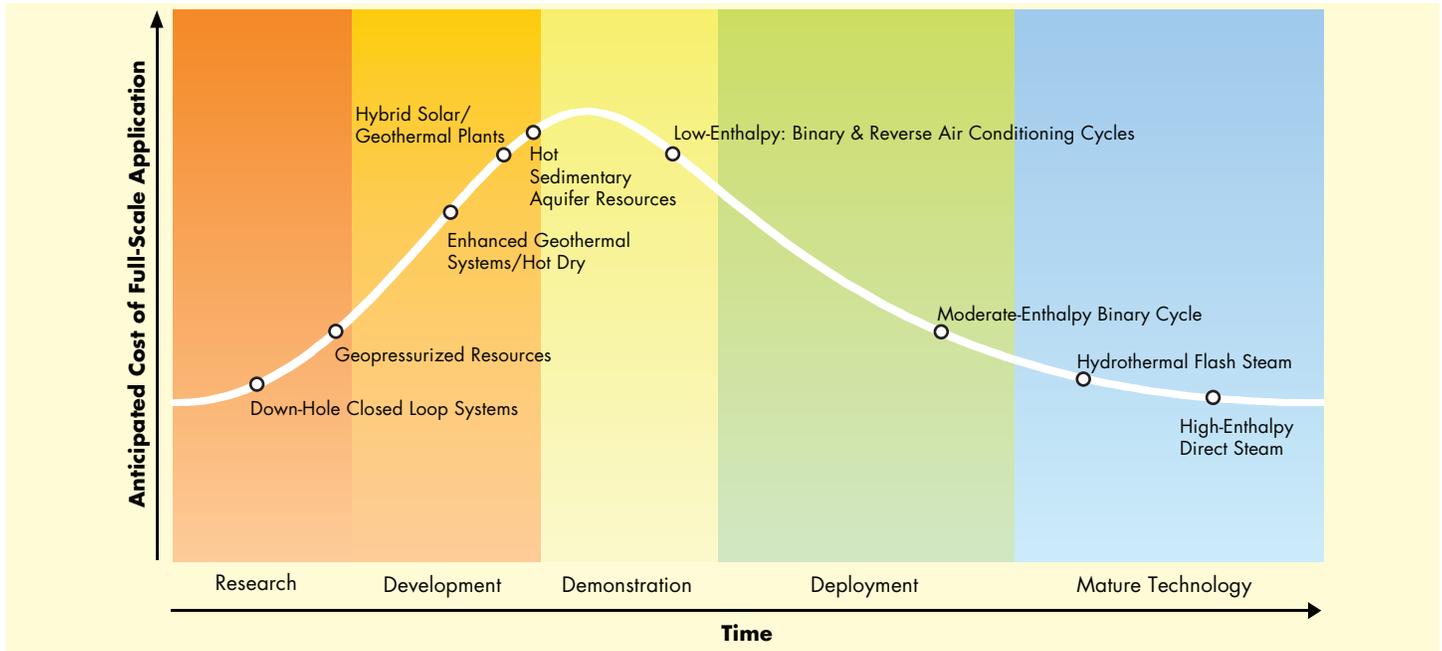


Figure 9 – Geothermal power generation technologies are at varying stages of development and commercial maturity, as shown by this Grubb Curve.

Power Generation

Geothermal power plants are unique in that they integrate fuel supply and power conversion technologies. Main components include the reservoir, wells, surface piping, turbine-generator train, and condenser and heat rejection system, along with the controls and electrical components required for plant operations and grid interconnection. Generally, below-ground fluid production systems are derived from the oil and gas industry, and above-ground conversion systems are based on traditional steam-electric power generation.

As shown in Figure 9, geothermal power technologies are at different stages of development, depending on resource type. Commercially mature direct- and flash-steam plants convert the highest-quality hydrothermal resources into electricity, binary-cycle technologies for moderate-enthalpy hydrothermal resources are commercially available, and technologies for lower-enthalpy hydrothermal and HDR resources are emerging, with potential to vastly expand power production. Advanced and hybrid technologies are in early development stages.

As a point of reference, Table 1 displays approximate capital cost ranges for near-term deployment of several geothermal power technologies, as well as cost targets for 2030. Embedded in the cost of well field development are the exploration costs, but these figures

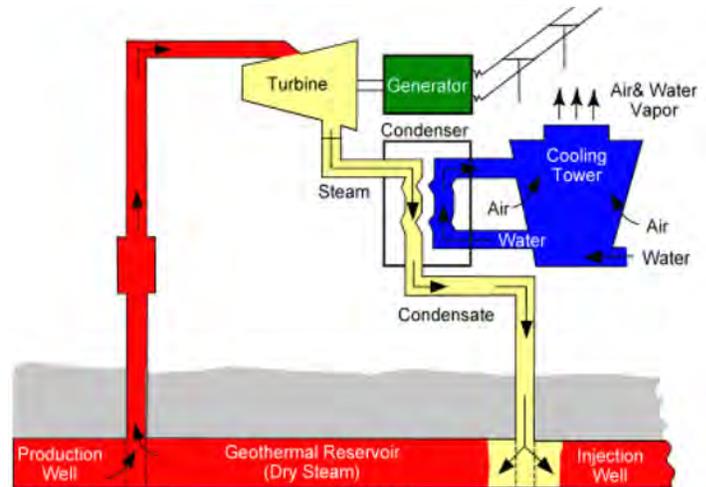


Figure 10 – Schematic of Direct-Steam Power Plant (Credit: Geo-Heat Center, Oregon Institute of Technology)

do not reflect O&M costs, nor do they account for the many other factors influencing site-specific capacity expansion decisions.

Direct-steam power plants utilize naturally occurring resources of pressurized steam, which are quite rare. The most well-known example, the Geysers field, fuels nearly half of current U.S. geothermal capacity. Another dry steam resource of similar size and quality is not expected to be found in North America. As shown in Figure 10,



Table 1 – Estimated Costs and Cost Targets for a 50-MWe Geothermal Plant (2008 \$) Source: EPRI

	Capital Cost (\$/kW)			
	Flash/Dry Steam	Binary Cycle	Reverse Air Conditioning Cycle	EGS - Binary Cycle
Well Field	\$750-\$1500	\$950-\$2000	\$750-\$1500	\$1800-\$6500
Power Plant	\$1200-\$1500	\$1500-\$1800	\$1800-\$2000	\$1200-\$2400
Current Totals	\$1950-\$3000	\$2450-\$3800	\$2550-\$3500	\$3000-\$8900
2030 Goals	\$1300-\$2000	\$1600-\$2700	\$1600-\$2500	\$1800-\$5000

pressurized steam drawn from a production well is piped directly through a turbine to generate electricity. Intensive development at the Geysers led not only to reservoir depletion but also a fundamental change in the technology of geothermal energy extraction: Turbine exhaust is now routinely run through a condenser, where the steam is turned back into liquid form to facilitate reinjection into the reservoir. Heat is rejected from the condenser via either wet or dry cooling towers.

Flash-steam power plants are suitable for liquid-dominated hydrothermal resources above about 180°C (360°F), which are accessible at shallow- and mid-range well depths across broad areas of the western United States. As shown in Figure 11, pressurized fluid is partially vaporized inside one or more flash tanks, which are large vessels allowing a portion of the liquid to expand to steam. Steam is piped from the top of a tank into the turbine, while the unflashed liquid, also known as brine, is drawn off from the bottom before being combined with condensate and reinjected underground.

In double-flash plants, brine from the first tank is introduced to a second, and the resultant steam is introduced through a second, lower-pressure turbine inlet. Two-stage plants are more efficient, yielding steam flow to the turbine typically equivalent to 18% to 25% of the mass of the hydrothermal fluid. Three-flash plants offer further efficiency gains. A figure of merit that improves as flash stages are added is the hot-water rate or brine rate—analogous to the heat rate at fossil plants but measured in the mass (tons) of geothermal fluid extracted per MWh of generation. Lower hot-water rates equate to lower production costs, which must be balanced against the capital cost of adding stages.

Binary-cycle power plants are the most cost-effective generation option for naturally occurring moderate-enthalpy hydrothermal fluids below 360°F (180°C). Such fluids are widely available at shallow- to

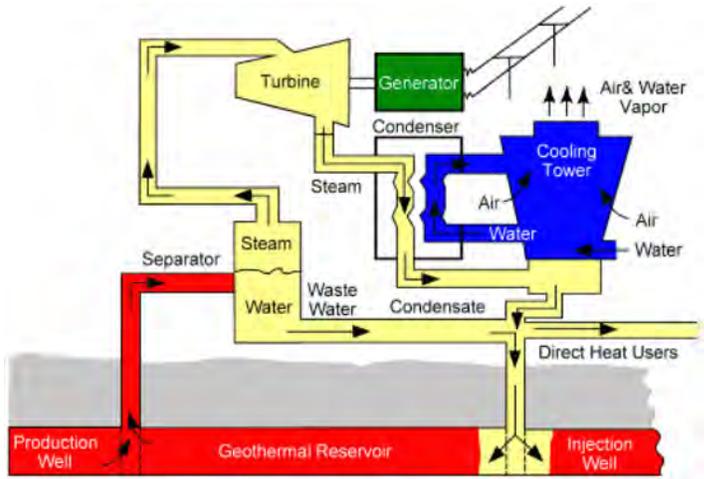


Figure 11 – Schematic of flash-steam power plant (Credit: Geo-Heat Center, Oregon Institute of Technology)

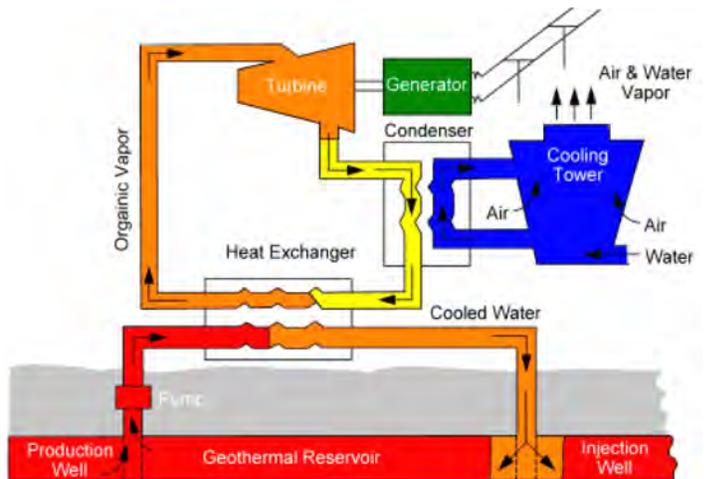


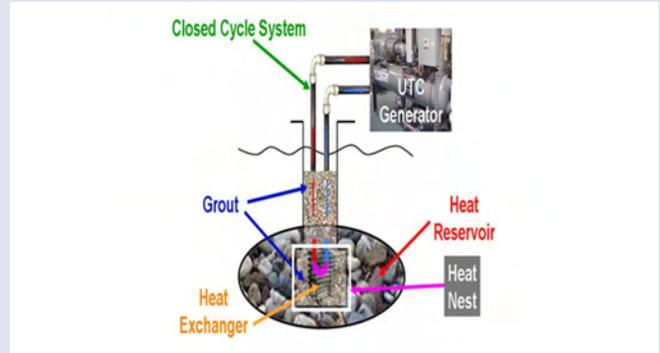
Figure 12 – Schematic of binary-cycle power plant (Credit: Geo-Heat Center, Oregon Institute of Technology)

Generating Power from Hot Dry Rock (HDR) Resources

Recoverable HDR resources in the United States are estimated to exceed 500,000 MWe of generating capacity and offer deployment potential of 100,000 MWe by 2050. Challenges to widespread application of enhanced geothermal system (EGS) technology appear resolvable, and EPRI is exploring an innovative single-hole concept for mining heat from HDR formations.

The feasibility of using EGS technology to fracture rock and create artificial reservoirs has been demonstrated at experimental projects in New Mexico and elsewhere, and small commercial-scale plants are generating electricity in France and Germany. Hydraulic stimulation is under way at the Cooper Basin in Australia, where Geodynamics Ltd. is implementing a 10- to 15-MWe demonstration as a stepping stone to an order-of-magnitude larger plant. Within the United States, multiple EGS projects are being pursued with federal funding supplemented by private sector commitments. To reduce future costs and risks specific to EGS technology, projects must be successfully implemented in different geological formations, and concerns relating to water use and induced seismicity must be addressed.

In 2009, EPRI began exploring a novel, closed-loop approach for mining heat from HDR formations while avoiding hydraulic stimulation and the need to drill both injection and production wells. The single-well engineered geothermal system (SWEIGSTM) technology, developed by GTherm, Inc., integrates a down-hole heat exchanger with specialized grout to maximize coupling with a surrounding environment modi-



The GTherm SWEIGSTM concept could accelerate energy capture from HDR resources. (Credit: GTherm)

fied for increased conduction. A working fluid travels through the Heat Nest™ region and back to the surface, where heat is transformed into electricity using either commercial binary-cycle or reverse air conditioning technology, depending on well temperature.

EPRI work focuses on modeling down-hole components and analyzing the potential of drilling, conduction, grout, and working fluid enhancements for maximizing heat extraction. Within a few years, SWEIGSTM technology could be ready for commercial application in new, depleted, or abandoned oil and gas fields, with individual wells yielding 0.5 to 1 MWe apiece. Economical power generation from other HDR formations will require scale-up to maximize heat capture from purpose-drilled, larger-bore wells.

mid-range well depths in the western United States and in some regions of the Plains and Gulf Coast states, including in HSA formations. Binary cycles also are the most likely option for harnessing HDR resources, as well as geopressured resources found in conjunction with oil and gas deposits at sites where existing infrastructure yields favorable economics.

Figure 12 illustrates a binary cycle. Hydrothermal fluid from a production well is kept under pressure and passed through a heat exchanger where it vaporizes a secondary fluid, usually an organic compound with a low boiling point such as isopentane or, in the case of the Kalina cycle, a water-ammonia mixture. The gaseous working fluid is passed through a specially designed turbine, lique-

fied in a condenser, and returned to the heat exchanger. Meanwhile, having given up its heat, the hydrothermal fluid is reinjected to the reservoir. The water and working fluid are confined to distinct, closed loops during the whole process.

In addition to their standalone applications, binary cycles may serve as bottoming cycles to generate power from brines at flash-steam units, providing an alternative to the use of a second or third flash stage for increasing productivity. Lower-temperature Kalina cycles may be added below binary or flash cycles. Topping cycles, such as a rotary separator turbine within a flash tank, also may be employed. Again, the improvement in hot-water rate must more than offset the capital cost of the additional cycles.



Present binary cycles can transform heat into power at hydrothermal fluid temperatures down to 105°C (225°F). *Low-enthalpy reverse air conditioning cycles* utilizing mass-produced commercial chiller (or industrial air conditioner) components may allow electricity production from lower-temperature, shallow hot spring systems. (See box, p. 23) Rather than consuming electricity to remove heat, the system essentially runs backwards—the heat exchanger absorbs heat from the hydrothermal fluid, vaporizing a working fluid and turning a centrifugal compressor into a radial inflow turbine that produces electricity.

This technology has been successfully demonstrated in Alaska since 2006. While potentially best suited for distributed cogeneration applications, these systems promise to decrease the minimum temperature necessary for commercially viable geothermal power generation to around 80°C (175°F), which is at the higher end of resources currently designated as non-electrical grade.

EGS technology extracts heat from HDR resources in a form suitable for electricity production. Either flash-steam or binary-cycle power plants may be used with EGS, depending on the temperature of geothermal fluid extracted from the artificial reservoir created by hydraulic stimulation. To minimize drilling costs, most early applications of EGS systems are expected to produce hydrothermal fluids suitable for power generation through binary cycles. (Tester & Herzog, 1990) Accordingly, once EGS technology is commercialized, significant but incremental advances expected in binary-cycle technology will have impact across a much broader resource base.

Down-hole, closed-loop heat exchange systems represent a promising alternative to EGS for generating electricity from HDR resources via a binary cycle. A working fluid circulates from the surface, through a heat exchanger installed in hot rock at the bottom of a well, and back to the surface, where it delivers heat to a second working fluid that drives the turbine. This down-hole, closed-loop approach is simpler and more controllable than using injection and production wells and an artificial reservoir to extract heat, bring it to the surface in the form of a hydrothermal fluid, and transform it into electricity. It could significantly lower development costs and risks for HDR resources, as well as avoid or reduce O&M challenges relating to reservoir management, air emissions, and materials degradation. Initial applications could come through installations in depleted or abandoned oil and gas wells, paving the way for green-field HDR projects. EPRI is exploring one particularly promising down-hole, closed-loop innovation. (See box, p. 11)

Hybrid power plant concepts integrate geothermal technologies with fossil and renewable generation options. Hydrothermal fluid may be used for preheating water or organic working fluids in coal, natural gas, and biomass steam-electric plants, helping reduce fuel consumption and emissions. Alternatively, concentrating solar thermal fields, gas turbines, and other combustors may supply supplemental heat to a flash-steam or binary-cycle geothermal plant, providing operating flexibility, reducing the risk of premature reservoir depletion, and augmenting capacity during peak periods. Co-located geothermal and fossil generation plants also may share well systems to support CO₂ capture and storage. Concepts like these, which leverage the attributes of individual generation options, may represent a bridge to widespread exploitation of HDR resources.

RDD&D Opportunities

Direct-steam plants are commercially mature but resource-constrained, while continuing incremental advances in flash-steam technology are expected. Substantial cost-performance gains are anticipated for binary and reverse air conditioning cycles to reduce costs, increase productivity, and unlock access to abundant and broadly available HDR resources. Specific RDD&D topics are listed below:

- Heat transfer fluids, binary cycles, heat exchangers, reverse refrigeration cycles, and direct contact condensers to harness moderate- and lower-temperature resources and substantially improve energy conversion efficiency
- Innovative energy capture and power production technologies and cycles optimized for HDR resources
- Advanced materials and supercritical plant designs for enabling order-of-magnitude gains in power production from high-temperature, high-pressure resources
- Hybrid geothermal-oil and geothermal-gas production wells and retrofit geothermal applications at abandoned wells to reduce development costs
- Hybrid geothermal-fossil, -biomass, and -solar energy plants to improve efficiency and reduce costs
- Hybrid geothermal-fossil generation-CO₂ capture plants for co-located energy production and carbon storage
- Analytical tools for modeling and comparing advanced geothermal concepts, applications, components, and systems to inform R&D investment and technology development.

Operations, Maintenance & Environmental Control

Geothermal power plants pose unique challenges because of their underground infrastructure. Reservoir management is critical to maintain adequate flow rates and sustain production, while harsh down-hole conditions and damaging hydrothermal fluid constituents take their toll on well, pump, piping, and power plant components. Environmental impacts extend beyond traditional concerns to include subsidence and seismicity.

Geothermal power plants generally operate as baseload units because, in the absence of a fuel cost, the fixed costs of operation far exceed variable costs. Due to fuel supply limitations, some direct-steam plants at the Geysers are cycled to maximize the time value of output. Reservoir lifetimes generally are predicted to be from 40 to 100 years, but fields often start declining much sooner than expected, leading to losses in productivity and revenues. Based on lessons learned at the Geysers, most plants inject spent hydrothermal fluids and brines back underground, adopt site-specific resource management plans, and monitor withdrawal rates and down-hole chemical and physical parameters for indicators of depletion. Wastewater injection is practiced at the Geysers in an effort to replenish the reservoir, but hundreds of megawatts of capacity remain idled. At fields in less arid climates, surface water may be used.

EGS technology also holds promise for increasing the productivity and extending the lifetime of existing hydrothermal production zones. It could enhance or restore the permeability of rock formations, as well as introduce hydrothermal fluids to areas with insufficient natural permeability. Related reservoir stimulation techniques, known as secondary enhancement of sedimentary aquifer play (SESAP), may provide means to increase permeability and production rates in HSA formations.

Relative to fossil generation, geothermal power plants are much less complex, operate at relatively low pressure and temperature, and have fewer auxiliaries. Capacity factors of 85% and higher are achieved in many instances, but direct-steam and flash-steam plants incur a significant cost penalty due to the severe operating environment created by saturated steam containing relatively high levels of non-condensable gases and dissolved and suspended solids. Not only can this reduce availability, but it also leads to maintenance costs about twice those of fossil power plants, due principally to corrosion of well casings, surface pipelines, and other components; deposition of mineral phases and corrosion products inside

production and injection wells, piping and vessels, and turbines (Figure 13); and erosion of surface piping, valves, and turbine blades. Temperature controls, chemical additions, and other interventions have alleviated but not eliminated some problems.

Extending the proactive failure management strategies and reliability-centered and predictive maintenance programs developed by EPRI for fossil, nuclear, and hydro plants is likely to reduce O&M costs at direct-steam and flash-steam plants. (See box, p. 19) Generally, binary systems are less susceptible to maintenance problems because lower-temperature, lower-energy hydrothermal fluids are characterized by lower impurity levels.



Figure 13 – Scaling and corrosion caused by impurities in hydrothermal fluids are major contributors to high O&M costs for geothermal power plants. (Credit: NREL)

The land-use requirements of geothermal power plants compare favorably to those of most central-station generation options. A plant itself only occupies 1 or 2 acres, while individual well fields may draw hydrothermal fluids under 100 to 200 acres of land that, aside from surface piping, may be used for agriculture, conservation, forestry, or other purposes as shown in Figure 14. However, geothermal plants require larger cooling systems than similarly sized fossil and biomass units because they are less thermally efficient. Conventional wet cooling towers utilize significant amounts of water, while current air cooling systems impose large parasitic losses. Geothermal plants also may require water for injection to sustain reservoir productivity or create artificial reservoirs. For communities facing wastewater disposal challenges, the Geysers field's demand for water has proven convenient, but other geothermal plants may compete for scarce resources with other uses.



Figure 14 – Geothermal power generation is compatible with other land uses, as demonstrated by steam pipelines for a plant in Ohaaki, New Zealand, that run through land used for grazing and agriforestry. (Credit: Evan Hughes for EPRI)

Aside from visible steam plumes, direct- and flash-steam plants produce minimal air emissions and liquid and solid wastes. No conventional pollutants and little if any CO₂ are released. When present in hydrothermal fluids in significant quantities, hydrogen sulfide is captured to prevent odors and the release of acid rain precursors, and it is converted to elemental sulfur for use as a chemical feedstock. Similarly, mercury controls are used at the few plants running on hydrothermal fluids that contain this contaminant. Settling ponds, water and solid waste containment and disposal systems, and other control measures may be employed on a site-specific basis. Again, binary systems pose even fewer environmental challenges because they operate on hydrothermal fluids with reduced impurity levels.

Land on top of, and immediately adjacent to, active geothermal reservoirs may undergo sinking due to the extraction of hydrothermal fluid, as has occurred due to water withdrawal for municipal, agricultural, and industrial uses. Subsidence is typically inconsequential and difficult to detect, but damage to roads and buildings induced by geothermal power production is a remote possibility.

Seismic issues represent a potentially more significant concern. In areas that are geologically active, the removal and injection of hydrothermal fluids and the associated thermal and chemical changes may induce minor earthquakes difficult to differentiate from naturally occurring events. However, most geothermal plants are not close to the major faults where large, damaging events are centered, and subsurface activities are in any case typically limited to depths less than 5 km; this is shallower than most seismic activity, which tends to occur at depths of between 5 and 10 km.

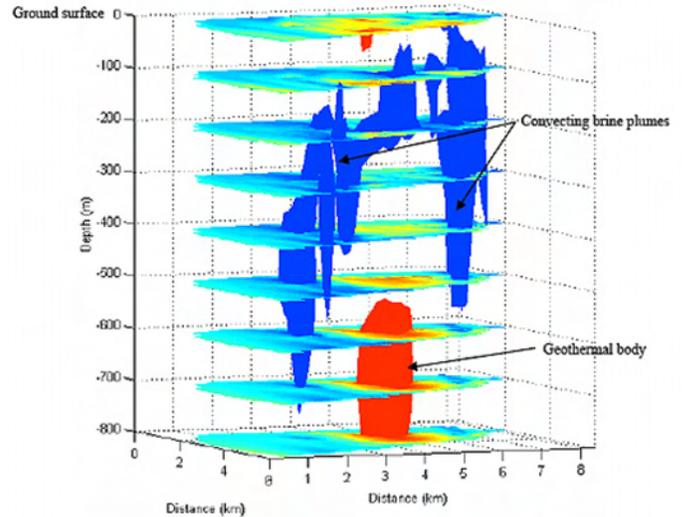


Figure 15 – Advanced analytical tools are required to monitor and manage geothermal reservoirs to maximize power plant productivity and avoid depletion. (Credit: Earth Resources Laboratory, MIT)

Concerns about induced seismicity persist due to an event in 2006 at an EGS demonstration project in Basel, Switzerland. A magnitude 3.4 earthquake occurred below the city during hydraulic stimulation in an injection well slightly deeper than 5 km located on a major fault line. Although the project was halted, geothermal development has not as yet been conclusively identified as the trigger of this earthquake. Even if it is identified, decades of industry experience support the conclusion that seismic risks, while not zero, may be minimized through prudent project siting, development, and operation. In the United States, all federally funded EGS demonstration projects are required to install seismicity monitoring networks as a means of building knowledge and reducing risks.

RDD&D Opportunities

Advanced technologies for managing and sustaining hydrothermal resources (Figure 15), reducing maintenance costs, and extending component lifetimes are needed to maximize productivity from existing geothermal plants and improve the economics of future installations. New systems and knowledge are required to reduce environmental impacts and address seismicity concerns. Specific RDD&D topics are listed below:

- Enhanced reservoir engineering methods, fine-resolution monitoring techniques, predictive tools, operating strategies, and management approaches to maximize energy production consistent with sustainable resource development

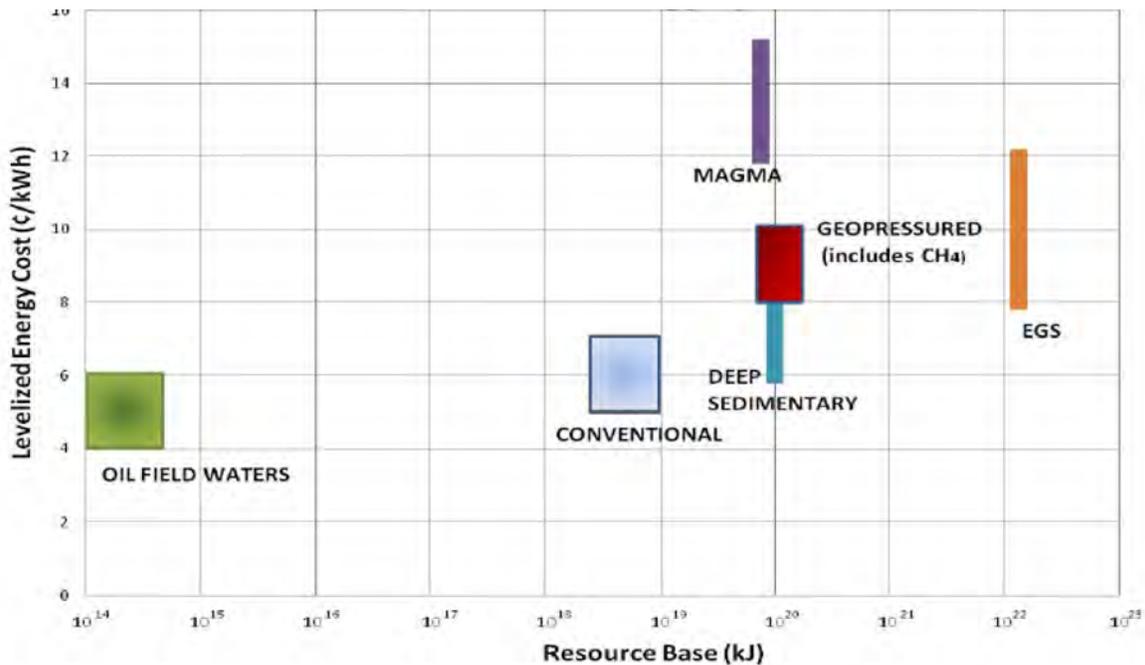


Figure 16 – Technology choice, cost, and potential are strongly dependent on the type of geothermal resource. (Credit: GEA Conference, Vancouver 2009)

- Hydrothermal reservoir enhancement, replenishment, rejuvenation, and life extension methods, including EGS and SESAP techniques
- New materials, linings, coatings, components, and control methods for reliable long-term performance in corrosive and aggressive brines and harsh underground environments
- Mechanistic studies, preventive and reliability-centered maintenance programs, and knowledge-based solutions and tools for reducing O&M costs and failure rates and managing component lifetimes
- Advanced NDE techniques—such as end-guided wave technology for well pipes—and analytical tools to support predictive modeling and proactive management of common degradation processes and failure modes for in-service components without adversely impacting unit availability
- Dry cooling towers and advanced cooling system designs for reducing water use and parasitic energy losses
- Comprehensive databases and predictive models of land subsidence and induced seismicity effects associated with geothermal plant development and operations.

Deployment & Integration

Power producers considering investment in new geothermal capacity are faced with interconnected resource, technology, policy, and siting challenges. The costs and risks of geothermal exploration and project development must be weighed against those of other generation technologies within complex and uncertain business, policy, and market frameworks. Comprehensive assessments must account for corporate positions on supply diversity, risk tolerance, regulatory compliance, sustainability, and other key issues. Existing and potential RPS requirements, climate policies, and government incentives must be considered.

The greatest risks for any geothermal project lie in accurately identifying, characterizing, and confirming the resource, difficult and costly front-end tasks that represent significant barriers. Early-stage project risks may be reduced through better cataloging of known resources and improved modeling techniques for site-specific resource analysis. Prospecting and exploration also are complicated by permitting and lease constraints. For example, on federal lands where the majority of U.S. geothermal power plants currently exist, developers must obtain lease rights to at least 2,000 acres before resource exploration can occur. EGS projects targeting HDR resources, where significant reservoir engineering and water



consumption are necessary prior to construction, pose even greater risks and regulatory challenges.

Geothermal power systems combine fuel supply and power conversion systems into one system. As a result, resource characteristics determine technology choice and project economics (Figure 16), and pre-development and capital costs are even more site-specific than for other power generation options. In general, the higher the temperature, the lower the cost of the electricity because higher-temperature fluids have more energy per unit mass, but depth, pressure, and steam, impurity, and salt content also are important. Mature hydrothermal technologies have a long track record, binary-cycle systems are proven but less well-established, and EGS and other early-stage technologies require large-scale demonstration projects to foster significant commercial investment.

Typically, geothermal projects are developed in increments of smaller generating capacity rather than with one single, large facility from the start, despite the lower cost of electricity that would be expected from economies of scale. The incremental approach reduces up-front capital investment, allows cash flow to begin sooner, and provides valuable cost-performance data informing the development of additional capacity.

Because geothermal plants are baseload power sources and may be dispatched to meet fluctuating loads, they avoid many of the grid integration issues faced by large-scale solar and wind projects. Capacity additions at existing fields also avoid the need for new transmission infrastructure, which can pose permitting challenges. Access to transmission lines may become an important issue as resources close to existing lines are developed and economics justify the pursuit of resources farther away from the grid. Similarly, access to sufficient water supplies—for cooling, for managing depleted fields, and for reservoir stimulation—is likely to become a limiting factor as high-quality resources tend to be located in the water-constrained areas of the western United States.

With major increases in deployment expected in the near future, supply bottlenecks also may result. Initially, access to drilling rigs may be constrained, followed by supplies of turbines and other components for plant construction. Personnel constraints also may pose a challenge—from geological and geophysical experts needed for exploration phases to the plant operators and technicians for ongoing O&M. A concerted effort to develop a trained workforce is required by the industry in partnership with educational institutions from technical schools to university graduate programs.

Political support and public acceptance are important (Figure 17). Most state RPS requirements include geothermal power among qualified sources for production of renewable energy certificates, while the U.S. American Recovery and Reinvestment Act (ARRA) signed into law in February 2009 provides tax and financing incentives motivating near-deployment. Climate policies and initiatives at the state and regional levels that assign a price to CO₂ emissions increase the competitiveness of geothermal capacity relative to fossil power plants, and a federal climate policy is anticipated.

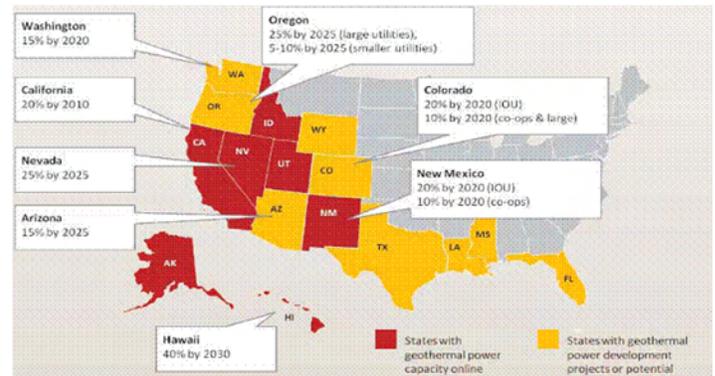


Figure 17 – RPS mandates are in place in many states with operating geothermal capacity, ongoing project development activity, or near-term project potential. (Credit: Islandsbanki, 2009)

Federal funding for geothermal power has dramatically increased, most recently in October 2009 when hundreds of millions of dollars of ARRA funds were awarded to geothermal projects consistent with priorities identified in the draft *National Geothermal Action Plan* developed by DOE's Geothermal Technologies Program. (DOE, September 2009, October 2009) Projects address some of the most critical RDD&D issues, including development of a comprehensive, nationwide resource database; innovative sensing, exploration, and drilling technologies; development of new, low-temperature geothermal fields; advanced technologies for accessing HDR resources, stimulating EGS reservoirs, and converting heat to power; and EGS demonstration projects.

As geothermal exploration and project development activities move into new areas of the country, public education about the benefits of geothermal power—relative to existing and future generation alternatives—is needed to reduce permitting barriers and ensure sustained political support and RDD&D funding. This may require research to address concerns relating to water resource usage, land subsidence, and induced seismicity.

RDD&D Opportunities

Decisions by business executives, regulators, policymakers, and the public will determine the extent to which geothermal power is employed for meeting future energy needs. Successful demonstration of EGS technology is critical to reduce technical risks and unlock the potential of HDR resources. To foster economic, political, and social conditions conducive to investment, the technical attributes and “public good” aspects of geothermal power options must be integrated within the decision-making frameworks employed by diverse stakeholders.

Specific RDD&D topics are listed below:

- Large-scale HDR/EGS demonstration projects in various geologic structures and at different depths to establish risk and potential and support the evaluation and optimization of reservoir creation, monitoring, and management technologies
- Best-practice project siting and design tools to maximize sustainable resource recovery, provide grid support, minimize conflicts, and streamline permitting and approval processes
- Comprehensive analytical frameworks incorporating current data and near-, mid-, and long-term projections of exploration, capital, O&M, and other costs
- Life-cycle cost analysis tools accounting for internalized and externalized factors to support more consistent analysis of investments in geothermal and other generation technologies
- Programmatic and cumulative environmental impact assessments for identifying and mitigating the possible effects of widespread deployment on water resources, seismic activity, and other issues
- Comprehensive and coordinated transmission development plans to support the utilization of geothermal resources in remote areas
- Methods and tools for public education and risk communication to increase awareness of the benefits, costs, and risks of geothermal power relative to other sources.

Implications & Conclusions

With nearly 100 years of commercial success, geothermal power plants have been proven as a reliable, cost-effective, and environmentally friendly source of electricity in the United States (Figure 18) and around the world. Development activity is accelerating globally. Meanwhile, existing RPS requirements and incentives,

recent federal funding commitments, the expectation that a new federal climate policy will assign some type of cost to CO₂ emissions, and other market forces are driving significant growth in U.S. geothermal power production. Projects currently in the development pipeline could more than double total U.S. capacity in just the next few years, and credible, long-term projections suggest that 10% or more of U.S. electric demand could be met by geothermal power by 2050.

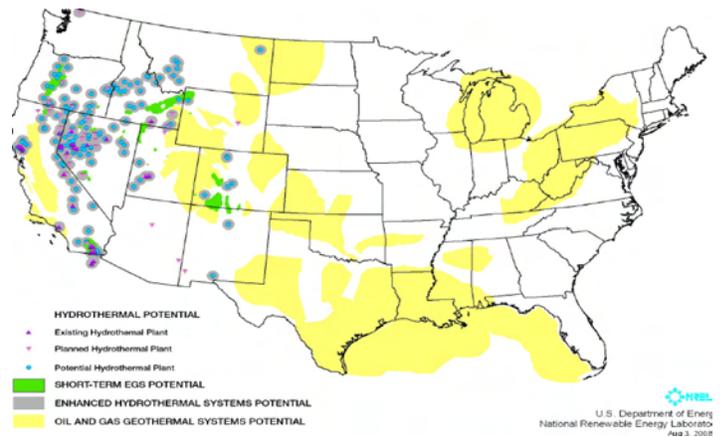


Figure 18 – Locations for planned and potential hydrothermal plants remain concentrated in the western half of the country, but co-locating geothermal power plants with oil and natural gas extraction infrastructure could extend electricity production into the Plains, Great Lakes, Appalachia, and Gulf Coast regions. (Credit: NREL)

To date, resource development has generally been restricted to geologically active areas where reservoirs of hot water and steam are found within permeable rock near the Earth’s surface and economical energy capture is possible using direct-steam or flash-steam technologies. These high-temperature generation options are mature. Recent advances in binary-cycle technologies are opening up access to the more abundant and widely distributed lower-temperature resource base. Significant progress with EGS technology is required to exploit the vast quantities of energy located in HDR formations that are ubiquitous but available deeper underground.

For existing geothermal plants, reservoir management and the corrosive and erosive nature of hydrothermal fluids pose continuing O&M challenges. For new capacity additions, conventional direct-steam and flash-steam plants already are competitive with other generation options in some markets—particularly in states with an RPS—and incremental cost reductions are anticipated. Commercial but still maturing binary technologies are slightly more expensive,



Figure 19 – As a baseload source of non-emitting renewable energy, geothermal power offers the potential for a significant near-term expansion in capacity, as well as for a major contribution to the nation's electricity supply mix in the carbon-constrained future. (Credit: NREL)

but their costs are expected to decrease substantially over the next decade. The most significant barriers to near-term development of all geothermal plants are the high costs and risks of exploration, resource verification, and well-field development.

Immediate RDD&D needs are thus tied to better resource assessment and characterization methods, drilling techniques, energy conversion pathways, and O&M capabilities. Advances in the first area will help locate and target high-permeability zones for down-hole resource verification, and progress in the second will decrease the cost of fluid collection and delivery systems and their marked impacts on project economics. Improved energy conversion cycles will support cost-effective power generation from lower-temperature resources. Enhanced reservoir monitoring and management techniques will help maintain plant productivity and extend project lifetime. New failure analysis, NDE, chemistry control, and maintenance techniques—along with corrosion- and erosion-resistant materials and coatings—will lower costs and increase capacity factors.

Over the longer term, the ability of geothermal power to account for a growing portion of U.S. electric demand depends on successful mining of HDR resources. Well-designed, carefully monitored, large-scale demonstrations of EGS technology are needed at multiple sites having different geologic characteristics, with the common objective of using hydraulic stimulation of large volumes of rock to create artificial reservoirs capable of heating sufficient quantities of hydrothermal fluid and maintaining the rapid flow rates required for economical power generation. Permeability enhancements at sites with natural hydrothermal reservoirs may represent an initial pathway for commercial EGS applications.

Current and planned EPRI projects are addressing several key areas for growing the role of geothermal power in meeting U.S. needs for clean, affordable, reliable, and sustainably produced electricity. (See box, p. 19) EPRI expects to continue collaborative work with utilities, independent power producers, national laboratories, equipment manufacturers, and other stakeholders to assess and address near-, mid-, and long-term RDD&D priorities.

References

- Anuta, J., "Probing Question: What Heats the Earth's Core." *Research Penn State*. March 27, 2006.
- Blackwell, D.D., & Richards, M. "Geothermal Map of North America." Published by American Association of Petroleum Geologists, 2004.
- DOE Geothermal Technologies Program, *An Evaluation of Enhanced Geothermal Systems Technology*. 2008.
- DOE Geothermal Technologies Program, *National Geothermal Action Plan (Draft)*. September 2009.
- DOE, "Department of Energy Awards \$338 Million to Accelerate Domestic Geothermal Energy." October 29, 2009. Accessed 11/15/09 from www1.eere.energy.gov/geothermal/news_detail.html?news_id=15589.
- EIA, "Renewable Energy Consumption and Electricity Preliminary Statistics 2008." July 2009.
- EPRI, *Geothermal Energy Prospects for the Next 50 Years: Special Report*. 1978.
- EPRI, *Next Generation Geothermal Power Plants*. TR-106223, 1996.
- EPRI, *Geothermal Heat Pumps Tech Update*. 1016076. 2008.
- EPRI, *Renewable Energy Technology Guide-RETG: April 2009 Update*. 1019300, 2009a.
- EPRI, *Modeling the U.S. Electricity Generation Mix: Effects of Technology, Policy, and Market Drivers*. 1015805, 2009b.
- EPRI and American Council on Renewable Energy, *Reinventing Renewable Energy: Toward a Technology Strategy for Improving Security, Creating Jobs & Reducing Emissions*. 1019521, 2009.

EPRI Research on Geothermal Power

EPRI's Renewable Generation Program (84) monitors and analyzes developments in the geothermal energy industry and in power generation technologies. In 2008, the Geothermal Interest Group (GIG) was formed to promote information exchange among utilities, power producers, and other industry participants and to identify priorities for future collaborative work. Two new EPRI projects are being launched in 2010.

EPRI's Renewable Energy Technology Guide (RETG), published annually and updated throughout the year, provides comprehensive information on the status and potential of geothermal power and other renewable generation options. For the past several years, cost-performance data and projections from the RETG and EPRI's all-encompassing Technology Assessment Guide have provided the basis for studies using the NESSIE model, which simulates capacity expansion and system operation for the U.S. electric sector based on alternative climate policy scenarios. These studies have quantified the growing contributions of geothermal power as a baseload renewable generation option when CO₂ pricing is in effect.

In 2010, a new Geothermal Energy Project Set (84E) will begin, based on GIG-defined priorities.

Geothermal O&M guidelines—based on actual industry experience and the reliability-centered and predictive maintenance

techniques developed by EPRI for other power generation systems—will be developed to provide an independent engineering resource for optimizing site-specific programs in light of state-of-the-art technologies and best practices for addressing common corrosion, deposition, and erosion problems. Draft guidelines will address inspection, NDE, remediation, and prevention methods to help power producers reduce costs, avoid forced outages, increase service intervals, and improve availability and profitability.

In addition, detailed engineering and economic assessments of power generation from moderate- and low-temperature geothermal resources will be conducted. One set of analyses will address technology status for HDR resources—encompassing both hydraulic stimulation via EGS and power conversion via binary cycles—based on worldwide developments and U.S. projects. Data from pre-stimulation, injection, and stimulation activities will be examined, and plans for long-term assessment of the performance of artificial reservoirs and the associated investment and production costs will be developed.

The second set of analyses will focus on reverse air conditioning cycles to inform design and development of small (up to 15 MWe), remotely operated, low-temperature geothermal plants based on modular, low-cost technologies and project implementation strategies.

EPRI and DOE, *Renewable Energy Technology Characterizations*. Palo Alto, CA: TR-109496, 1997.

Islandsbanki, *United States Geothermal Energy Market Report*, 2009.

Jennejon, D., *U.S. Geothermal Power Production Development Update*. Geothermal Energy Association, Washington, DC: 2009.

Lund, J.W., Freeston, D.H., and Boyd, T.L., "Direct Application of Geothermal Energy: 2005 Worldwide Review," *Geothermics*, 34: 691-727, 2005.

MIT, *The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century*. Cambridge, MA: 2006.

Southwest Research Institute, *Assessment of Geopressured Energy Resources on the Gulf Coast of the US: Report to EPRI*. San Antonio, TX: 1983.

USGS, *Assessment of Geothermal Resources of the U.S. – 1978*. Circular 790, 1978.

Tester, J.W., and Herzog, H.J., "Economic Predictions for Heat Mining: A Review and Analysis of Hot Dry Rock (HDR) Geothermal Energy Technology." MIT, Cambridge, MA: July 1990.

Wisian, K.W., Blackwell, D.D., and Richards, M., "Heat Flow in the Western U. S. and Extensional Geothermal Systems," *Proceedings 24th Workshop on Geothermal Reservoir Engineering*, 24: 219-226, 1999.

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Renewable Generation (Program 84)

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