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Geothermal Power

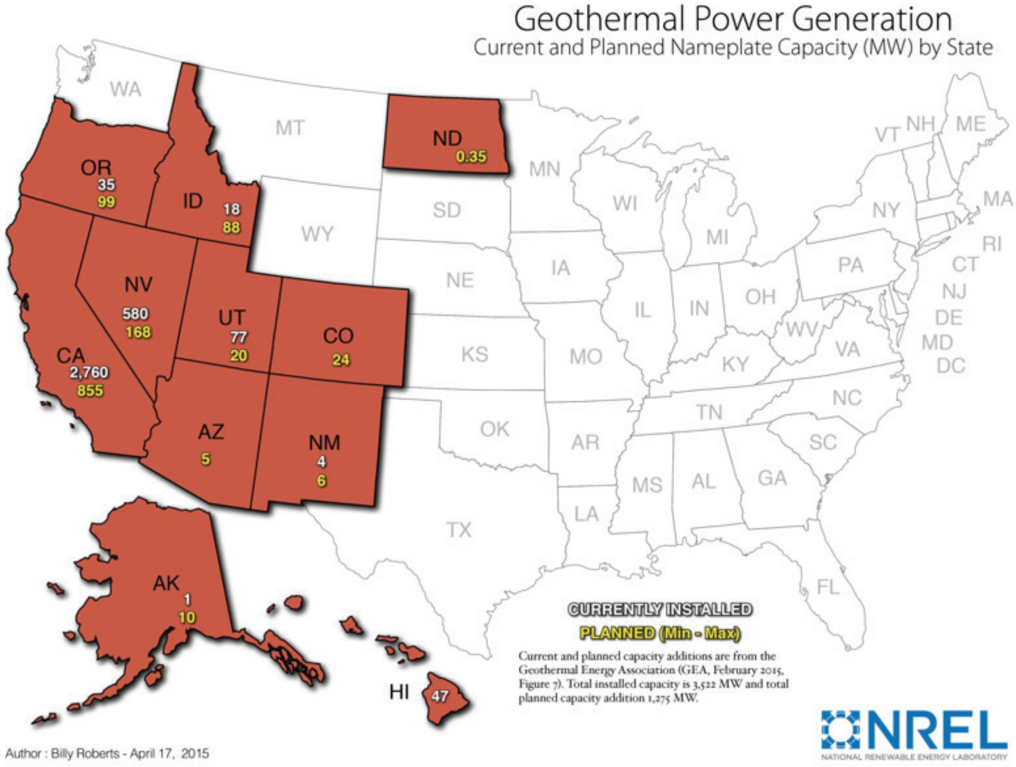
Chapter 4: Technology Assessments

Introduction

Geothermal power taps into earth's internal heat as an energy source. While geothermal currently constitutes less than 1% of total U.S. electricity generation,[1] it is regionally much more significant in the western United States. Vast amounts of heat are contained in the interior of the earth from the slow decay of radioactive elements and the heat remaining from earth's formation. This heat flows to the surface at low rates everywhere on earth (terrestrial average is ~60 mW/m^2). Specific locations, such as settings of crustal extension or near magma emplacement, have anomalously high heat flow. Geothermal power is now being produced in eight western states—California, Nevada, Utah, Oregon, Hawaii, Alaska, Idaho, and New Mexico—with over 3,000 MW of capacity online (Figure 4.B.1). Production is particularly significant in California, where geothermal is half of in-state renewable power production and 5% of total power production, and in Nevada, where geothermal now provides over 10% of the state's in-state electricity. However, nationally (and globally), the demand for geothermal power generation is tempered by the high up-front costs and early-stage risk associated with geothermal development.

Figure 4.I.1. Geothermal Installed (Current) and Planned Nameplate Generating Capacity in MW_e by State.[2]

Credit: National Renewable Energy Laboratory



Geothermal Power Generation

Current and Planned Nameplate Capacity (MW) by State

Current and planned capacity additions are from the Geothermal Energy Association (GEA, February 2015, Figure 7). Total installed capacity is 3,522 MW and total planned capacity addition 1,275 MW.

Author : Billy Roberts - April 17, 2015

Despite the relatively low surface flux of heat, owing to the low conductivity of rocks, high temperatures occur at accessible depths. Several geothermal technologies exist or are in development to capture this heat for power generation (if the fluid temperature is sufficiently high, >~150°C, although new power conversion technologies are pushing down the threshold for economic power generation) or direct use for heating, cooling, or industrial uses (typically lower temperature fluids, <~150°C). Specific locations have a favorable combination of high heat flow and natural fluid circulation that make them suitable for geothermal power generation. The naturally circulating hot fluid can be tapped to generate power in these naturally occurring hydrothermal systems. Enhanced geothermal systems (EGSs) are engineered reservoirs created to produce electricity from geothermal systems that are not otherwise economical owing to lack of water and/or permeability.[3] In an EGS, fluid is injected into the subsurface, which causes preexisting fractures to reopen. This increases permeability and allows fluid to circulate throughout the rock and transport heat to the surface where electricity can be generated. Though the concept has existed for several decades to engineer fracture networks in the subsurface to mine geothermal heat, an EGS is an immature and high-risk technology. The United States Geological Survey (USGS) estimates that there are ~9 GWe of identified geothermal resources and an additional ~30 GWe of undiscovered geothermal resources.[4] With EGSs, the USGS estimates a mean electrical power resource of ~517 GWe in the United States.[5]

This technology assessment reviews the current state of the art and identifies key research, development, demonstration, and deployment (RDD&D) needs to realize the potential of geothermal energy. The technology assessment will largely focus on EGS technologies, given the large resource potential. Two areas are identified as the major technological challenges for geothermal development: (1) developing the subsurface engineering technologies and practices necessary for economic deployment of EGSs and (2) developing technologies that can reduce the high costs of drilling to access geothermal resources (which include both drilling technologies and characterization technologies). The high up-front costs, particularly drilling costs, are a major challenge for geothermal development because they occur when risk is still high. The result is that it is difficult to obtain financing for new geothermal developments, driving a need to reduce risk in early stages of development. Technology improvements in the areas of subsurface characterization and drilling will help reduce the high up-front costs and/or increase the success rate of exploratory wells and therefore make new geothermal developments more attractive.[6]

The challenges in EGSs are further divided into the following areas[7]:

- **Subsurface characterization:** Efficiently and accurately locate target subsurface geologic environments and quantitatively infer their evolution through time.
- **Accessing:** Safely and cost-effectively drill to prospects with high probability for success.
- **Engineering:** For an EGS to succeed, methods are needed to create large networks of fractures to create enough surface area per reservoir volume to avoid uneconomically rapid thermal drawdown.[8] An added challenge comes from achieving this goal in challenging high-pressure/high-temperature environments.
- **Sustaining:** Maintain these conditions over multi-decadal time frames throughout complex system evolution.
- **Monitoring:** Improve observational methods to advance understanding of the multi-scale complexity throughout system lifetimes

As part of a broader Department of Energy (DOE) strategy to integrate systems-oriented RDD&D into multi-office technology teams, the Geothermal Technologies Office is leveraging the subsurface crosscutting technology team (made up of a broad crosscut of DOE offices involved in subsurface research) to accelerate advancements in subsurface technology and engineering aligned with these challenge areas. The Subsurface Technology and Engineering Research, Development, and Demonstration (SubTER) Crosscutting Team, in collaboration with the national laboratories, has identified adaptive control of subsurface fractures and fluid flow as a key crosscutting theme and an energy "grand challenge." The ability to control fractures and have real-time control or mastery of subsurface fluid flow while understanding and mitigating the implications of induced seismicity can have a transformative effect on numerous industries and sectors, impacting the strategies deployed for subsurface energy production and storage.

Technologies

Characterization Technologies

Technologies for subsurface characterization will reduce the high risk associated with finding and developing geothermal reservoirs, which in turn will reduce the cost of geothermal power in new areas. Maturing EGS technologies (discussed below) will help make current or future unviable geothermal resources economical and eventually greatly increase the amount of economically viable geothermal resources. The characterization needs for EGSs are still being defined as the technology matures. Unlike other renewable energy sources (e.g., solar and wind), a geothermal resource is not confirmed until a well is drilled into a target reservoir and flow is tested, costing millions of dollars. Current exploration success rates for identifying and drilling a viable resource target are such that a developer will typically perform exploration drilling at five sites in order to successfully confirm and develop one commercial project.[9] This low success rate is the source of the very high up-front costs during early development and high associated risk, which are the primary deterrents for rapid development of our geothermal resource potential. Therefore, characterization technologies are critical to advancing geothermal energy. Reservoir identification and subsurface characterization rely on four groups of tools based on: geophysics, geochemistry, remote sensing, and geology. These tools are used to assess geothermal potential by identifying target reservoir temperature, permeability, fluid availability, and geologic structures. RDD&D on characterization should focus on investigations of existing hydrothermal systems to better understand the key attributes of viable resources and methods and technologies to evaluate promising geographic regions for target sites for development with a quantifiable risk profile.

Geophysical exploration techniques are used primarily to identify and map subsurface structures that help define geothermal systems, such as fracture networks and orientation, lithological variability, heat flux, and the presence of fluids. The tools employed consist of acoustic (seismic) and electromagnetic waves, variations in local gravity and magnetic fields, and thermal gradients. Currently, the available geophysical tools lack the ability to accurately identify and image fluids in fractures or fluid flow and are unable to remotely predict temperatures at target depths. There is a lack of detailed heat-flow maps and limitations to predicting open fracture locations. Translating resistivity data into meaningful inferences about reservoir permeability is currently a complex, time-consuming process. Presently it is challenging to use geophysical data to confidently identify a geothermal system and to determine system size and whether a geophysical anomaly is related to current or past geothermal activity. The issue of the non-uniqueness of inversions of geophysical data must be addressed. Promising RDD&D pathways include the development of small-scale geophysical sensors that can be deployed in well bores along with research into new techniques for integration of multiple types of geophysical data and integrating geophysical techniques with other ways of probing the subsurface.

Geochemical techniques provide information regarding fluid and heat source, subsurface temperature, and local and regional fluid flow paths and histories. The chemical and isotopic compositions of fluids collected at the surface provide subsurface temperatures by using a variety of empirical and experimental water-rock geothermometers. Fluid and heat sources can often be identified through characteristic isotopic signatures, particularly water, helium, and carbon isotopes. In favorable cases, spatial variations in fluid chemistry and isotopic compositions reveal important information on flow paths of geothermal fluids through a system. Geochemical and isotopic technologies for identifying fluid and heat sources in geothermal systems are well established. However, the geothermal industry lacks reliable tools for estimating subsurface temperatures, fluid flow paths, and rates as well as for identifying hidden systems. Recent advancements in chemical and isotopic geothermometers based on water-rock thermodynamics need to be vetted. Key RDD&D needs include reliable technologies for mapping fluid flow histories, including fluid residence ages and identification of surface signals and tools for identifying hidden systems.

Remote sensing techniques enable large-scale mapping of surface features, such as mineral, vegetation, and thermal properties, as identifiers of geothermal resources. Passive sensors detect natural emitted and reflected radiation. Active remote sensing uses the reflected, or backscattered, signal from energy emitted at predetermined wavelengths. Satellite and airborne imagery can map zones of secondary mineral precipitation associated with emerging geothermal fluids and attributes, such as heat flux. Aerial photography and terrain mapping with laser ranging also illuminate surface structural features associated with geologic settings. However, with the exception of regional light detection and ranging (LIDAR), which, although costly, has been widely used for exploration, the feasibility of other remote sensing techniques has yet to be vetted as viable exploration tools on a large scale. Challenges remain in utilizing hyperspectral, forward-looking infrared and thermal imaging data, and there is an ongoing need for high-resolution, low-cost strain maps to enable remote sensing. The area to be surveyed is often vast, and the data sets can be large; hence, current automated regional reconnaissance data analysis and processing are inadequate. Especially for data-sparse areas, there is insufficient experience in the use of wide-area reconnaissance tools. Key RDD&D needs include research into new frameworks, combining expert-driven and data-driven methodologies to use remotely sensed data to quantify key properties of interest, such as strain, and to quantify the probability of the existence of a geothermal resource. This research pathway is discussed below in the Play Fairway Analysis section.

Geologic techniques provide the historical and structural framework within which geophysical, geochemical, and remote sensing data are interpreted. When combined with the other three technical areas, a geologic model for an exploration area can be developed and used as guidance for subsequent exploration strategies. Surveying and mapping the local and regional geologic structures, lithologies, and past and present strain rates are the most common geological methods for identifying potential geothermal sites. However, many geologic features of a potential geothermal exploration site are currently challenging to understand. These include the site's tectonic context, structure setting and detail, strain-stress inversion, and permeability at depth and at fracture scale. Regional active structures, such as the structural settings of hydrothermally active systems, tend to be insufficiently understood. It is challenging to age date hot spring deposits, and reliable methods do not currently exist for determining if a hot feed lies below thermal anomalies. In addition, the limited availability of sufficient geologic maps for exploration hinders the ability of using other exploration technologies for effectively detecting geothermal resources.

Beyond the specific challenges in the geophysics, geochemistry, remote sensing, and geology domains, various crosscutting issues currently affect all geothermal exploration technologies. In general, there is insufficient understanding of what geological environments best provide the necessary attributes for natural hydrothermal systems or EGSs. If there was more insight into why natural systems exist, this knowledge could be applied toward more efficiently finding hidden systems or developing EGSs. Defining such occurrence models will require input from all technical disciplines involved in geothermal exploration. With respect to data management, there is currently no world atlas of geothermal occurrences and no classification scheme that systematically links characteristics of the subsurface reservoir to measurements made at the surface across each geothermal setting.

Crosscutting barriers also exist in data synthesis, including the lack of multidisciplinary conceptual models that integrate geophysical, geochemical, remote sensing, and geological data; the high cost of 3 D and 4-D integrative data software; and the lack of geothermal-specific software. Even where data and tools exist, they may not be sufficiently leveraged by geothermal developers. For example, the extensive body of oil, gas, and mining industry knowledge—as well as federal agency tools such as the National Science Foundation's Earth

Scope, NASA's airborne science surveys (e.g., InSar, Hyperspec, and LIDAR), and USGS surveys and maps—could be used more effectively.

Play Fairway Analysis

The oil and gas industry has used the "play" concept of resource exploration for many years with extensive success. It is an essential component of oil and gas exploration decision making; grouping petroleum occurrences and accumulations into type categories or families has significantly helped in managing the high risks inherent in resource exploration and development. While many aspects of this approach have been used in geothermal exploration for decades, the geothermal play fairway analysis program seeks to migrate the rigorous statistical risk quantification aspects of the play concept to the geothermal sector to improve exploration management tools. A play is a combination of unique geophysical, geologic, structural, and/or stratigraphic elements that have resulted in a geothermal resource. A play can be based on fields or prospects in a given structural basin or region or can be a global-scale categorization. The play fairway is the area in a basin or region where examples of an individual play type actually occur and/or are projected to exist with high probability. The process of developing a play fairway analysis consists of several steps. First, existing relevant geologic, geophysical, and geochemical data for the area of interest is compiled. The second step generally involves examining, interpreting, and integrating the compiled data sets to determine the possible play types within the particular region and the necessary conditions required for each play to occur. In the third step, on the basis of the compiled data and play type, a probability map is constructed for each attribute that needs to exist for that particular play type. Generally, this step involves complex modeling that incorporates and integrates, in a statistical manner, the tectonic, structural, and thermal evolution of the region and the play development. In the final step, the individual attribute probability maps are used to generate a composite probability map. This map should summarize the probability that a play exists, given a specific set of causative factors, and highlight those areas within the region where there is a high chance of successful target drilling and resource development.

The challenge for the geothermal community is addressing the complex geologic nature of high resource potential regions. Most oil and gas resources occur within sedimentary structures, basins, domes, etc. By their nature, sedimentary sequences are repetitive and extensive in scale. The sedimentary facies concept can be reliably extrapolated over large distances and incorporated into the play analysis. In the United States the high geothermal resource potential area, principally the western states, is extremely complex with respect to geologic structure and history. Primarily as a result of this complexity, presently there is no well-defined classification scheme that systematically links characteristics of the subsurface reservoir to measurements made at the surface that would facilitate development of attribute probability maps. Furthermore, the key parameters that indicate the presence of geothermal resources vary across different environments, creating another level of complexity as each type of setting may have different attributes requiring different tools and analytical approaches. Case studies, information on the habitats and mesoscale tectonic settings of geothermal systems, and occurrence trends are also insufficiently described; there is a need to explore new areas and to delineate anomalous areas.

Access—Drilling Technologies

The exploration and extraction of the earth's resources necessarily requires access to the subsurface. Drilling technologies are employed for the exploration of all earth's resources and are the means for extraction for many resources, including geothermal.

While exploration of geothermal resources employs a wide variety of nonintrusive field studies, drilling is required to confirm that the target resource is at the required temperature and can support requisite flow rates for the intended application. Exploration drilling requirements for geothermal development include the construction of temperature gradient wells and resource confirmation wells. For a new resource, temperature gradient wells represent the first foray into the subsurface and are needed to map the temperature subsurface profile of the resource site and to provide reasonable estimates of the resource temperature. Depths of temperature gradient wells vary but can bottom out anywhere between the surface and the target resource. Temperature gradient wells are commonly drilled with smaller drill rigs at "slimhole" diameters (less than six inches but commonly less than four inches). These holes are generally drilled with standard rotary methods, but increasingly wireline coring techniques (originally developed for the mining and civil industries) are being employed. Resource confirmation wells are necessarily drilled to the depth of the reservoir and are developed to confirm resource temperature and allow flow testing of the reservoir to ensure the reservoir can support the required flow rates for the development project. Similar to the temperature gradient wells, these wells are developed by using standard rotary techniques at diameters suitable for flow testing. Some operators drill these wells at full production diameters, but some industry operators are drilling these wells at smaller diameters by using standard wireline coring techniques.

After confirming the resource can support the needs of the developer, production and injection wells are drilled. Because of flow rate requirements and possible pumping requirements, these holes (particularly the production wells) are commonly constructed at diameters significantly larger than those associated with other extractive industries; 12¼-inch-diameter production intervals are not uncommon.

The technologies used to drill geothermal wells are similar to those used to explore and extract other earth resources. However, geothermal well construction and well operations face the following unique combination of challenges:

- While the oil and gas sector has adopted advanced fixed cutter polycrystalline diamond compact bits (which were first developed with DOE funding from the Geothermal Technologies Office), the geothermal industry has seen only minor adoption because of the high rock strength, abrasiveness, and fracture formations commonly encountered in geothermal environments. Fixed cutter bits have the potential to easily double the average daily penetration if designed appropriately and run in a manner that will allow operations in harsh geothermal environments.[10]
- Drilling, well logging, and testing equipment are limited by temperature issues associated with geothermal environments. Materials and electrical component development is needed to expand the operating temperatures of drilling tools, such as downhole motors, measuring while drilling, and logging while drilling assemblies as well as subsurface logging and monitoring tools. For example, commonly employed elastomeric materials for sealing tools and for use in wellbores are inadequate for extended operations in geothermal wells, and there is a paucity of electronic components needed for high-temperature applications.
- The small size of the geothermal industry poses direct challenges because the scale of the sector does not support the refinement of fit-for-purpose techniques and practices. Example opportunities include geothermally trained rig crews, use of modern drill rigs, better data acquisition, and rig automation. Specific techniques, such as using mechanical-specific energy for increasing the rate of penetration, reducing downtime, and reducing overall drilling time and risk could be appropriately translated and adopted more fully from the oil and gas industry.
- Lost circulation is a significant issue in geothermal drilling operations, and alternative methods to deal with lost circulation are needed. Materials to mitigate lost circulation while drilling without permanently plugging the formation in high-temperature environments need advancements. Diverter materials that can potentially be used for this purpose have been developed, but alternatives need to be expanded.
- Wellbore integrity during the construction of the well, throughout its useful life, and after abandonment is an important issue for all constructed wells, and wellbores associated with geothermal development are no exception. Improved cements, remediation materials, casing systems, and practices are needed to ensure that wells developed for geothermal energy production are constructed in a manner that allows success during drilling and operations and long-term environmental safety.

Well construction costs are a dominant capital cost in geothermal development. However, these costs can be decreased through continued RDD&D to address the challenges outlined above. As described above, a variety of well construction needs exist relative to geothermal development. Accessing and modifying drilling technologies from other industries or development of fit-for-purpose drilling systems will aid in driving down well construction costs along with more efficient drilling practices.

Subsurface Engineering

EGSs can be developed through directed modifications of the subsurface to engineer desired subsurface conditions. In principle, an EGS encompasses all technologies and methodologies dedicated to improving or creating reservoirs that can provide fluids to the surface at sustained temperatures and flow rates needed for economically viable power generation. The primary pathway to achieve this result is to use thermal and hydraulic stimulation technologies to create an interconnected network of fractures through which water can circulate to extract heat from the reservoir. Significant technical challenges exist in the ability to predict the physical properties associated with the engineered fracture system. EGSs open up much larger potential resources and reduce the risks of drilling by providing options to create a viable energy production system from a much broader set of initial reservoir conditions. An EGS spans the continuum from a reservoir management and enhancement tool for hydrothermal systems to a tool to expand hydrothermal systems at the margins or to develop greenfield sites that have the appropriate subsurface temperatures but cannot support the required flow rates.

Over the last five years, separate EGS demonstration sites have actively pursued efforts to either expand existing geothermal fields or to develop new resources in areas where formation permeability is too low to support geothermal energy production. While the EGS demonstrations are ongoing, these projects have already yielded positive results through expansion of power output at one of the demonstration sites[11] and added reserves at another location.[12]

DOE is currently in the process of establishing the Frontier Observatory for Research in Geothermal Energy (FORGE).[13] FORGE will be a dedicated site and innovation hub, where the subsurface scientific and engineering community will be eligible to develop, test, and improve new technologies and techniques in an ideal EGS environment. This will allow the geothermal and other subsurface communities to gain a fundamental understanding of the key mechanisms controlling EGS success, in particular how to initiate, sustain, and control fracture networks and fluid flow in the subsurface. This critical knowledge will be used to design and test methodologies for developing large-scale, economically sustainable heat exchange systems, thereby paving the way for a rigorous and reproducible approach that will reduce industry development risk. Essential to this process is a comprehensive instrumentation and data collection effort that will capture a higher-fidelity picture of the EGS creation and evolution processes than any prior demonstration in the world. Finally, a dedicated FORGE allows for the highly integrated comparison of technologies and tools in a controlled and well-characterized environment as well as the rapid dissemination of technical data to the research community, developers, and other interested parties.

Technology development related to EGSs is not substantially different than that directed toward development of preexisting conventional geothermal resources. Issues related to resource exploration and subsurface access and monitoring are similar and complementary. EGSs can benefit greatly from advancements in other fields, such as materials science, that can facilitate developing tools that can withstand higher temperature and pressure environments. However, some technology issues, as follows, are more important to EGSs than traditional geothermal development:

- Zonal isolation is critical to EGS development. The ability to stimulate the rock mass, inject fluids, and produce fluids from select regions of the wellbore is critical for the technical and economic viability of EGSs.

- Stimulation technologies that can affect the formation and modify permeability needed to supply sustained fluid flow at temperatures are required.
- Advances in technologies to measure the stress state in the subsurface are needed to improve risk quantification for induced seismicity and to develop practices to minimize induced seismicity. Appropriate management of induced seismicity is key to public acceptance of EGSs.
- Drilling systems that can most favorably orient the wellbore and be actively controlled and interrogated in high-temperature, hard drilling environments are required.
- Robust surface-based and subsurface systems to image the development, operation, and evolution of EGS reservoirs are needed.

While EGS development still faces many technical challenges, directed RDD&D can advance EGSs to the point that they are commercially viable. EGS technologies hold great promise to unlock a substantial energy resource.

Additional Value Streams

A complementary strategy to advancing technologies to reduce the cost and risks associated with geothermal power developments is to advance technologies to derive more value from the resource. There is a significant positive financial advantage to optimizing the utilization of produced geothermal fluids downstream from power production. Owing to the large volume of produced fluids, the energy content post power production remains significant. The produced fluids, having reacted with reservoir host rocks, may also be fertile with potentially strategic chemicals. These are emerging sectors within the geothermal community and potentially ripe for rapid development and deployment.

Combined Heat and Power

Typically, geothermal fluids, after providing thermal energy for generating power, have temperatures ranging from ~40°C–100°C. Coupled with the economically necessary high fluid throughputs, these "waste" fluids are a significant thermal energy source. Presently, common practice is reinjection of the waste fluids for reservoir management and to satisfy environmental requirements. Technologies are being developed to use this energy source and improve the economics of geothermal energy production. For instance, international groups are evaluating the feasibility of using the waste heat to drive water desalination plants. Waste heat can be used for green houses, residential and building heat, and other applications that employ relatively low temperature thermal energy. Combining heat and power is a potentially very fertile area of technology development that could significantly alter the economics of geothermal power production. The utilization of thermal wastewater should also take advantage of emerging technologies by providing thermal energy with moderate to low temperature catalysts used in producing hydrogen, biofuels, and organic solvents.

Mineral Extraction from Fluids

While research and development (R&D) in advanced tools and techniques seek more cost-effective means to geothermal development, added revenue streams through strategic element and/or mineral extraction may hold the potential to contribute to more economically competitive projects. Common minerals and elements entrained in geothermal fluids include silica, lithium, manganese, zinc, and sulfur. Additional rare earth elements (REEs) and near REEs may also be relatively prevalent in the brines or may be associated with the geothermal system host rock as either primary or alteration mineralogy. Besides their significant market value, these chemical elements have strategic importance in that they are critical for domestic industries that produce everything from mobile phones and laptops to green technologies and national defense systems. Critical materials extraction continues to gain traction both in government initiatives and in industry research. In 2010, DOE released its first critical materials strategy outlining the vital role that REEs and other materials play in the clean energy economy.[14] The report identified supply risk as a key barrier, emphasizing the importance of taking steps to further advance mineral extraction processing and supply knowledge in the United States. Assessment of occurrence in geothermal fluids is ongoing. Further development and integration of mineral extraction into geothermal energy production offers a unique opportunity for the geothermal industry to expand its market value beyond power production.

Opportunities for the Future

Flexible Power

Historically, energy storage is not a technology that has been addressed within the geothermal industry. However, with grid management becoming more and more complex, timely delivery of energy to the grid (flexible power) has become an area of increased interest. In the past, the geothermal community has extolled the benefits of geothermal because it can provide baseline energy continuously. The need to stabilize the grid and provide more energy during peak usage and less during low demand periods has led the power providers to prefer "flexible power" that can be ramped up or down as needed. One way for geothermal power producers to increase flexibility in power generation is to allow fluids to bypass the generating turbines during low demand periods, reinjecting the unused hot fluids. This is presently being done at the Ormat Puna Geothermal Plant.[15] Pacific Gas and Electric Company has also cycled their geothermal units at the Geysers Power Plant to provide flexible power in the past.[16] Although this is an adequate stopgap approach, clearly as the demand for flexible power increases, more efficient technologies or reservoir management schemes will need to be developed.

Carbon Dioxide Geothermal

Previous and current attempts to create and operate EGSs in the United States, Japan, Europe, and Australia have all employed water as heat transmission fluid. Water has many properties that make it a favorable medium for this purpose, but it also has serious drawbacks. Water is a powerful solvent, which in the context of EGSs is not a desirable property because it means that it can literally dissolve some (mineral) components of the rocks and, depending on fluid temperature and dissolved chemical concentrations, can precipitate other minerals elsewhere. Depending on where and how much dissolution and precipitation occurs, this leads to the twin problems of either generating short-circuiting flow paths that will cause premature breakthrough of cold injected waters at the production well(s) or plugging (clogging) existing pathways and thereby choking the flow or causing unacceptably large increases in fluid pressure. Another problem is that some water losses are inevitable as the fluid circulates in what is essentially an "open" system, so that not all injected fluid can be recovered at production wells. Such fluid losses can be costly or intolerable in certain regions, such as the western United States, where water is a sparse and valuable commodity.

Recent scientific developments have suggested that it may be possible to overcome all of these problems by using a different heat transmission fluid, namely, carbon dioxide (CO_2). At the conditions expected for EGSs—temperatures in excess of 150°C, pressures of a few hundred bars—CO_2 is a "supercritical fluid," which means that it can exist only as a single fluid phase rather than as liquid and/or gas. CO_2 has a viscosity that is 40% that of liquid water, which means that substantially larger CO_2 volumes would flow for a given injection pressure.[17] Additionally, the pressure difference between injection and production wells makes it more likely that a CO_2 system will establish a thermosiphon effect, where pumping of wells is not required. However, at the temperature and pressure conditions of interest for EGSs, CO_2 has somewhat lower density than water so that there would be less mass transport for a given volumetric flow. Also, CO_2 has a heat capacity two-fifths that of water, meaning that a given mass flow would transport a smaller amount of thermal energy than for water. A number of studies indicate that, overall, CO_2 is superior to water as a heat transmission fluid, achieving somewhat larger heat extraction rates when the same injection pressure is applied. An ancillary benefit to a CO_2 EGS is the potential for CO_2 sequestration as precipitated carbonate minerals and feldspar to clay conversion at the fringes of a CO_2 EGS reservoir. An anticipated RDD&D challenge associated with the use of CO_2 as a working fluid lies in the likely requirement that the reservoir needs to be completely dried before CO_2 is injected in order to avoid problems associated with the formation of carbonic acid. Technologies coupling CO_2 geologic sequestration and EGSs should be pursued and developed. The vast deep sedimentary basins that are targets for sequestration can also provide geothermal heat.

Grid Integration

Geothermal as a Baseload Resource

Geothermal has traditionally been a baseload resource, operating continuously. By their nature, geothermal resources are always available and highly reliable, making geothermal the only baseload renewable energy resource other than hydropower. Unlike wind and solar energy, whose availability are constrained by diurnal and weather patterns, the production of geothermal fluids from the subsurface is always available for electricity generation. Even hydropower can be subject to seasonal restrictions or complicated by water and environmental needs, such as lack of precipitation impacting reservoir levels or downstream flow requirements/restrictions for water needs or habitat (species) considerations. Once accessed, geothermal resources can be produced continuously, regardless of surface conditions.

Despite geothermal's baseload nature, there has been concern and confusion about its reliability. Most of this stems from misunderstandings and inconsistent definitions of the "capacity factor" of geothermal resources. Often, the terms capacity factor and "availability factor" are used interchangeably for geothermal. Availability factor refers to the time that a geothermal power plant is capable of operating or generating electricity. As mentioned, the availability factor for geothermal plants is very high. Geothermal resources are capable of producing continuously, and the plants require little downtime for maintenance, resulting in availability factors of 90%–95% annually. Capacity factor refers to the actual annual generation relative to the "theoretically possible" annual generation if the power plant ran continuously year round. For geothermal, confusion arises owing to various calculations of the theoretically possible annual generation. Capacity factors are often calculated by using the nameplate generator capacity on geothermal power plants. However, geothermal power plants usually have large parasitic or operating loads, such as powering injection or production well pumps and operating power plant cycle recirculation pumps that are powered internally by the plant. These loads can use up to 30% of the power generated by the plant itself. The result is that the power delivered to the grid is small relative to the theoretically possible nameplate generation capacity, resulting in an apparently low capacity factor and leading to comments or beliefs that geothermal power plants have low capacity factors. There is no simple solution to this because the design net or target generation capacity is not a readily available number. Because geothermal plants try to maximize their net output to generate as much revenue as possible, the ability of power plants to meet their power purchase agreement (PPA) generation targets might be a better measure of the ability of geothermal plants to meet their design outputs. Another solution may be to standardize the capacity factor definition among industry and also report annual plant ability. Regardless, a need exists to analyze geothermal power plant generation reliability and how it is reported so that an accurate view of the true capacity factors of geothermal plants is possible.

Despite having a high availability factor, output from geothermal power plants can be impacted by ambient conditions. Because of their relatively low operating temperatures, changes in the ambient temperature can lower the temperature differential driving the thermal power plant and result in significant decreases in net power generation output. This is especially true for binary or organic Rankine cycle geothermal power plants that operate at the low end of the geothermal electricity generation spectrum (roughly 150°C–200°C) and rely on air cooling. During hot summer days, output from these plants can drop as much as 30%–50%, depending on operating conditions. Larger flash and steam geothermal plants are more immune to these swings because they operate at higher temperatures and are able to use some of the condensate from the turbine for water cooling (cooling towers). Research into the use of hybrid cooling (air cooling with water spray) at binary plants has been explored to increase power output during hot days. Also, hybrid plants that combine geothermal with solar thermal (concentrating solar) and/or solar photovoltaic power have been studied regarding normalizing power output over the course of the day.[18] A detailed technology assessment of these hybrid plant and cooling technologies is needed to explain the opportunity, the R&D required, and the potential impacts if the R&D is successful.

Geothermal as a Dispatchable Resource

While geothermal power plants can serve as baseload generation units as noted above, with the proper design and incentives, geothermal power can also provide either firm or flexible electricity or can be designed to form more intermittent electricity generation resources. Geothermal plants can ramp up and ramp down electricity generation output quickly so geothermal projects can provide flexibility and ancillary services. Most geothermal PPAs are designed to compensate them for baseload generation and offer no incentives for flexibility or ancillary services.[19] Further, solicitations for new renewable generation often do not account for or credit the ability of geothermal to provide these services. For example, the California Public Utility Commission mandated that integration costs not be considered when evaluating bids in its 2011 Renewable Portfolio Standard solicitation.[20] There are concerns about the risk that variable production from geothermal resources could have in terms of damage to the subsurface reservoir, but geothermal plants can be designed to continue full production from the reservoir while bypassing the power plant in part to control electricity generation. Another question is whether the benefits to the grid and potential compensation to geothermal plants for providing flexible generation outweigh lost revenue from not operating at full capacity at all times. Since geothermal plants have high up-front costs (and relatively fixed operating costs), the additional revenue from operating as a flexible generation provider must be adequate to make debt payments from plant construction and must be advantageous relative to baseload generation. The potential of using geothermal as a dispatchable resource requires R&D into the ability and cost of designing or converting geothermal plants to this type of operation (including potential impacts on the geothermal resource) and analysis into the cost benefits to both the grid and the geothermal operator under various future scenarios that include large amounts of variable or intermittent electricity generation.

Summary

Geothermal resources currently provide cost-competitive low-carbon, firm but flexible power generation in specific geographical regions. Removing technical barriers will promote increased capacity in these geographies with improved reservoir management tools and broaden the geographic footprint of geothermal power generation. “Breaking the code” to EGSs has the potential to significantly lower the risk of geothermal development, which could lead to rapid growth of the geothermal industry and create high-paying jobs that must be located where the resource exists in the United States. The research needed to advance subsurface technologies links tightly with broader “grand challenges” in subsurface science. Through fundamental science and cross-disciplinary research, geothermal power provides important motivation to strengthen the ties between basic research and technology innovation.

Currently, the geothermal industry is small and minimally capitalized. Technology advancement would be slow or even nonexistent without federal funding. Federal funding also provides critical motivation for researchers to seek applications for technology innovations in the geothermal sector. An EGS is a high-risk, high-reward proposition. In order to make EGSs a reality as a cost-competitive energy generation technology, high-risk demonstration projects with the freedom to learn through failure are necessary. DOE has funded a portfolio of demonstration sites in recent years that have provided important lessons and have led to the first electricity delivered to the grid in the United States from an EGS. DOE is currently embarking on a large-scale field observatory to push EGS technology even farther. FORGE will be a dedicated field site to test high-risk technologies and make vast amounts of data openly available to promote innovation.

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Glossary and Acronyms

3D	Three-dimensional
4D	Four-dimensional
Binary cycle	In geothermal, a turbine cycle employing geothermal energy to heat a separate working fluid (binary fluids) for power production.
CO_2	Carbon dioxide
DOE	U.S. Department of Energy
EGS	Enhanced geothermal systems
Flash cycle	In geothermal, a sudden extreme lowering of the pressure of the geothermal fluid, causing some of the hot liquid to rapidly vaporize, or “flash” into steam.
FORGE	Frontier Observatory for Research in Geothermal Energy
GEA	Geothermal Energy Association
GWe	Gigawatt electric
Induced seismicity	Seismicity that is induced by manmade activities such as fluid injection, reservoir impoundment, mining, and other activities.
InSAR	Interferometric synthetic aperture radar
LIDAR	light detection and ranging
MW	Megawatt
MWe	Megwatt electric
mW/m^2	Milliwatt per square meter
NASA	National Aeronautics and Space Administration
PPA	Power purchase agreement
Rankine Cycle	A standard power generation cycle that makes use of a liquid-vapor phase transition of the working fluid to achieve higher efficiencies.
R&D	Research and development
RDD&D	Research, development, demonstration, and development
REE	Rare earth elements
Sedimentary facies	Different, but contemporaneous and juxtaposed, sedimentary rocks.
Stimulation	In geothermal, defined as activities that are undertaken to increase the permeability in a targeted subsurface volume via injecting and withdrawing fluids into, and from the rock formations that are intended to result in an increased ability to extract energy from a subsurface heat source (examples would be fluid pressurization, hydrofracture, chemical stimulation, etc.).

Strategic chemicals	(aka Strategic Minerals, aka Critical Minerals) is a broad-based category that constitutes various minerals and elements; the majority of which are minor metals. Geography and availability of domestic supply often defines which minerals are deemed "critical" for any particular region or country.
SubTER	Subsurface Technology and Engineering Research, Development, and Demonstration
USGS	United States Geological Survey
Wireline coring	Retrieving a cylindrical sample of rock or “core” from the center of a wellbore
Zonal isolation	Methods used to stimulate individual areas of the reservoir or “zones” while bypassing other zones.