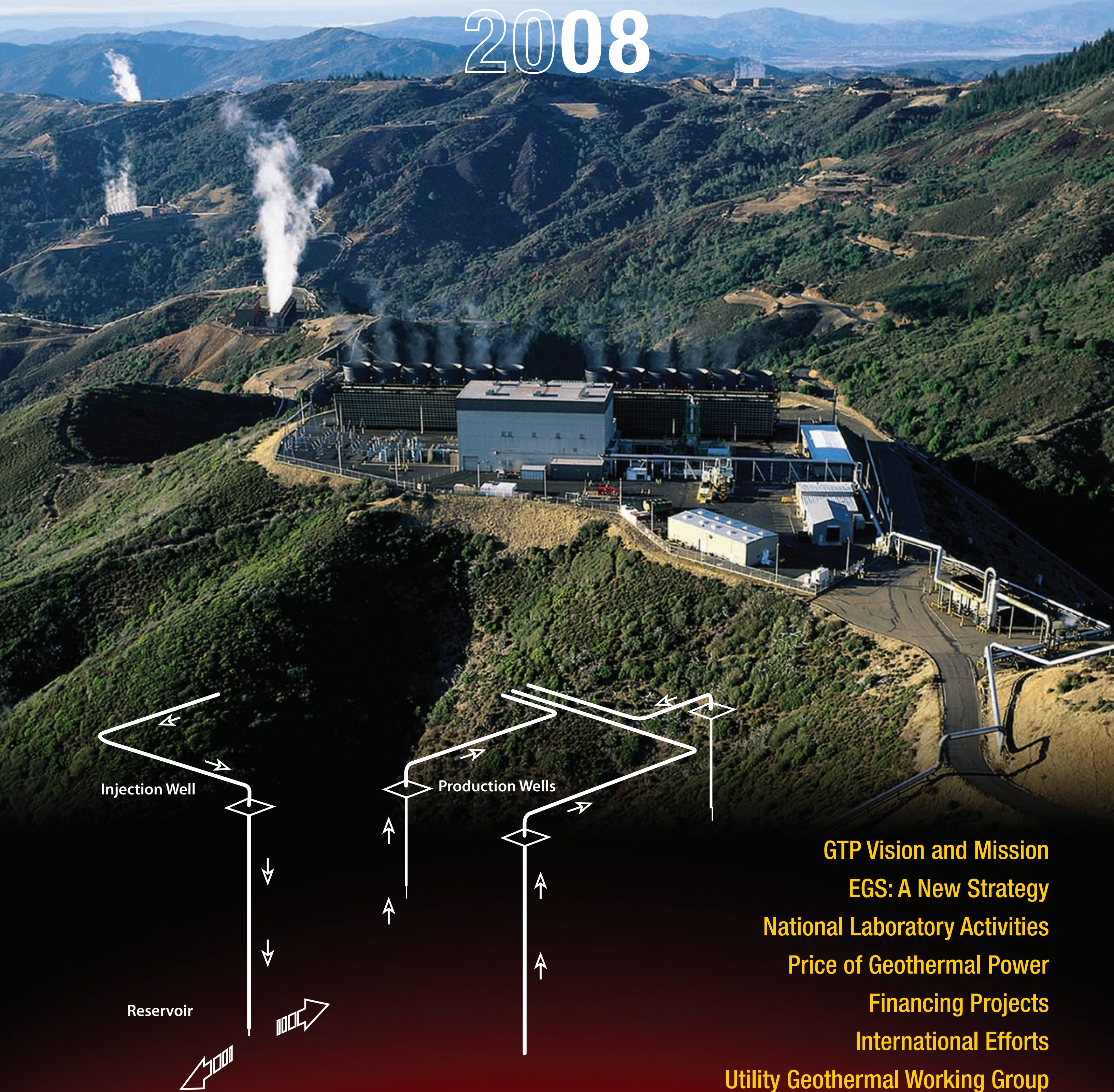
Geothermal Technologies Program

# Geothermal Tomorrow

2008






U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

CHANGE FOR THE BETTER WITH ENERGY STAR

*On the cover: Calpine's 35 megawatt Sonoma Geothermal Power Plant at The Geysers field in Northern California. Courtesy of Calpine Corporation*

# About "Geothermal Tomorrow"

Geothermal power is a renewable, low-carbon option for producing base load electricity across the United States. Improved technologies have the potential to access vast untapped geothermal energy sources, which experts estimate to contain 50,000 times the energy of all oil and gas resources in the world. Increased development of geothermal energy can help address the critical issues of global warming, pollution, and energy independence, as well as give people better control of their local energy resources and a secure, safe, domestic source of energy.

The U.S. geothermal industry leads the world in online capacity of geothermal energy. The potential for growth is substantial, with the international market for geothermal power possibly exceeding $25 billion over the next 10 to 15 years. Currently, U.S. technology and industry are at the leading edge of this international growth.

Many technical challenges, however, must still be addressed and resolved if the United States is to unlock the full potential of geothermal energy. Achieving next-generation geothermal power requires advances in basic science and applied technology, with a strong focus on developing enhanced geothermal systems that can expand the available resource base and strengthen the economic viability of production. The U.S. Department of Energy's Geothermal Technologies Program is committed to supporting the geothermal industry with research and development to help geothermal energy fulfill its potential. This publication brings together contributors from the Program and the geothermal community to highlight the current status and activities around the growth of this global resource.

## Contents

DOE Geothermal Technologies Program Vision and Mission:

# A Letter from the Program Manager

*Dear readers and colleagues:*

I am delighted to have recently taken over the Geothermal Technologies Program (the Program) in the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy. I join the Program at a very exciting time; it has been awarded a $30 million dollar budget from the Senate and $50 million from the House for the 2009 fiscal year after a two year struggle with limited funds. The budget increase demonstrates a tremendous surge of public support for geothermal energy and speaks volumes about the fantastic work the Program has accomplished. With this year's increased funding I am certain that the Program will continue to grow exponentially.

Our team has produced some great resources for the geothermal industry. We are currently developing a Multi-Year Plan to outline specific goals to accelerate commercialization. We are also producing a National Geothermal Database that will catalog temperature, depth, seismicity, hydropressure, and permeability throughout the United States. This will be a great resource that will mitigate risk and facilitate investment. This is going to be an asset for the geothermal community—so feel free to let us know what you feel should be included in the National Geothermal Database.

The Program has refocused on Enhanced Geothermal Systems (EGS)—a technology we see as the future of not just the geothermal industry, but of the renewable energy industry as a whole. Natural geothermal systems depend on three factors to produce energy: heat, water, and permeability. Although heat is present virtually everywhere at depth, water and permeability are less abundant. Previously, geothermal energy sources were limited to sites where all three of these factors were favorable. EGS, however, consist of engineered reservoirs created to produce energy from geothermal resources deficient in economical amounts of water and/or permeability. With EGS, we can transform geothermal from an energy source useful only in a select few areas to a viable source of base load energy for much of the United States.

An EGS is created by first digging a well into hot basement rock, then injecting water into the well at a high pressure so as to promote fracturing deep within the rock, creating a reservoir. A second well is drilled to intersect the resulting reservoir, allowing water to be circulated so this heat can be extracted. Multiple wells may be drilled into the field to increase yield. The resulting energy is clean, renewable, domestic, reliable, and may be used as a source of base load power. DOE sponsored a study completed by experts from the Massachusetts Institute of Technology which found that 100,000 megawatt electrical (MWe) of geothermal energy could be produced in the United States by 2050 with significant investment in EGS technologies.

Despite great potential, geothermal energy faces several barriers to growth. These issues include limited geothermal siting opportunities, inadequate technology, and high startup costs. It is my goal to lead the Program in mitigating these barriers and in developing technology that will allow geothermal resources to be explored in regions previously, and erroneously, deemed unsuitable. It is my hope that geothermal energy will no longer be tethered to a small number of naturally occurring sites, but that we will lead in finding the potential wherever it may exist. Additionally, we are working hard to develop strategic partners in government

Sierra Pacific

*Desert Peak Geothermal Plant, 65 miles northeast of Reno, Nevada.*

and industry to help accelerate commercialization opportunities in EGS technologies that will lower costs and expand potential. Partnered with industry and academia, the Program will continue to promote this great, clean, renewable, domestic resource: geothermal energy.

Currently, the United States has 2,930 MWe of installed geothermal capacity and about 2,900 MWe of new geothermal power plants under development in 74 projects. Geothermal energy generated 14,885 gigawatt-hours (GWh) of electricity in 2007, which accounted for 4% of renewable energy-based electricity consumption in the United States (including large hydropower). These statistics are a great start, but we need to think bigger. We need to move beyond incrementalism and start considering growth of hundreds of megawatt units rather than 5-10 MWe.

Policy is an important tool for getting more geothermal energy into the market. We need technology-neutral, carbon-weighted, long-term incentives that account for externalities and level the playing field for renewables in today's competing power markets. The Program is working with Western Governors to support new energy corridors that will bring clean, renewable energy resources into our energy portfolio. EERE is currently evaluating options to support the development of transmission infrastructure that will further remove geothermal investment barriers.

As high energy costs and environmental concerns force us to reevaluate our energy use, the nation looks for solutions and alternatives. There is no silver bullet that will solve our problems, but an integrated portfolio of energy alternatives will help the nation to successfully navigate the coming years. Geothermal energy, through the work and support of the Program, has the promise to play a critical role in the solution. We have entered a new era in government support for geothermal energy. Our new goals are bigger and braver than ever—but we're more confident than we have been in the past. The geothermal industry has reached a turning point—we're going to help restore geothermal to its rightful place in the portfolio of alternative energy sources to help enhance our security, better our environment, and stimulate our economy.

Sincerely,
Ed Wall

*Program Manager*
*Geothermal Technologies Program*
*U.S. Department of Energy*
*Energy Efficiency and Renewable Energy*

## Enhanced Geothermal Systems:
# A New Strategy for a Renewed Program

A U.S. Department of Energy-sponsored study by a panel of independent experts led by the Massachusetts Institute of Technology (MIT), *The Future of Geothermal Energy* examined the potential of geothermal energy to meet the future energy needs of the United States. The MIT study calculated the tremendous amounts of heat present at depths of 3 to 10 km below the Earth's surface (Figure 1). The panel concluded that geothermal energy could provide 100,000 MW or more in 50 years by using Enhanced Geothermal Systems (EGS).

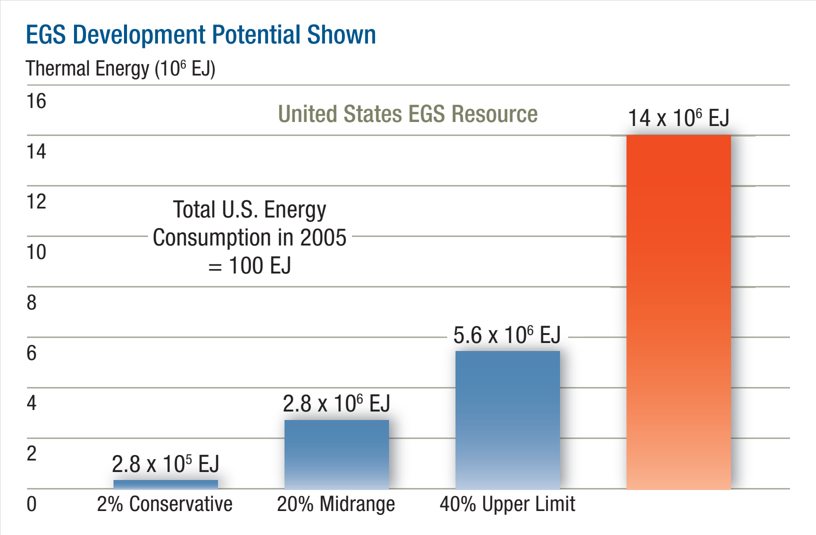



*Figure 1. Potential of EGS development in the United States.*

Heat is naturally present everywhere within the Earth and is inexhaustible for all intents and purposes. Water is not nearly as abundant within the Earth as heat, and most subterranean fluids are derived from surface waters that have seeped into the Earth along porous pathways such as faults in rock. The permeability of rock—a measure of the ease of fluid flow—results from pores, fractures, joints, faults, and other openings that allow fluids to move. High permeability implies that fluids can flow rapidly through the rock. Permeability and, subsequently the amount of fluids, tend to decrease with depth as openings in rocks compress from the weight of the earth above.

At shallow depths, typically less than 5 kilometers (km), the presence of heat, water, and porous rock can result in natural hot water reservoirs. These hydrothermal reservoirs have impermeable or low-flow boundaries that impede the movement of fluids. Often, hydrothermal reservoirs have an overlying layer that bounds the reservoir and serves as a thermal insulator, allowing greater heat retention. If hydrothermal reservoirs contain sufficient fluids (water or steam) at high temperatures and pressures, those fluids can be extracted through wells to generate electricity and/or heat.

An alternative to dependence on naturally occurring hydrothermal reservoirs involves engineering hydrothermal reservoirs in hot rocks for commercial use. This alternative is known as EGS.

## The Promise of EGS

To achieve the goals outlined in the MIT study of large scale (100,000 MW) use of cost-competitive geothermal energy, significant advances are needed in site characterization, reservoir creation, well field development and completion, and system operation, as well as improvements in drilling and power conversion technologies. These technology improvements will also support ongoing development and expansion of the hydrothermal industry. To realize the promise of EGS as an economic national resource, researchers will have to create and sustain a reservoir over the economic life of the project.

EGS reservoirs are made by drilling wells into hot rock and fracturing the rock sufficiently to enable a fluid (water) to flow between the wells. The fluid flows along permeable pathways, picking up heat from the rocks, and exiting the reservoir via production wells. At the surface, the fluid passes through power plant turbines where electricity is generated. Upon leaving the power plant, the fluid is returned to the reservoir through injection wells to complete the circulation loop (Figure 2). If the plant uses a closed-loop cycle to generate electricity, none of the fluids vent to the atmosphere. The plant will have no greenhouse gas emissions other than water vapor that may be used for cooling.

## EERE Strategy

In order to achieve the maximum potential of EGS, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy plans to advance and build from current geothermal technology to develop the sophisticated technologies required, while at the same time generating benefits in the near-, mid-, and long-term. This will require a systematic, sustained research and development effort by the federal government and a strong partnership with industry and academia to ensure full development.

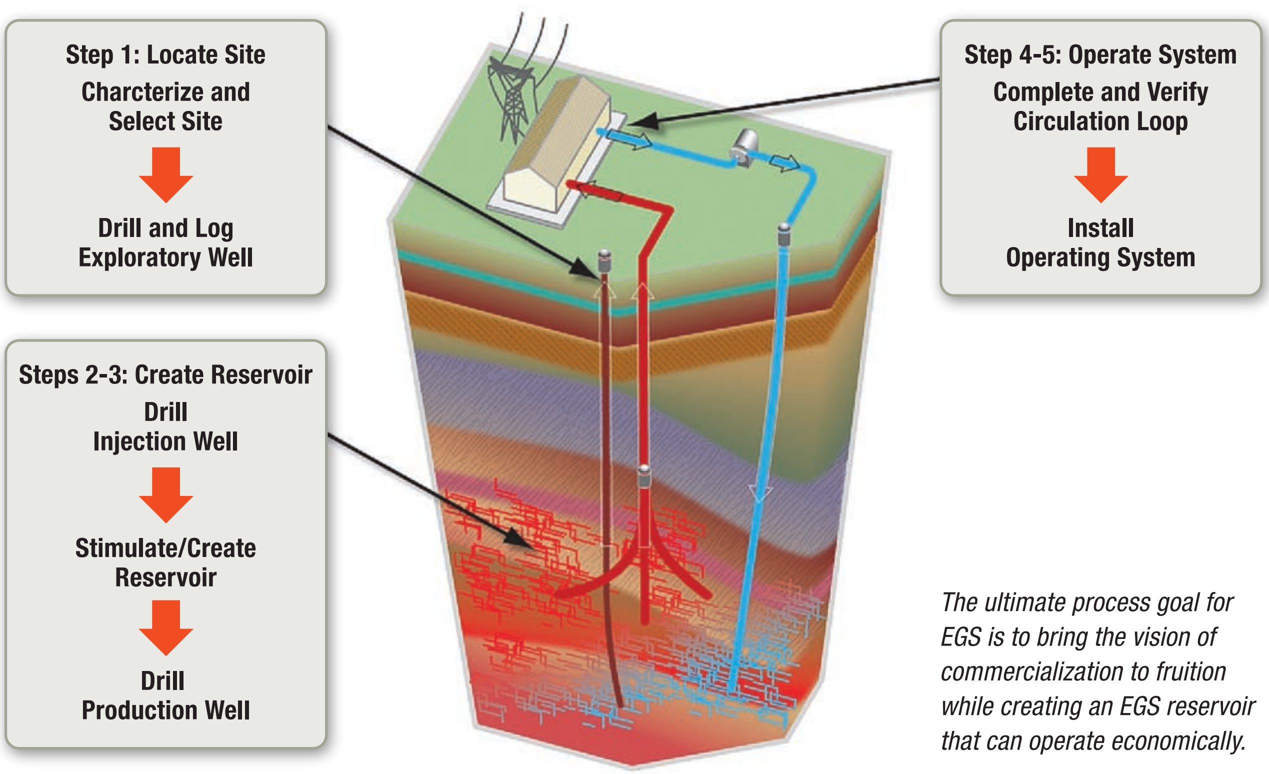
A broad knowledge base about reservoir creation and operation will be essential for the eventual commercialization of EGS on a scale envisioned by the MIT study. This knowledge can be gained only by experience with field demonstrations in a variety of geologic environments reflecting a range of reservoir conditions. Immediate technology improvements are needed in reservoir predictive models, zonal isolation tools, monitoring and logging tools, and submersible pumps. These improvements and others stemming from the evaluation are essential for reaching the long-term potential of EGS.

The MIT study provides a firm basis for bringing the vision of commercialization of EGS technology to fruition. The process goal is to create an EGS reservoir that can operate economically.

## EGS Future

The authors of the MIT study based their technical assumptions on results from available field tests, published reports, and well-established theory. The study's findings are credible, in particular the conclusion that 100,000 MW from EGS technology can be achieved within 50 years. As the study points out, significant constraints exist in creating sufficient connectivity between wells to meet economic requirements for reservoir productivity and lifetime. Overcoming these constraints will require substantial reservoir testing in a number of different geothermal environments as well as research-driven improvements in technology. Investments in excess of over $1 billion over 15 years will most likely be required to encourage sufficient deployment of EGS technology to produce 100,000 MW.

Figure 2. EGS Development Sequence




*The ultimate process goal for EGS is to bring the vision of commercialization to fruition while creating an EGS reservoir that can operate economically.*

# Activities in Geothermal Research and Development at the DOE National Laboratories

The U.S. Department of Energy (DOE), through its Geothermal Technologies Program (GTP), works closely with the geothermal community to advance geothermal technologies and the U.S. geothermal industry. This includes partnering with industry, universities and colleges, research facilities, and, especially, the DOE national laboratories. Three national laboratories are particularly active in support of GTP's endeavors and have the expertise and technology in place to provide leadership where needed in research and development projects to help realize the full potential of geothermal energy. In this article, National Renewable Energy Laboratory, Lawrence Livermore National Laboratory, and Idaho National Laboratory review their activities and future plans in support of GTP.

*Installation of a PPS-coated steam vent at Cove Fort in Utah.*

## Geothermal Technologies Program Activities at the National Renewable Energy Laboratory

The National Renewable Energy Laboratory (NREL) supports DOE in renewing and expanding its efforts to move geothermal energy forward. NREL staff has participated in and continues to lead and participate in activities related to Enhanced Geothermal Systems (EGS) technology validation and integrating outcomes into program plans.

### Evaluation Workshops

NREL was an active participant and leader in a series of workshops in 2007 that evaluated the assumptions, analytical methods, and conclusions presented in the 2006 report by the Massachusetts Institute of Technology, *The Future of Geothermal Energy*. This report provides a strong argument that with appropriate and reasonable investment from the public and private sectors, geothermal energy could make a substantial contribution to the nation's energy portfolio.

The workshops included discussion on reservoir creation, reservoir management and operations, and well field construction, and led to the publication of the DOE report, *An Evaluation of Enhanced Geothermal Systems Technology*. These efforts set the stage for the renewal of the geothermal program with an emphasis on EGS development.

With this renewal, NREL has initiated 13 projects to help GTP reach its objectives. These projects support systems demonstration projects and meet program needs in systems integration, energy analysis, strategic planning, field program support, and communications and outreach.

## Systems Demonstration Support

For GTP's field demonstrations of EGS, NREL is contributing expertise in developing site selection criteria and solicitation strategies, as well as participating in the industry proposal merit reviews. NREL provides oversight and technical monitoring of field projects and management of field-related subcontracts.

## Strategic Planning and Analysis

NREL supports GTP in developing strategic plans, including the *Geothermal Technologies Program Multi-Year RD&D Plan for Enhanced Geothermal Systems*, which will guide program activities for 2010-2020. This plan addresses the near-term priorities for cost-shared research with industry, as well as field projects for achieving EGS technology readiness for commercialization. NREL has participated in several internal program meetings to develop the plan and has the lead in developing the key technical section. This plan will guide GTP in fulfilling aggressive goals for making geothermal a significant contributor to the energy portfolio of the United States. NREL is also assisting the program in developing a GTP Management and Operations Plan to achieve EGS technology readiness for commercialization.

## National Geothermal Action Plan

NREL has responsibility for assisting GTP with the development of a comprehensive National Geothermal Action Plan (NGAP) for conventional hydrothermal production and EGS. NREL has developed and placed a subcontract with Deloitte to complete this action plan. NGAP will serve to inform the Inter-Governmental Panel on Climate Change and the public of the qualities, capabilities, progress, and goals of geothermal energy and GTP. NGAP will analyze the current state of geothermal energy as a viable energy source and its current and potential contribution to the national grid, and discuss the short-, mid-, and long-term potential development scenarios of geothermal energy including an evaluation of transmission infrastructure requirements.

The plan will also describe geothermal energy in relation to DOE's strategic goals— energy security, scientific discovery and innovation, and environmental responsibility—and examine the environmental benefits and impacts of geothermal energy as it relates to climate change, water, land use, and air quality. In addition, the plan will develop visionary goals and strategies that mitigate the risk for geothermal energy in aiding national energy diversity and reliability.

## Program Systems Integration Support

NREL has initiated its systems integration role in GTP's activities to help it reach the goal of developing EGS. NREL is developing an integrated baseline that will address technical scope, and will define, initiate, and manage systems-related subcontracts and integrate with in-house efforts.

## Analysis, Evaluation, and Modeling

Of the 13 projects NREL is initiating in support of GTP, seven are focused on analysis, evaluation, and modeling activities that address critical program needs for assessment of geothermal and EGS markets:

- Macro modeling of the potential geothermal energy contribution
- Techno-economic modeling of EGS
- Analyses of program risk
- Integrated energy modeling for budget support
- Analysis of geothermal $CO_2$ impact
- Assessment of power conversion technologies
- Assessment of data requirements for accelerating EGS commercialization.

NREL analysis is working to improve the representation of geothermal to address renewable energy technologies in evolving new energy market models. There are many energy market models that have been used to assess the potential of geothermal power and other technologies in the United States, but two shortcomings remain that are especially acute for geothermal power: 1) Regional aggregation doesn't allow for the consideration of more local transmission constraints; and 2) uncertainties in future fuel prices, technology improvements, and policies will continue to drive the energy sector.

A model now exists at NREL for capacity expansion in the U.S. electric sector—the Regional Energy Deployment System—with more than 350 regions in the United States that explicitly consider transmission issues. A second model—the Stochastic Energy Deployment System—is


*Keith Gawlick, of the National Renewable Energy Laboratory, field testing coatings at the Mammoth Pacific Geothermal Power Plant in the Sierra Nevada Mountains.*

## Geothermal $CO_2$ Impact Analysis

This NREL project is assessing the $CO_2$ impact of deploying geothermal energy, specifically for EGS. The project objective is to assess the projected $CO_2$ impact of geothermal generation in general, and the component estimated to be the result of planned program activities, based on published studies and modeling of the geothermal representation used for the fiscal year 2010 benefits estimation process. $CO_2$ emission reduction is a key element of DOE's strategic environmental goal and an increasingly important metric for assessing the value of program activities in the budget formulation process.

under development and led by NREL with a team from six national labs that explicitly addresses future uncertainties in technology performance, cost, fuel prices, and policies.

Presently, a rudimentary representation using supply curves for hydrothermal power is included in each of these models. This task will improve that representation and conduct analysis of geothermal power market potential within the models.

## Geothermal Market, Policy, and Technology Analysis

NREL developed the initial concept for gaining a firm understanding of the technical, economic, and market potential of all geothermal technologies (hydrothermal, EGS, heat pumps). Such an understanding is required to inform decision-makers in the identification of the most efficient use of resources. Both historical and projected metrics will be gathered to determine technology improvements and commercialization opportunities. The project will conduct analyses of market, policy, and technology status by evaluating of the impacts of research and testing options. Additionally, results of the analyses will provide information to researchers, policy-makers, and investors on areas to target for greater cost-reduction and market transformation.

## Power Conversion Technology Evaluation

NREL is also supporting GTP's EGS field experiment program by evaluating the current state of power conversion technology and assessing R&D requirements in this area. NREL is performing a detailed assessment of the needs for EGS power conversion and evaluating the ability of current technologies to meet those needs with the primary purpose of identifying gaps in technology that must be addressed for long-term EGS viability.

## Growth to Assist and Represent GTP

To meet the needs of the renewed geothermal program, NREL has transitioned to a new geothermal technology manager with a strong geoscience and energy background who is adding positions to the laboratory's capabilities in support of GTP. NREL has added two energy analysts and a systems integration engineer. Staff have provided support to GTP by making or participating in presentations to key stakeholders in the geothermal community including Al Gore and the Alliance for Climate Protection, the Google Foundation, the X-Prize Foundation, and the leaders of the Hawaii Energy Initiative.

Geothermal Technologies Program Activities at

# Lawrence Livermore National Laboratory

Lawrence Livermore National Laboratory (LLNL) has a long history of R&D work in support of geothermal power. Key areas of research include advances in scaling and brine chemistry, economic and resource assessment, direct use, exploration, geophysics, and geochemistry. For example, a high-temperature, multi-spacing, multi-frequency downhole electromagnetic (EM) induction logging tool (GeoBILT) was developed jointly by LLNL and EMI to enable the detection and orientation of fractures and conductive zones within a reservoir. LLNL researchers also conducted studies on the use of geothermal energy for desalination to stave off increased salinity in the Salton Sea, an important aquatic ecosystem in California.

Since 1995, funding for LLNL's geothermal research has decreased, but the program continues to make important contributions to sustain the nation's energy future. Current efforts, as well as future research, focus on developing Enhanced Geothermal Systems (EGS) and improving technologies for exploration, monitoring, characterization, and geochemistry.

## Techniques to Assess Geothermal Resources

Most known geothermal resources in the Basin and Range geological province of the western United States are associated with active fault systems. Studies show that hydrothermal fluids in active fault systems circulate from deep underground through high permeability fractures to relatively shallow levels where they can be accessed for production. For example, at the Dixie Valley field, hydraulically conductive fractures within the Stillwater fault zone are oriented so that fractures are critically stressed for normal shear failure under the regional tectonic stress field.[1] In general, the expectation is that geothermal resources occur in areas where seismic strain across faults is extremely high and where faults are favorably oriented with respect to the regional strain tensor. In the Basin and Range, these faults would strike perpendicular to the direction of maximum extension. Geothermal resources may also occur in areas where fault-normal extension associated with shear strain is the greatest.[2]


*GeoBILT EM Induction logging tool being deployed at Dixie Valley.*

Until recently, mapping ground displacements of less than 1 centimeter (cm) was extremely difficult. LLNL is applying a new technique called repeat-pass Interferometric Synthetic Aperture Radar (InSAR), and refining it for geothermal applications. InSAR uses radar imaging of Earth's surface to identify potential geothermal resources. Satellite-borne synthetic aperture radar images the Earth's surface during two orbits, recording data at the surface position and using the same viewing geometry during both orbits. The maximum separation (spatial baseline) between the

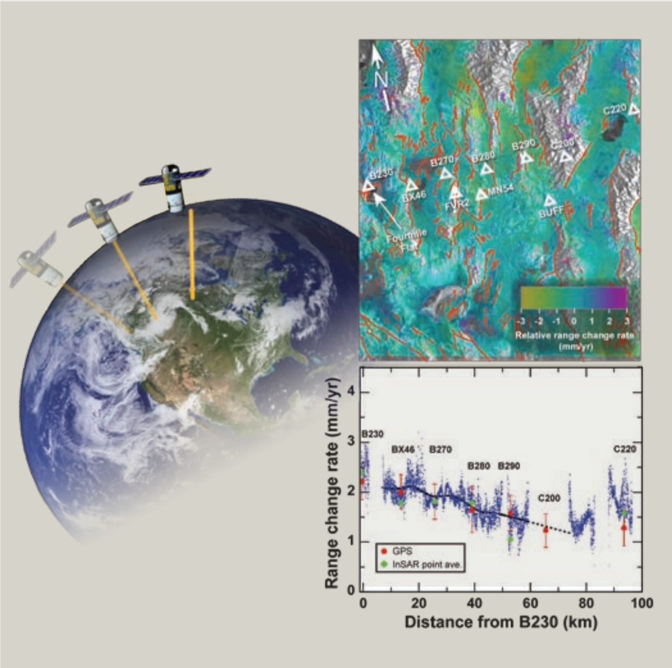



*Figure 1. InSAR is used to investigate the role strain concentration plays in localizing geothermal resources in the western Basin and Range.*

two orbital positions is generally 1 kilometer (km) or less, depending on the radar frequency. The difference between the phases of the two radar returns is proportional to any change in the range from the ground to the radar caused by a subsurface displacement that occurs between orbits. The topographic contribution is subtracted using a digital elevation model or additional orbits. The displacement contributions are then mapped over the entire radar scene to produce a phase difference map, or interferogram, that can be converted to a range-change map (Figure 1). Under favorable conditions, InSAR can measure displacements as small as a few millimeters. Displacement maps of geothermal regions using InSAR detect changes in elevation that can be used to manage geothermal systems and locate regions of high strain that are favorable for drilling.

## The Stochastic Engine

Geophysical data are difficult to acquire and, once obtained, are often hard to interpret. Computer models can be made more meaningful when they take the uncertainty in those measurements into account and combine multiple measurements into one analysis. Stochastic models often require large numbers of calculations to evaluate many different descriptions of a problem. These evaluations allow us to understand how a small amount of data can result in a range of interpretations. Using high-performance supercomputers such as Thunder and Atlas, LLNL scientists explore groundbreaking ideas in statistical theory to develop quantitative stochastic descriptions that provide a more complete picture of the subsurface.

This technology, called a stochastic engine, links predictive models, advanced statistical methods, and refined search methods. Using this technology, scientists can incorporate a proposed subsurface configuration into a computer model and produce a geophysical simulation. The simulated result is compared to actual data. If the result is consistent with observed data, it becomes part of the final analysis, leading to a clear understanding of which outcomes are very likely, less likely, and where more information could best be used.

The stochastic engine concept uses techniques developed at LLNL and has been applied to a number of research areas, including environmental remediation, $CO_2$ sequestration, and geothermal exploration. The power of the stochastic engine stems from its ability to refine a model by successively narrowing possible configurations of a hypothetical model with the refinement done over progressive layers of data.

For example, suppose an area of interest is known to be composed of seven distinct rock layers that could be either highly fractured or intact. Geophysical measurement such as EM induction, seismic velocities (Vp/Vs), or gravity of that volume, gives an observed value of 11. The stochastic approach calculates which configurations of rock layers, and in which positions, give values close to 11. Each case with a value near 11 is passed to the next stage of analysis. There, the model will continue to restrict possible configurations but base its decisions on other data types such as water, temperature, or pressure. For the simple case cited here, scientists can easily compile and compare all possible configurations. For a large area, however, the possibilities are far too numerous and we rely on computational techniques. The stochastic engine helps narrow the solutions by performing an efficient intelligent search through the collection of possible reservoir configurations, rapidly identifying the configurations that most closely match all the data. The stochastic engine is designed to choose system configurations that are consistent with observed data, allowing much more tightly constrained answers than conventional methods. The goal is to find not a single answer, but many answers. The objective is to adapt the stochastic engine to jointly invert multiple geothermal exploration data sets for better defined drilling targets to improve the success rate in finding economic geothermal resources.

## EGS—Evolution in Controlling Fracture Permeability

EGS is a technology that can be used to improve the energy recovery from a reservoir that has insufficient permeability or fluid. The use of EGS has the potential to increase geothermal electrical generation to more than 100,000 MWe in the United States by 2050.[3] One technical challenge limiting our ability to utilize enhanced geothermal energy recovery is the changing nature of fracture permeability. Mechanisms such as mineral precipitation and dissolution, flow rate, and stress can affect the underground environment, causing subsurface flow to slow over time or stop completely. EGS research performed at LLNL is aimed at understanding the mechanisms and rate of change to predict the evolution of fracture permeability and to evaluate strategies to enhance and maintain permeability in a given location.

To develop EGS, geophysicists and geochemists in LLNL's Geothermal Program combined laboratory experiments and computer modeling to characterize the hydraulic and geochemical properties of various soil samples (Figure 2). As part of this project, they assessed how effective stress, fluid chemistry, and temperature will affect permeability in natural and artificial fractures. They also used current technologies to analyze data from past field experiments, allowing them to separate the physical and chemical processes that affect fracture evolution. Statistical analysis of fracture apertures for two core samples demonstrated that EGS produced fractures with similar aperture distribution and spatial correlation will have different rates of permeability evolution depending on fluid composition and flow rate. Preliminary results from hydraulic modeling indicate that variations in particle residence times will affect local geochemical reaction rates.

LLNL's expertise in geochemical modeling is critical to the success of EGS and other geothermal technologies. These models help researchers interpret experimental data and extrapolate

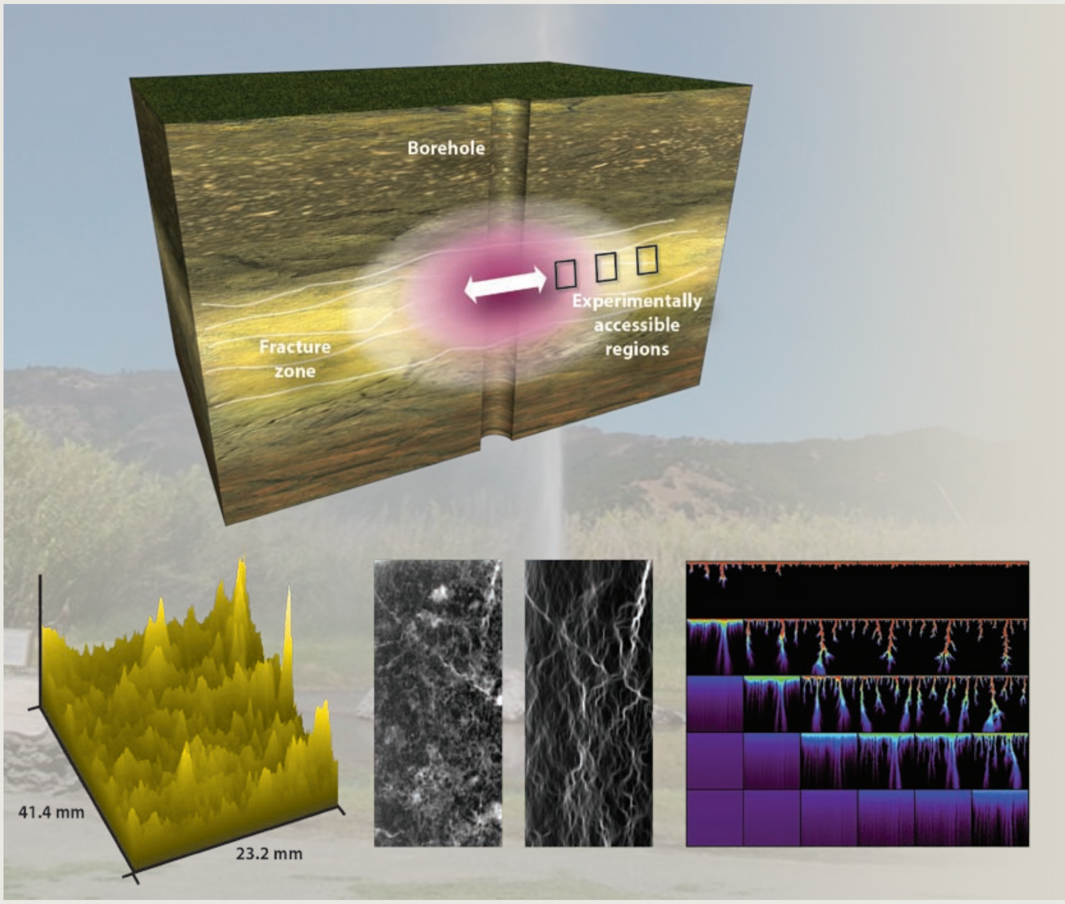



*Figure 2. Top: Schematic showing an enhanced geothermal reservoir. Permeability is increased in the hot region, and fluids are pumped into the reservoir. Bottom: Integrated laboratory-scale experimental/computational investigations (fracture aperture, flow streamlines, model showing development of channeling, left-to-right) lead to better models of mechanisms that alter transmissivity in EGS and provide insights into the scaling of important coupled hydraulic/mechanical/chemical/thermal processes that aid in creating and maintaining fracture permeability.*

the results to a broader range of expected conditions. For example, geochemical modeling can simulate the physical changes occurring in a fractured system during fluid transport and predict how different injection fluids will affect permeability during the average fluid residence period. Numerical models of representative geothermal reservoirs can also be used to optimize production and maximize reservoir lifetime.

A common problem in geothermal recovery is that minerals such as silica and lithium precipitate through flow channels, reducing fracture permeability. Removing the minerals is an expensive, time-consuming process that limits the usefulness of enhanced geothermal recovery. To improve the long-term effectiveness of an EGS reservoir, researchers need to reduce the costs for maintaining fracture permeability. One approach, developed by a team of LLNL geochemists and an industrial partner, is to extract commodity metals from the reservoir for use in other applications. This work recently led to technology licensing for a proprietary process to convert extracted lithium to lithium carbonate, a key component in batteries for electric vehicles and energy storage technology.

## Geothermal Research to Improve Energy Security

Energy security is a pressing challenge for the United States—one that offers tremendous opportunity for scientific innovation. Energy recovery through EGS could help reduce the nation's dependence on imported oil. However, more work is needed before EGS can be successfully deployed on a nation-wide scale. In particular, the lifetime of EGS reservoirs is not long enough to make it a cost-effective approach for geothermal recovery. In addition, researchers need improved tools to locate the optimum sites for geothermal production and new technologies to access the energy trapped deep underground.

LLNL offers a unique combination of computational, theoretical, modeling, and experimental capabilities that directly address many of the nation's energy problems, including geothermal energy. LLNL's Geothermal Recovery Program, together with other national laboratories, industry and industrial partners, is building on its past successes in exploration technologies, geochemical analysis, and EGS processes to develop integrated geophysical approaches for geothermal energy production. Future research activities will focus on enabling technologies for better site selection, reservoir management, and EGS.

Geothermal Technologies Program Activities at

# Idaho National Laboratory

Idaho National Laboratory (INL) currently provides technical support to the U.S. Department of Energy's (DOE) Geothermal Technologies Program (GTP) to develop analytical tools that provide insight into how DOE's geothermal research can impact the cost of generating electrical power. This work is being done in support of the Strategic Planning and Analysis Project area that is managed by Arlene Anderson at DOE Headquarters.

## Geothermal Evaluation Model

In 2005, a spreadsheet model referred to as the Geothermal Electricity Technologies Evaluation Model (GETEM) was developed to provide DOE with insight into how its research could affect the cost of producing geothermal energy. Based upon user input, model estimates are developed for costs associated with exploration, well field development, and power plant construction that are used with GETEM's estimate of operating costs to predict a levelized cost of electricity (LCOE). The model then allows its user to evaluate how technology improvements could impact those projected power generation costs. Results help DOE prioritize research areas and identify where research is needed. The model also aids GTP in conforming to Government Progress and Results Act (GPRA) requirements for annual assessment and reporting of improvements in geothermal electric systems.

GETEM was developed by a team consisting of personnel from DOE, national laboratories, and industry, with the lead role in the development shared by Dan Entingh from Princeton Energy Resources International and Gerry Nix from NREL. A requirement for GETEM's development was that there is a referenced basis of the LCOE projections. Ideally these projections would be based upon actual cost data; unfortunately little actual data is in the public domain and, when available, frequently lacks the detail necessary to adequately characterize both cost and performance. In lieu of actual data, published engineering studies were used to develop the cost and performance correlations used in GETEM. The correlations used to characterize the energy conversion systems were based largely upon the information reported in Electric Power Research Institute's (EPRI)

1995 Next Generation Geothermal Power Plant (NGGPP) study. The correlations for well costs were based on Sandia National Laboratory's analysis of historical geothermal drilling costs. These costs were reported by Mansure at the 2005 Geothermal Resources Council Annual Meeting.

## Recent Development

During Fiscal Year 2008 (FY08), DOE has supported modifications to GETEM to address limitations in the model that have been identified since its original development. These changes to the model are largely being made by personnel at INL.

One of the premises in the original development of GETEM's correlations was that the costs reported in the 1995 EPRI NGGPP study were representative of the conversion system costs in 2004. Given the dramatic increases in steel costs that have since occurred, estimates using GETEM's original correlations are no longer representative of commercial plant costs. The model's LCOE projections were further limited by its use of correlations to predict plant performance and cost as functions of the resource temperature only; they did not account for the functional relationship between the plant cost and performance. Plants that are designed to more efficiently convert geothermal fluid energy into electrical power are more expensive. Generally, more efficient (and expensive) plants are used when a resource has higher well field development costs, while less efficient plants are used with resources that are less expensive to develop.

To address these shortcomings, in 2008, GETEM was modified to improve the conversion system correlations, with a focus on air-cooled binary plants. Based on prior work done at INL, correlations were developed that predict the cost of the plant as a function of the plant performance for a given resource temperature. Prior work at INL also provided an indication of relative contributions of labor and material to the cost of major equipment items. These relative cost contributions provided a means to make adjustments to the predicted equipment costs to account for the changes in costs of fabrication materials and labor with time. This was accomplished by using the Producer Price Index (PPI) and Consumer Price Index (CPI) reported by the U.S. Department of Labor for the different materials and equipment found in the plants. The model can go either forward or backward in time from the reference year costs (2002) using these PPIs to predict equipment and plant capital costs for the desired year.

With the inclusion of the relationship between plant cost and performance, a macro was incorporated into the spreadsheet model that varies the plant performance (and cost) until the LCOE is minimized. The model now trades off the additional cost of a more efficient plant with either the additional power that can be produced from a given well field or the reduced well field size (and cost) for a fixed power output. An example of this trade-off is shown in Figure 3. The lower line in this figure shows the plant contribution to the LCOE as a function of its performance. At lower performance levels, the cost of the well field necessary to support the 15 MW plant output increases due to the cost for added wells and increased geothermal pumping requirements (which also affects the plant cost contribution at lower levels of performance). The results in this figure illustrate that the minimal LCOE does not necessarily occur at conditions that produce the minimal plant contribution to generation costs.

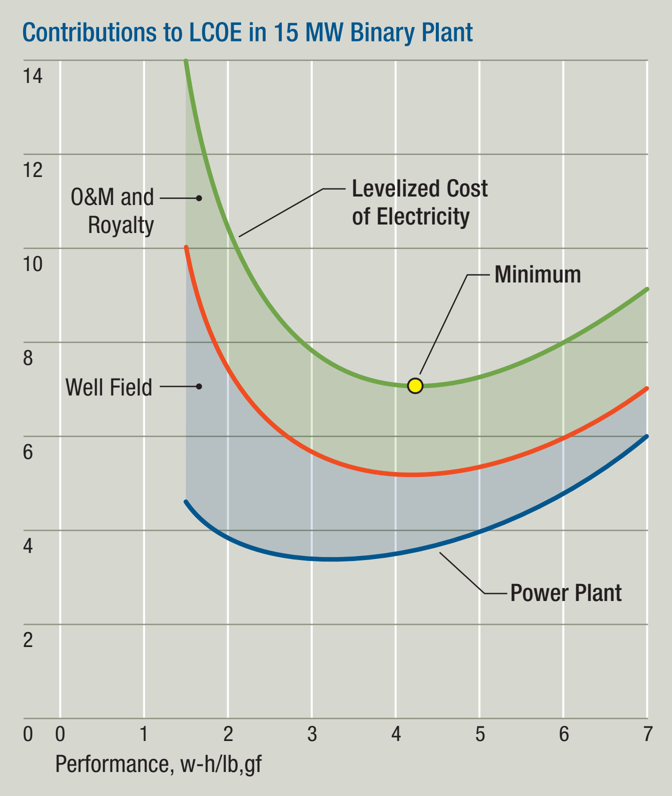



*Figure 3. Effect of plant performance on LCOE for a 15 MW binary plant.*

These changes to GETEM have been completed along with some initial changes that were made to facilitate the evaluation of EGS resources. A beta version of the model has been distributed to solicit comments and feedback on the reasonableness of the estimates produced.

## GETEM's Future

Ongoing efforts are focused on modifying the GETEM model so it better represents the generation of power from EGS resources. Initially, work has focused on developing a model that characterizes the performance of the total system, including a subsurface EGS heat exchange system and production and injection wells. The production well model being incorporated predicts the necessary setting depth for the production pump based on the user's postulated hydraulic performance of the subsurface heat exchange system.

In addition, a simple model is being included for the subsurface heat exchange process. Based on a postulated fracture system, production fluid temperatures are predicted as a function of time and flow. These fluid temperatures are used to estimate the degradation in plant output with time and to establish when it is necessary to replace the EGS reservoir and/or drill additional wells. Options are also being included that allow the user to establish a stimulation cost as a function of the size of the reservoir. This model does not realistically depict a subsurface heat exchange system; however, the trends it predicts are expected to be representative of how different parameters defining the subsurface system will affect produced fluid temperature.

Estimates for pump settings, well flows, production fluid temperatures, and stimulation cost all affect the project cost and the LCOE. Incorporating these parameters into the recent version of the model allows users to vary the different postulated scenarios for the subsurface heat exchange system (including reservoir depth) and assess how these changes affect the power generation costs from EGS resources, as well as hydrothermal resources.

These modifications to the model are currently in progress; it is anticipated that the initial changes (for the binary conversion system) will be completed by the end of FY08. At that time there will be a limited distribution of the revised model for beta testing. Once those changes have been incorporated, efforts will focus on providing a means of updating the well costs.

Although most of the changes described will likely be completed by the end of FY08, as more insight is gained, and the important parameters for EGS development are better defined, further modifications will probably be needed. At some point in 2009 it is expected that the model with the revisions now in progress will be made generally available to the public. Those parties interested in receiving a copy of the model should forward their requests to:

**Arlene Anderson, U.S. Department of Energy**
E-mail: *arlene.anderson@ee.doe.gov*

**Greg Mines, Idaho National Laboratory**
E-mail: *gregory.mines@inl.gov*

**Charles Visser, National Renewable Energy Laboratory**
E-mail: *charles_visser@nrel.gov*

Idaho Operations Office Contract DE AC07 05ID14517

**References**

1. Barton, C.A.; Hickman, S.; Morin, R.; Zoback, M.D.; Finkbeiner, T.; Sass, J.; and Benoit, D. "In-Situ Stress and Fracture Permeability Along the Stillwater Fault Zone, Dixie Valley, Nevada." Presented at the Twenty-Second Workshop on Geothermal Reservoir Engineering. Stanford University. Stanford, California. January 27–29, 1997.
2. Blewitt, G.; Coolbaugh, M.; Holt, W.; Kreemer, C.; Davis, J.; and Bennett, R. "Targeting of Potential Geothermal Resources in the Great Basin from Regional Relationships Between Geodetic Strain and Geological Structures." GRC Transactions; Vol. 26, 2002; pp. 523-526.
3. Tester, J.W. et al. "The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century." Presented in an assessment by an MIT-led interdisciplinary panel. MIT. Cambridge, Massachusetts. 2006.

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# The Price of Geothermal Power

Geothermal power plant developers are seeking ways to supply attractively priced renewable energy to utilities. The price that a geothermal power plant developer can offer to a utility in a power purchase agreement (PPA) largely depends on a number of factors, including the power conversion technology used to generate the electricity, power plant size, and four additional factors:

1. Development costs
2. Financing charges
3. Operating and maintenance (O&M) costs
4. Resource credits.

**Development costs**—costs to get the plant sited, constructed, and put online—are significantly higher than those of fossil-fueled power plants. The development cost to build a natural gas power plant is about one third of the total costs. Development costs of a geothermal facility, in contrast, represent two thirds or more of total costs.

**Financing charges**—Customer owned utilities such as municipalities and electric cooperatives have interest rates of about 5%-6%. Independent power producers may have interest rates of 15% and higher.

**O&M costs**—cover charges for running the power plant and servicing and replacing equipment.

**Resource credits**—provide incentives for renewable energy projects.

## Development Costs

Development costs include all expenditures associated with exploration, drilling, permitting, construction, and ancillary investments such as transmission costs. The development costs for a typical 20 MW power plant are shown in Table 1. These costs are rules of thumb. Actual costs can vary based on factors such as time delays, geology, environmental restrictions, project size, and transmission access.

The cost of time delays is significant, sometimes adding $10 to $20 or more per MWh or more to the cost of power. The time delays typically occur in the first two stages of development where the risks are higher and the cost of capital is greater than the last two stages.

**Table 1. Typical Geothermal Power Plant Development Costs**

| Development Stage | Cost ($/kW) |
|---|---|
| Exploration and resource assessment | $ 400 |
| Well field drilling and development | $ 1,000 |
| Power plant, surface facilities, and transmission | $ 2,000 |
| Other development costs (fees, working capital, and contingency) | $ 600 |
| **Total development cost** | **$ 4,000** |

### Exploration and Resource Assessment

Successful exploration results in the discovery of a geothermal resource capable of providing geothermal fluid to run a power plant and produce electricity. Exploration activities include regional reconnaissance and district exploration, and encompass prospecting, acquisition of rights, and field analysis. The activities are not linear, that is, developers may start acquiring land and mineral rights even before significant prospecting has begun.

Regional reconnaissance screens a large area of hundreds of square miles. The reconnaissance narrows prospecting efforts and involves geologic studies, analysis of available geophysical data, and geochemical surveys to identify more limited areas for detailed exploration.

District exploration uses geophysical surveys and temperature gradient measurements and focuses on smaller areas of 5,000 acres or more to site the first production well. Activities could include gravity surveys, ground magnetic surveys, magnetotelluric surveys, electrical resistivity surveys, and seismic surveys. The final step in district exploration is its most expensive activity—drilling the first deep exploration well.

**Well Field**

Well field drilling and development includes siting and drilling exploration, and production injection wells, testing well flow rates and reservoir engineering. Ideally, exploration wells can be also used as production or injection wells. A successful set of wells results in high fluid temperatures and flow rates. According to the Geothermal Energy Association, exploration wells have an average success rate of 20%–25%, while production and injection wells have an average success rate of 60%–90%. Reservoir engineering determines the best location for injection wells and the flow rates that result in the most stable production.

**Power Plant, Surface Facilities, and Transmission**

These expenditures embrace the cost of the power plant and the geothermal fluid piping system, grid connection, ancillary infrastructure, and pollution abatement systems and environmental compliance work that include engineering, regulatory, documentation, and reporting activities.

The power plant consists of a series of unit operations and equipment such as pumps and motors, turbines, cooling towers, and transformers. The piping system connects the power plant with all production and injection wells. Grid connection includes the substation and transmission lines needed to move the output to the market and, if needed, to the well pumps. Ancillary infrastructure includes office buildings, roads, utilities, and other structures.

Pollution abatement systems and environmental compliance work is a large umbrella—geothermal power projects have to comply with federal, state, and local regulatory requirements, which vary according to location. For example, National Environmental Policy Act requirements apply if the project is on federal land.

State and local agencies, such as air and water boards, may require air and water discharge permits, and each agency may also have reporting requirements. Beginning in the exploration phase, there may be a need to consult with the state historic preservation office or Native American tribes if cultural resources are affected, and the U.S. Fish and Wildlife Service if plant or animal species of concern may be affected. Other federal regulatory agencies involved in the process include the Bureau of Land Management, the U.S. Forest Service, and the Federal Energy Regulatory Commission.

**Other Development Costs**

During geothermal development, legal services are needed to ensure quality in contract, performance, and reporting documents. A contingency reserve is necessary to provide working capital and to cover unexpected costs due to delays and unforeseen requirements. It also covers any margins required by the developer or owner.

*Geothermal well drilling at the Long Valley Exploratory Well near Mammoth Lakes, California.*

## Financing Charges

Financing charges are affected mainly by the amount of upfront capital needed to cover the first two development stages, the time line of these two stages, and the loan terms that allow the developer to repay the upfront costs and finance the second two development stages. The costs of the first two stages, exploration and well drilling and development, generally are not financed by utilities, banks, or other lending institutions. Venture and equity capital or in-house reserves are sources for funding the first two development stages.

For the purpose of this article, an 18% return is assumed for the investment in the first two development stages over a four-year period. Investors correctly interpret geothermal investments as high risk due to historical delays in having a project sited, developed, and online. For example, exploration at the Glass Mountain Known Geothermal Resource Area in Northern California began over 20 years ago. The exploration resulted in discovering a resource that could be commercially viable, but there is still no power plant.

Different types of utilities and lending institutions have varying interest rates and terms. For the purpose of this article a developer can compare two scenarios:

- 10% and 15 years (bank financing)
- 6% and 30 years (utility financing).

Each scenario assumes that the plant life is the same as the loan term and there is no salvage value to the plant afterwards. Zero salvage value may be a harsh assumption. However, in 15 years, the technology may have advanced to where the existing plant may need upgrading to meet new requirements.

If these two scenarios cover the boundaries of reality, the developer would expect to pay $48 to $87 per MWh for the project financing, assuming a 92% plant factor. Plant factor is defined as the rated capacity and the percentage of the year that the power plant is producing electricity.

## O&M Costs

Fuel costs for geothermal power plants are insignificant. Expenses are costs for steam field management and geothermal fluid impacts on equipment and are covered in the power plant design costs and operations and management (O&M) costs.

O&M costs include those charges for employee salary and benefits, equipment replacement reserves, utilities, and administration. Most new geothermal power plants coming online are going to be closed loop, air cooled, binary cycle plants. The O&M costs are assumed to be at a level of about $15 per MWh—lower than the typical plant.

## Resource Credits

Geothermal power and other renewable resources may use rapid depreciation or other incentives such as the Production Tax Credit (PTC) to reduce the final costs to supply output to the market. The PTC currently is $9 per MWh. Other incentives such as pollution credits may apply in the future.

## The Bottom Line

The cost of geothermal power, based on the above discussion and assumptions, is likely to be in the range of $63 to $102 per MWh, excluding any reduction due to resource credits. One caveat, a major impact on geothermal power cost is the local, regional, national, and global competition for commodities such as steel, cement, and construction equipment. Geothermal power is competing against other renewable and non-renewable power development, building construction, road and infrastructure improvements, and all other projects that use the same commodities and services. Until equipment and plant inventories rise to meet the increase in demand for these commodities and services, project developers can expect the costs to rise well above the background inflation level.

Warren Gretz

*Jets shown prior to being attached to a geothermal system at The Geysers Geothermal Power Plant in California.*

David Parsons

# Financing Geothermal Projects

In principle, the financing of geothermal power projects is not much different from the financing of other energy projects. It is about the allocation and management of risks among the various parties, with a few notable exceptions. The need to secure a fuel supply is essential to any energy project; whether the source of fuel is geothermal brine or conventional fuels. A distinct difference between geothermal and other energy technologies, though, is that the developer "pre-pays" the fuel cost in exploration and drilling expenses. Developers new to geothermal are sometimes surprised by the cost, lead time, and complexity involved in permitting and developing geothermal resources. Ensuring that the technology selected is compatible with the available resource is essential to long-term success. Finally, the geothermal industry has attracted a long list of developers and entrepreneurs who usually come in from other industries, often with the idea that developing a geothermal project is relatively simple compared to other, more traditional, energy projects. Some of these new developers lack the experience, skills, and capital required to deal with the considerable challenges they will undoubtedly face in the process. By employing the services of a team with geothermal experience, these "newcomers" may avoid the pitfalls that can derail potentially successful projects.

## Project Financing

Classic energy-project financing involves a developer raising funds (usually through a special purpose subsidiary created and incorporated for the specific project) through various mechanisms from financing institutions, usually in the form of equity, debt, or a combination of the two.

The participation of the financial entities may be attained through various business structures such as partnerships, leases, corporate investments, and combinations of the three. Issues of tax, cost accounting, and of course economics are the drivers in the process, but the underlying fundamentals are clear: risk versus reward. The more confident the investors feel that there is "real" credit support behind the project, the better the financial terms they will agree to provide with their investment.

The elements that are analyzed in the financing process are those that may affect the financial performance of the project over time. Typically, the main elements are:

- Power Purchase Agreements (PPA) are a major financing support element. But for specific terms and conditions such as pricing, indexing, termination clauses, and term, the reality of the last years requires that the power purchaser have a solid credit position.
- Fuel supply availability (brine or steam), cost, and projected longevity of the supply. Developers should be prepared to pay a significant risk premium when trying to finance projects with unproven or undeveloped geothermal resources. The up-front cost of developing the geothermal resource means that the overall efficiency of the power plant strongly influences the return on investment.
- Site control for the entire resource, including the ability to preclude competing interests. Competition for leases and geothermal rights is often intense.

- Field performance experience of the technology which will produce the power. Few manufacturers have a long-term track record for utility-scale geothermal systems.
- Experience and credibility of the developer.
- Other elements such as structure of the deal, regulatory issues, and electricity transmission issues.

## The Geothermal Resource

Geothermal projects are attractive because they produce base-load power and thus geothermal projects can generally qualify for firm long-term contracts with utilities. Despite these advantages, developing a geothermal power project is a complicated process that new developers must approach carefully. Geothermal projects have distinctly different challenges than other, more traditional, renewable technologies such as wind, solar, and biomass. Geothermal projects require subsurface exploration and well field development and have greater upfront risk because the geothermal resource is not confirmed without drilling.

The geothermal resource is key to the success of a geothermal project and has a profound effect on financing terms. Resource critical parameters (temperature, permeability, fluid production, brine chemistry, etc.) include the ability to support power production on a sustainable long term basis.

Other details that need to be addressed include:

- Land ownership issues
- Permitting and other regulatory issues
- Transmission issues.

Financial institutions usually come on board once the geothermal resource has been fully explored and at least partially developed. At this stage, financial investors will have to be satisfied that the resource has the potential to deliver energy (and revenue) over a long period of time.

Nearly as important as the resource is the ability of the developer to demonstrate their team has the talent required to acquire, develop, and manage the geothermal field effectively. The major geothermal operators in the geothermal industry, such as Ormat, have an in-house talent base, which includes land teams, geologists, reservoir engineers, and other technical personnel. The ability of the developer's team to communicate freely among all these disciplines, on a continuous and near instantaneous basis, ensures that issues and problems in resource development and management are addressed expeditiously and effectively.

Financing partners will seek assurances that the developer has:

- Critical mass of skilled, talented, and experienced personnel
- Sufficient funds to address any resource related contingencies that may arise over the term of the financing.

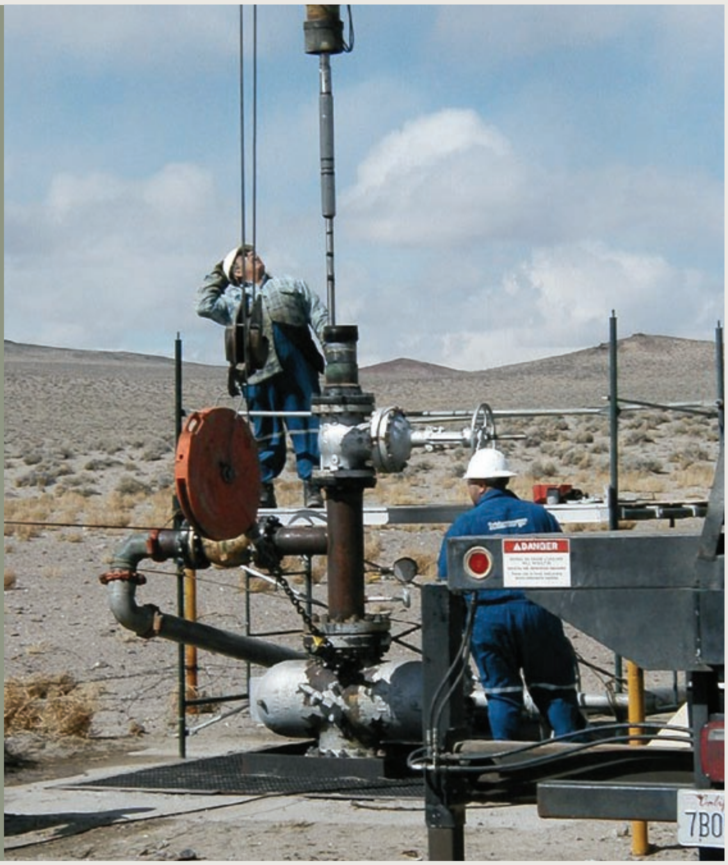
## Power Plant Technology

There is no standard approach to geothermal technology. Rather, the developer must adapt the plant to the available resource. For decades, premier geothermal resources were developed using standard steam turbines. These standard steam turbines are compatible with high temperature geothermal resources, but not with cooler geothermal resources that produce mostly hot fluid and not much steam. Because the geothermal resource base in the United States is mostly composed of these cooler geothermal resources, power

David Parsons

*Condensers being retrofitted with direct contact condensers at The Geysers Geothermal Power Plant in California.*

plant technology has advanced to capture this resource base. Today's developers will find that steam technology is not applicable for most present-day projects; they will find that binary cycle plants will be the preferred solution. Binary cycle plants typically utilize an Organic Rankine Cycle (ORC). The ORC operates by exchanging heat between geothermal fluid and a secondary working fluid, which is typically an organic fluid (such as pentane or isobutene) with a low boiling point. The organic fluid is vaporized to drive




Patrick Laney

*Drilling exploration crew performing initial well logging tests at the Desert Peak site in Nevada.*

the turbine. Although the need for an integrated solution drives many developers to binary plants using the ORC, one size does not fit all. The temperature, flow, and chemistry of the resource require specific technological and engineering solutions in order to maximize return on investment.

Financial institutions may be reluctant to provide non-recourse financing for a power plant technology that was not field proven and tested over many years in different resource areas. The reality is that geothermal power plants are expected to be of "utility grade." Developers selecting non-utility scale technologies such as Kalina cycle and reversed refrigeration may find it difficult to secure financing.

## Developers

The following are key issues a lender or investor considers before financing a project:

- **Committed developer.** One of the most important elements in putting together a geothermal power plant is a long term process. Our experience shows that the development of a geothermal project takes three to five years from site acquisition to commercial operation. One needs the capital and the commitment to go through the process, which many times does not yield a project at all. This commitment is required for the long term, as all projects have implementation issues that begin only after the financing closes.

- **Management team with the proper disciplines.** As the development and operation of a geothermal project are very challenging, the financial parties will look for developers who are astute enough to secure the services of the most experienced technical personnel in the field.

- **Well capitalized developer.** Geothermal power plants may present financial challenges during the operational phase. Geothermal projects may have long term issues with the well field and power plant. These unforeseen elements may require a temporary injection of capital on short notice.

## Summary

The geothermal industry is unique within the energy market, and as such the financing process of geothermal projects contains certain unique key elements that determine the ability of a geothermal plant developer to reach successful completion.

Based on Ormat's experience, we identified the main elements to support non-recourse project financing, as discussed in this article:

- Availability of the geothermal resource
- Proven technology used in the geothermal power plant
- Credibility and record of the developer.

When all of these elements are present, a geothermal project is likely to be successfully financed.

# International Geothermal Efforts – 2008

## Introduction

As the global demand for clean, reliable, renewable energy increases, geothermal energy is becoming an attractive solution. This is true not only in the United States, where current production is approaching 3,000 MWe, but at numerous locations on six continents. An area of increased emphasis is Enhanced Geothermal Systems (EGS).

Some of the most integrated and profound policy developments have been occurring in Australia, where significant governmental commitment and financial support are advancing the country's EGS Hot Dry Rock efforts. Another notable development can be found in Europe, with the ENhanced Geothermal Innovative Network for Europe (ENGINE) project.

What follows is an incomplete and brief survey of geothermal developments outside of the United States in 2008.

*The Wairakei Geothermal Power Plant in New Zealand.*

## Australia and New Zealand

Australia and New Zealand have been consistent developers of geothermal energy and continue to advance their interests in development.

Australia's state and federal governments have been supportive of developing EGS infrastructure and have set forth ambitious plans to expand geothermal development as part of the country's renewable energy portfolio. But, there has been a perceived minor setback—the latest federal budget presented a deferral of access to the A$50m geothermal fund until approximately July 2009.[2]

**Table 1. Estimated Production of Geothermal Energy by Country and MWe in 2010[1]**

| Country | MWe | Country | MWe |
|---|---|---|---|
| United States | 3,000 | Russia | 185 |
| Philippines | 1,991 | Kenya | 164 |
| Indonesia | 1,192 | Nicaragua | 143 |
| Mexico | 1,178 | Turkey | 83 |
| Italy | 910 | Papua New Guinea | 56 |
| New Zealand | 590 | France | 5 |
| Iceland | 580 | Portugal | 35 |
| Japan | 535 | China | 28 |
| El Salvador | 204 | Germany | 8 |
| Costa Rica | 197 | Ethiopia | 7 |

Australia has engaged in the Onshore Energy Security Program (OESP) and has committed A$58.9m over five years to Geoscience Australia (formerly the Australian Bureau of Mineral Resources). The Otway Basin along the Limestone Coast in South Australia is a region of interest. Three sites for development have been identified, possibly producing 1,600 MWe for 30 years.[3]

Mighty River Power in New Zealand plans to invest more than NZ $1 billion to develop 400 MWe of new geothermal generation by 2012 in the Taupo Volcanic Zone on the North Island.[3] The Kawerau plant is scheduled for completion by the end of 2008 and is expected to generate 90 MWe.

### The Creation of a New International Geothermal Partnership.

A delegation from the U.S. Department of Energy (DOE) traveled to Reykjavik, Iceland in August 2008 for the signing and initial workshop of the International Partnership on Geothermal Technology (IPGT), a new agreement between geothermal technology leaders Iceland, Australia, and the United States. The DOE's Acting Assistant Secretary for Policy and International Affairs, Katharine Fredriksen, Australia's Ambassador to Iceland, Sharyn Minahan, and Iceland's Minister of Industry Energy and Tourism, Ossur Skarphedinsson signed the Charter document on August 28, 2008. New Zealand attended as an observer.

The signing countries signaled their commitment to aggressively pursue advanced geothermal technologies, such as Enhanced Geothermal Systems (EGS), as part of a solution to energy security and global climate change concerns. "EGS has the potential to be the world's only ubiquitous form of baseload renewable energy," said Acting Assistant Secretary Fredriksen. "This partnership will bring together countries with expertise in geothermal energy to accelerate the development of EGS, bringing this technology to the market in the near-term to confront the serious challenges of climate change and energy security."

## Europe

In 2007, the European Commission (EC) began funding the ENGINE program. ENGINE's main objective is to coordinate research and development initiatives for unconventional geothermal resources and EGS and aspires to develop up to 20 demonstration sites.[4] ENGINE sets forth four research areas for geothermal development:

- Exploration: finding access to potential reservoirs at depth
- Geothermal wells: improving drilling and completion technologies
- Reservoir engineering: stimulating fluid flow underground
- Exploitation: improving efficiency.

In June 2008, the pilot plant of Soultz-sous-Forêts in Alsace, France, was inaugurated by the French Prime Minister François Fillon. The first installed Organic Rankine Cycle (ORC) module of 1.5 MWe is providing electricity to the grid. This European project, mainly funded by France, Germany, and the EC (with collaboration of several other countries including the UK and Switzerland), started in 1987. Much of the technology was adopted from the Rosemanowes site in Cornwall, which benefited from earlier DOE experiments at Fenton Hill. Shell and Enel were also involved with this project. The first successful, commercially-funded EGS project is in Landau, Germany. The project was completed in 3.5 years and is producing up to 3.6 MWe.[5]

**Table 2. Preliminary List of ENGINE EGS Demonstration Projects by Country and Site Name**

| Country | Project |
|---|---|
| France | Roquette, Rhine Graben |
| Germany | Bruschal<br>Groß Schönebeck<br>Landau<br>Unterhaching |
| Hungary | Fábiánsebestyén<br>Zala County |
| Iceland | Icelandic Deep Drilling Program |
| Poland | Podhale |
| Slovakia | Košice |
| Turkey | Green Campus Izmir |

## Asia

Exploration is taking place in several regions including India, the Kyrgyz Republic, China, Indonesia, and the Philippines.

*The 120 megawatt Nesjavellir Geothermal Power Plant in Iceland.*

In India, GeoSyndicate Power Private is working in collaboration with Panax Geothermal from Australia to exploit "wet" projects in the Godavari rift in Andhra Pradesh and the Himalayan Geothermal Province in Ladakh where there are high-heat flows.

High-heat flows have been detected in the Kyrgyz Republic and exploration licenses have been issued for several groups seeking high-heat producing granites in the Inylchek region of the republic.

Researchers have been assessing thermal resources in several regions of China and notable surveillance work has been conducted in Yunnan Province for the Rehai (Hot Sea) geothermal field of Tengchong County, where more than 815 thermal springs have been identified; 354 of which were measured at temperatures above 113°F (45°C).[3] An additional 105 MWe could be developed in Gu'an County, Hebei Province.[3]

At the time of this writing, 17 companies (including Chevron) are planning to bid for geothermal projects in West Java, Indonesia, possibly generating as much as 315 MWe.[6] The three power plants are Tangkuban Perahu (220 MWe),

Gretar Ivarsson

Cisolok Sukarame (45 MWe), and Tampomas (50 MWe). The Philippines is allowing the Philippine National Oil Company-Energy Exploration Corporation to drill geothermal wells in a restricted buffer zone adjacent to the Mt. Kanlaon Natural Park.

## North America and the Caribbean

Geothermal development has been acute in Mexico and Central America. Notable developments have been producing geothermal energy in El Salvador, Nicaragua, and Costa Rica for many years. Canada has begun exploration with an eye to development with the Canadian Geothermal Energy Association regrouping in 2007.

Nicaragua developed a 35 MWe operation on the Momotombo reservoir in 1983. Over the years production decreased dramatically and, by 1999, power-plant generation stood at 9 MWe. Reinjection was initiated and currently the plant is producing 30-35 MWe.[3]

Interest has been developing in the Caribbean, and drilling began on Nevis at the Spring Hill site in 2008; steam was located later that year at 3,720 feet.

## Africa

Another region of interest for geothermal development has been the East African Rift Valley. The United Nations estimates this region may be able to produce more than 400 MWe. In 2007, the World Bank had committed up to $13 million to the African Rift Geothermal fund, which will operate in six countries: Kenya, Uganda, Tanzania, Ethiopia, Eritrea, and Djibouti. Kenya was the first of these countries to develop geothermal energy and has the largest geothermal plant in Africa—near Naivasha (Olkaria), yielding 130 MWe.[3,7] Kenya Electricity Generating Company plans to install an additional 1,260 MWe by 2018 from four potential geothermal areas in the Kenya Rift—Olkaria, Menengai, Longonot, and Eburru—and also plans to develop at least 300 production and 60 reinjection wells over the next 10 years.[3]

## South America

The International Geothermal Association shows no production of electricity in South America. A report indicates Bolivia may have the capacity to produce 280-370 MWe. Chile has become interested in exploring its geothermal-resource potential after the abrupt curtailment of natural gas shipments from Argentina.

## Summary

As stated in the introduction, this is neither a comprehensive nor a complete survey of international geothermal development—it is merely a snapshot that provides a sample of efforts and initiatives across the globe. What is important to note is that there is an increased interest in geothermal development in 40 or more countries and all indications show this interest will be persistent and durable in light of international energy demands and the need to develop clean, renewable, baseload energy.

**References**

1. Bertani, R. “Geothermal Power Plants Commissioned in the Third Millenium.” *IGA News;* Vol. 72, April-June 2008; pp. 5-10.
2. *HDRPL Geothermal Newsletter.* Issue 20, June 2008.
3. *GRC Transactions;* Vol. 32 (preprint), 2008.
4. Robertson-Tait, A.; Ledru, P.; Goldstein, B.; and Nathwani, J. “Current EGS Funding Initiatives in Europe, Australia, and the United States.” *GRC Bulletin;* Vol. 37/3, May-June 2008; pp. 18-24.
5. Baria, R.Personal communication by e-mail. 18 June 2008.
6. “Chevron, Medco to Tap RI Geothermal Potential.” *The Jakarta Post* online http://old.thejakartapost.com/headlines.asp. Accessed June 7, 2008.
7. “UN to Ensure Geothermal Explorers in East Africa.” EcoEarth.Info online http://www.ecoearth.info/. Accessed March 22, 2007.

UGWG

# Utility Geothermal Working Group Update

The Utility Geothermal Working Group (UGWG) was formed in September 2005, at the Geothermal Resources Council's annual meeting in Reno, Nevada. It is a group of utilities and ancillary associations formed under the U.S. Department of Energy's Geothermal Technologies Program. UGWG is supported by six organizations:

- American Public Power Association (APPA)
- Bonneville Power Administration (BPA)
- Geothermal Resources Council (GRC)
- National Rural Electric Cooperative Association (NRECA)
- U.S. Department of Energy (DOE)
- Western Area Power Administration (Western).

The Working Group's mission is to accelerate the appropriate integration of three geothermal technologies into mainstream applications: power generation, direct use, and geothermal heat pumps (GHP). In addition to the six support organizations listed above, the UGWG members include:

- Arizona Public Service
- Ormat Technologies, Inc.
- Palo Alto Utilities
- Redding Electric Utility
- Salt River Project
- Sandia National Laboratories
- Seattle City Light
- South San Joaquin Irrigation District
- Springfield Utility Board
- State Working Groups
- Idaho National Laboratory.

## Webcasts and Workshops

To help accomplish its mission, the UGWG conducts periodic training events in the form of Webcasts and workshops. Events focus on geothermal and other renewable applications, technologies, and issues. Since its formation, the Group worked with its members and GRC staff to shape utility training sessions at the 2006 and 2007 GRC meetings. These training sessions provided an opportunity for more utilities to attend the high quality meetings. Other workshops and Webcasts have focused on topics such as:

- Power Generation
- Direct Use
- Geothermal Heat Pumps
- Transmission Issues
- Project 25x25
- Renewable Energy Credits
- Coal Fired Power Plants
- Public Participation
- Clean Renewable Energy Bonds
- Geothermal Heat Pump Economics.

## Power Generation and Direct Use Findings

Utilities are continuing on the path of integrated resource planning (IRP) to provide energy services to their customers. IRP demonstrates that energy efficiency remains the first choice in a utility resource portfolio and that direct use is an application that utilities continue to avoid. On the other hand, geothermal power generation is of interest to utilities. Geothermal power plants are capital-intensive, requiring most of the funding up front before the project


OIT Heat Center

*The Creamery Brewpub and Grill is one of the case histories described in UGWG workshops. It uses geothermal energy from the Klamath Falls, Oregon, geothermal district heating system for all its heating purposes. Uses of geothermal energy include space heating of approximately 11,000 ft² (1,022 m²) of restaurant/pub space, snow-melting of about 1,000 ft² (93 m²) of sidewalks, and generation of hot water for the brewing process. In cold months the brewery saves about $1,100 in space heating expenses and saves around $300 per month in energy used to brew the beer.*

produces any revenue. Utilities are more confident in the plants and are willing to negotiate a financeable power purchase agreement (PPA) with a developer, if the following five conditions are met:

- Delineated geothermal resource with a bankable report that defines probable long term performance
- Defined permitting path without pitfalls
- Credible developer with a proven project management track record
- Control of entire geothermal resource to preclude competing interests for same fluid/steam supply
- Use of proven technologies.


*The UGWG conducts several geothermal technology workshops each year.*

Utilities are willing to enter into PPAs if the output compares favorably with the "default power plant", which is currently a gas-fired combined cycle plant. Utilities estimate purchasing power from the default choice in the range of $65 to $90 per MWh, which includes capital, O&M, and fuel costs.

The price that a geothermal power plant developer can offer to a utility in a PPA largely depends on 1) the exploration, drilling, and development costs of getting the project online and 2) the financing charges associated with the costs. Costs for a typical 20 MW power plant are shown in Table 1.

| Table 1. Costs For a Typical 20 MW Power Plant | |
|---|---|
| **Development Stage** | **Cost (Millions of $)** |
| Exploration and resource assessment | $ 8 |
| Well field drilling and development | $ 20 |
| Power plant, surface facilities, and transmission | $ 40 |
| Other costs (fees, operating reserves, and contingencies) | $ 12 |
| **Total cost** | **$ 80** |

Using the above costs as a basis, a typical geothermal power plant has a capital cost of $4,000/kW. This capital cost is translated to a MWh cost by applying an annual factor reflecting interests rates for financing the total capital cost.

- At an annual factor of 0.2, reflecting an interest rate of 18% – 20%, capital costs are $104/MWh.
- At an annual factor of 0.15, reflecting an interest rate of 13% – 1 5%, capital costs are $ 76/MWh.

There are no fuel costs and the typical O&M cost for a plant is about $15/MWh. The O&M costs assume that the power plant uses Organic Rankine Cycle (ORC) technology for energy conversion with air to air cooling towers. ORC technology uses a moderately high molecular mass organic fluid such as butane or pentane to absorb the heat from geothermal fluid and drive the turbine. The technology has the benefits of high-cycle and turbine efficiencies, low turbine mechanical stress, reduced turbine blade erosion, and the fact that a full time operator need not be present.

If the power plant uses a different technology or water to air cooling towers, the O&M costs are likely to be higher. Using these two annual factors and adding the O&M cost to the annualized capital costs, the developer may be able to offer a utility output in the range of $91 to 119/MWh. This price could be lowered if the utility were to finance the power plant construction.

## Geothermal Heat Pump Findings

GHPs represent an energy-efficient technology making strong gains as a viable alternative heating and cooling system, both in the United States and around the world.[1] Although this technology has been in existence since the 1940s, it still has not realized its full market potential, but the technology is gaining ground. The UGWG and one of its four major support organizations, Western, developed a report that describes the reasons why geothermal heat pump technology appeals to electric utilities and end users, and explains why this appeal has not been enough to sustain a national market.

Western also developed two worksheets that provide the economics of GHP versus other heating, ventilation, and air conditioning (HVAC) options from the customer and utility perspective. This report and the spreadsheets help readers to:

- Understand the benefits geothermal heat pumps offer customers and electric utility providers
- Describe market potential and appeal of geothermal heat pumps
- Document tactics and strategies that some electric utilities have used to develop sustainable and effective geothermal heat pump programs.

Twelve utility programs with successful geothermal heat pump installations were selected to be included in this report. These are not all the utilities currently offering geothermal heat pump programs. Nor are they some of the geothermal "pioneers" that first established utility programs. Rather, these are the utilities still committed to selling and promoting this technology. The selected utilities featured in this report have found the right alchemy of program elements to create innovative and successful geothermal programs.

The report identifies one major barrier to expanding GHP applications –costs that the customer must incur without utility financing. The GHP typically has a 20% premium when compared to traditional air-source heat pump system installations.[2] Cost premiums are associated with designing and installing ground loop systems that operate year-round without auxiliary back-up units. According to one Energy Information Administration (EIA) report, these systems have a payback period of two to 10 years when energy and maintenance costs are accounted for.[3] Other reports have indicated simple payback periods of five to eight years. The large variance in payback discourages implementing these systems. Typically, businesses and individuals look for a return on an investment within a two to three year payback, and a longer payback is highly unattractive for consumers and businesses alike.

If the utility were to step in and finance all or part of the GHP system for customers, the customers may likely enjoy a positive cash flow from the start of the system operation. The utility could place a lien on the customers' properties and charge an interest rate, in the form of a loop lease, which is digestible for the customer and financially prudent for the utility.

To illustrate a typical residential application, the following assumptions are used and compare to a GHP system with a conventional HVAC system that uses a natural furnace for heating and electrically served air conditioning for cooling. Sources for assumptions are DOE and EIA. If the conventional source is propane, oil, or electric resistance for heating, GHP economics are better.

- Electric Rate = 10¢ per kWh
- Electric AC Use = 1,660 kWh per year
- Gas Rate = $1.50 per therm
- Gas Heating Use = 900 therms per year
- GHP System Cost = $10,000

Using the above assumptions, conventional HVAC costs $1,516/yr. The GHP costs are $1,390/yr, assuming that a loop lease is available to finance the GHP system costs. Loop leases vary due to loan terms. If the utility offers 6% financing and 30 year terms, the loop lease is $330/yr.

Does it make sense for a utility to offer a GHP program that includes a loop lease to the customer? Utility economics are less straight forward than customer economics. The utility needs to assess how the program affects its peak period (summer vs. winter), including the impact of the default heating option (electric resistance vs. other fuel sources such as natural gas or propane.

If the GHP system is replacing electric resistance heating, the utility saves about 40% in peak demand in the summer and winter, and loses about 70% of revenues from kWh sales. GHP makes sense if the peak demand savings and interest revenues from the loop lease more than offset the revenue losses and any other losses resulting from implementing the program. Other revenue losses include actions such as rebates, rate reductions, or lower interest rates.

## Conclusions

The UGWG finds utility members are interested in two of the three geothermal technologies—power generation and geothermal heat pumps. Direct use appears to be too far afield from their core business to pursue at this time. Based on the results of training and interaction with the members over the past year, the UGWG plans to continue promoting the two geothermal technologies of interest to its members. The focus will be on workshops, training programs, and field assessments that cause more geothermal power plants to be developed and more geothermal heat pumps to be put into the ground.

**References**

1. Johnson, K. *Geothermal Heat Pump Guidebook.* 3rd Edition. 2007; p. 3
2. "Geothermal Heat Pumps." Sacramento Municipal Utility District. January 2007.
3. Kavanaugh, S. *Ground-Coupling with Water Source Heat Pumps.* 2004; p.10.

# State Policies Provide Critical Support for Renewable Electricity

Growth in renewable energy in the United States over the past decade has been propelled by a number of forces, including rising fossil fuel prices, environmental concerns, and policy support at the state and federal levels. Arguably, the two most-important types of state policies for supporting electricity generation from geothermal and other forms of renewable energy are renewables portfolio standards (RPS) and utility integrated resource planning (IRP) requirements. Within the western United States, where the vast majority of the nation's readily-accessible geothermal resource potential resides, these two types of state policies have been critical to the growth of renewable energy and promise to continue to play a fundamental role for the foreseeable future.

## Renewables Portfolio Standard

A renewables portfolio standard (RPS) requires utilities and other retail electricity suppliers to produce or purchase a minimum quantity or percentage of their generation supply from renewable resources. RPS purchase obligations generally increase over time, and retail suppliers typically must demonstrate compliance on an annual basis. Mandatory RPS policies are backed by various types of compliance enforcement mechanisms, although most states have incorporated some type of cost-containment provision, such as a cost cap or a cap on retail rate impacts, which could conceivably allow utilities to avoid (full) compliance with an RPS target.

Currently, 27 states and the District of Columbia have mandatory RPS requirements. Within the 11 states of the contiguous western United States all but three (Idaho, Utah, and Wyoming) now have a mandatory RPS legislation (Utah has a voluntary renewable energy goal), covering almost 80% of retail electricity sales in the region. Although many of these state policies have only recently been established, the impact is already evident: almost 1,800 MW of new renewable capacity has been installed in Western states following the implementation of RPS policies. To date, wind energy has been the primary beneficiary of state RPS policies, representing approximately 83% of RPS-driven renewable capacity growth in the West through 2007. Geothermal energy occupies a distant second place, providing 7% of RPS-driven new renewable capacity in the West since the late 1990s, though geothermal's contribution on an energy (MWh) basis is higher because the nameplate capacity of a generator (essentially its maximum instantaneous output) is expressed in units of megawatts, while the amount of energy produced by a generator over some period of time is expressed in megawatt-hours.

Looking to the future, a sizable quantity of renewable capacity beyond pre-RPS levels will be needed to meet state RPS mandates: about 25,000 MW by 2025 within the Western United States (Figure 1). Geothermal energy is beginning to provide an increasingly significant contribution, as evidenced by the spate of new projects recently announced to meet state RPS requirements. Most of this activity has been driven by RPS policies in California and Nevada, where the Geothermal Energy Association has identified 47 new geothermal projects, in various stages of development, totaling more than 2,100 MW.[1] Additional geothermal projects in Arizona, New Mexico, Oregon, and Washington are also under development to meet those states' RPS requirements.

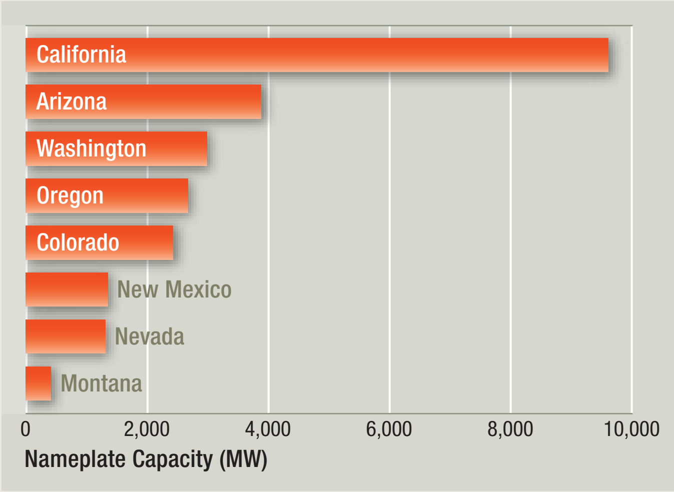
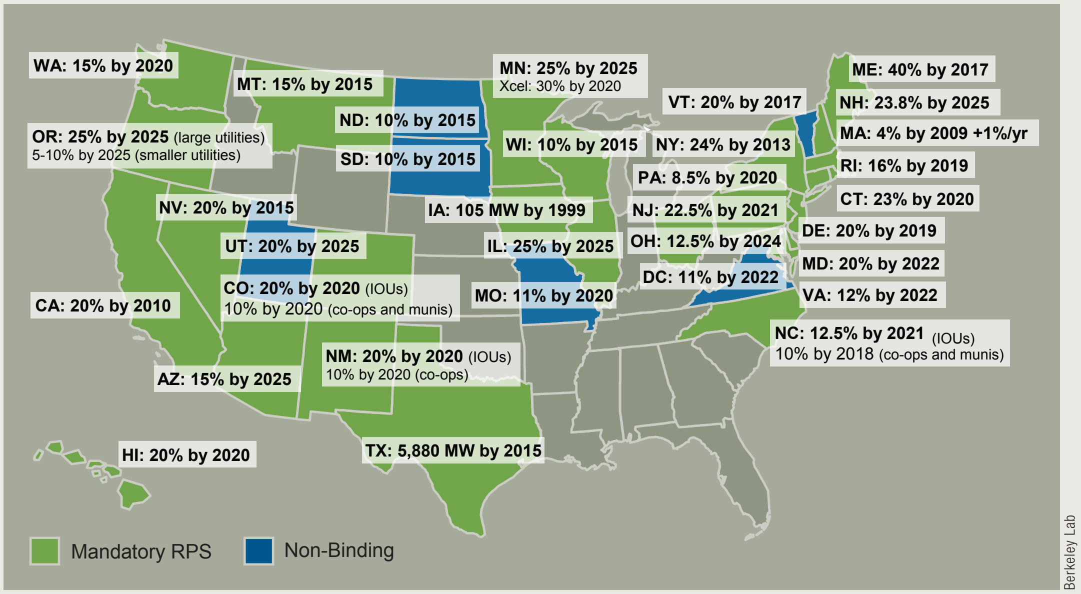



*Figure 1. New renewable capacity needed by 2025 to meet western RPS requirements (beyond pre-RPS levels).*

## Integrated Resource Planning

The other major state policy driver for renewable electricity growth, particularly in the West, is IRP. (IRP is also alternatively referred to as least-cost planning, long-term procurement planning, and default supply resource procurement planning). IRP was first formalized as a practice in the 1980s, but the practice was suspended in some states as electricity restructuring efforts began. A renewed interest in IRP has emerged in the past several years with three western states (California, Montana, and New Mexico) re-establishing IRP. Other states are developing new rules to strengthen their existing processes.

In its barest form, IRP simply requires that utilities periodically submit long-term resource procurement plans in which they evaluate alternative strategies for meeting their resource needs over the following 10 to 20 years. However,




*Renewable Portfolio Standards by state.*

many states have developed specific requirements for the IRP process that directly or indirectly support renewable energy. The most general of these is an explicit requirement that utilities evaluate renewables, and that they do so on an equivalent or comparable basis to conventional supply-side generation options. Many states also require that utilities include various types of risk analyses within their IRP. For example, utilities are often required to evaluate fuel price risk within their resource plan, which can reveal the value of renewables as a hedge against rising fuel prices.

Of particular importance for supporting renewable energy is the increasingly common requirement that utilities evaluate the potential costs and risks associated with future greenhouse gas regulations. Virtually all of the major western utilities that prepare IRPs incorporated future carbon dioxide regulations in their analyses of alternative resource strategies in their most recent resource plans. Some state public utility commissions (California, New Mexico, and Oregon) have even specified particular carbon dioxide emission allowance prices utilities are required to include in their analyses, or have established other requirements related to how utilities undertake analysis of carbon regulation risk.

The impact of IRP on renewable energy development is most apparent in states without an RPS, where the IRP process has often led directly to procurement or construction of new renewables. For example, in its 2004 IRP, Idaho Power selected a preferred resource portfolio containing new geothermal resources, and subsequently issued a Request for Proposals for 100 MW of geothermal energy that has since culminated in the signing of at least one power purchase agreement (for the output from a new geothermal unit at the Raft River Project in Idaho). Similarly, many of the Washington and Oregon utilities were actively procuring new renewable resources prior to enactment of those states' recent RPS laws, in part as a result of IRP. Even in states with an RPS, IRP has played an important role in supporting renewables development, in some cases leading utilities to pursue greater levels of renewables than is strictly required for compliance with the RPS. For example, in its most recent IRP, Public Service Company of Colorado opted for a resource portfolio—including 20 MW of new geothermal power—that far exceeded the quantity of renewables needed to meet the state's RPS requirements.

## Conclusion

Together, state RPS policies and IRP requirements are creating strong demand for new renewable electricity generation capacity, which is driving the development of new geothermal resources in the Western United States. Both types of policies are relatively stable and are therefore likely to continue to support new renewable electricity generation for the foreseeable future. The extent to which geothermal energy ultimately benefits from these policies will depend largely on how well it can compete against other renewable resource options.

### References

1. "Developing Plants in the U.S." *The Geothermal Energy Association* online http:www.geo-energy.org/information/developing.asp.

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