Tackling Climate Change in the U.S.

Potential Carbon Emissions Reductions from Geothermal Energy by 2030

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The Oregon Institute of Technology has been using a geothermal district heating system since 1964. The system heats 11 buildings (600,000 square feet), provides domestic hot water, melts snow on 2300 square feet of sidewalk, and cools five buildings (277,3000 square feet) during the summer. The district heating system saves about $225,000 each year in heating costs compared to the previous fuel oil boiler system.

The scale of stored geothermal energy is so much larger than current demand that even very low geothermal energy recovery could offset a substantial fraction of today's fossil fuel demand.

There is a vast resource of geothermal energy stored as heat in water and rock strata at drillable depths of about 2 to 6 miles (3 to 10 kilometers [km]) within the earth. Hot water and steam do flow naturally to the surface through fractures, vents, and other high-permeability features, and those resources can be put to use. But these make up a few fortunate cases and are rarely of a high capacity or of the energy intensity needed to economically convert thermal energy to electricity.

There are also geothermal reservoirs throughout the world that have relatively high permeability and contain fluids at shallow depths that are tapped to extract steam or hot water to "mine" geothermal energy for electric power generation. These reservoirs are termed "hydrothermal convective" systems, and some can produce power at costs that compete with conventional energy sources. These, too, are a limited set of resources that offer recoverable heat to satisfy part of the United States' energy demand.

However, an overwhelming proportion of sources of geothermal energy reside in the stored thermal energy contained in rock systems that are uneconomic to tap because of depth, relatively low permeabilities, or lack of water as a carrier fluid for the heat energy. Research sponsored by the U.S. Department of Energy (DOE) seeks to greatly expand the competitive potential of geothermal power generation. A long-term goal is to develop Enhanced Geothermal Systems (EGS) for energy recovery. EGS technology offers ways to overcome these limitations, but such resources are not yet viable as heat mines to provide energy at competitive prices.

The Geothermal Resource

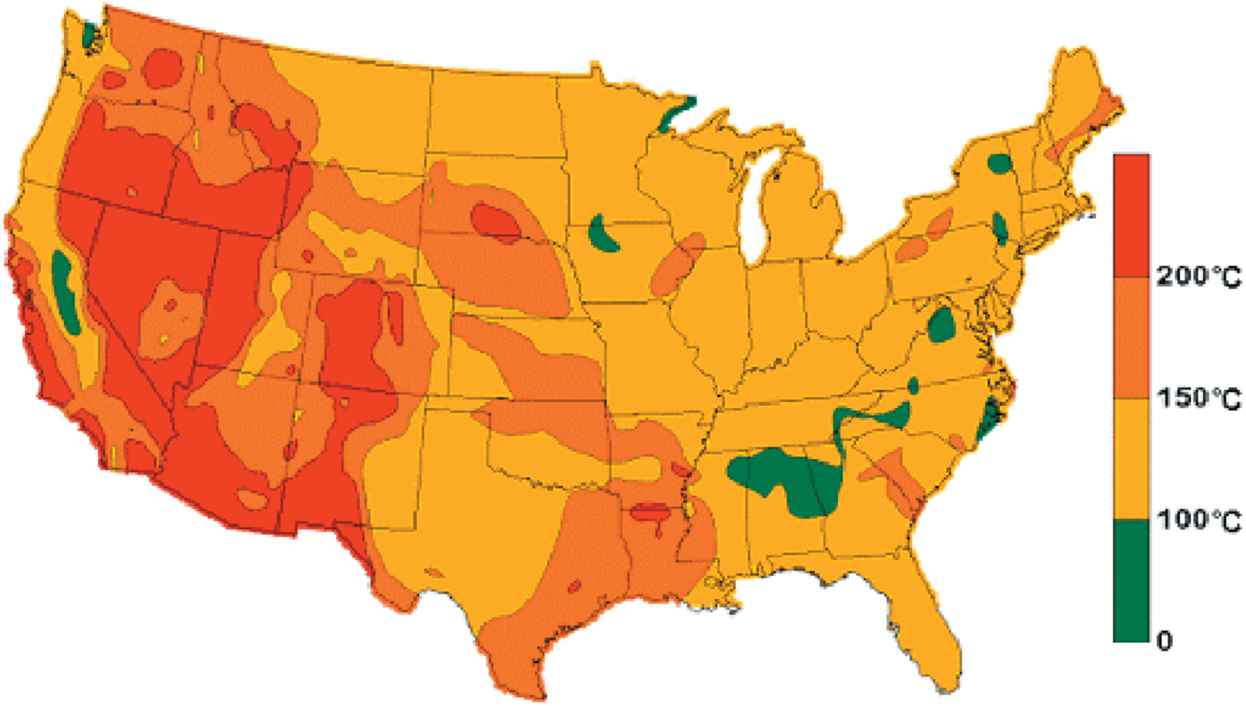

Figure 1: Geothermal Temperatures at 6-Kilometer Depth

The geothermal resource in the United States is geographically diverse, as measured by distributions of temperatures at various depths. Figure 1 illustrates this in a map of geothermal temperature contours at a depth of 6 km.[4] Table 1 lists estimates of energy distributions as total stored thermal energy, or total heat-in-place.[2]

As listed in Table 1, the energy content stored at 3 to 10 km depths in U.S. geothermal resources is vastly greater than the national annual energy demand. For example, DOE Energy Information Administration (EIA) [5] reports that in 2003, the total U.S. energy demand accounted for about 98 quads, of which 84 quads were from fossil fuel sources, while the geothermal resource storage is about 14 million quads. (1 quad = 1 quadrillion British Thermal Units [Btu] = 1.06 exajoules [1E18 joules]) This is reassuring, in that the scale of stored geothermal energy is so much larger than current demand that even very low geothermal energy recovery could offset a substantial fraction of today's fossil fuel demand. The sum of stored energy-in-place plus steady-state conduction upward from earth's core could sustain foreseeable geothermal energy withdrawals over very long time periods. And geothermal energy offers deep cuts in the very large rates of emissions of carbon dioxide and other greenhouse gases (GHGs) produced by burning fossil fuels to generate electricity. Ultimately, opting to develop geothermal energy sources would virtually eliminate the GHG emissions for every unit of offset fossil fuel.

TABLE 1:
Estimates of U.S. Geothermal Resource Base
Total Stored Thermal Energy Content*
Tester et al. [2]

Resource type	**Heat in Place at Depth = 3 to 10 kilometers (Expressed as 1,000 quads)**
Hydrothermal (vapor and liquid dominated)	2.4 - 9.6
Geopressured (includes hydraulic and methane energy content)	71 - 170
Conduction-Dominated EGS (depths of 3 to 10 km, above ambient surface temperature)	
• Sedimentary EGS (or "Associated EGS," at margins of hydrothermal fields, showing reduced permeabilities)	> 100
• Basement EGS	13,900
• Supercritical volcanic EGS	74
TOTAL, all sources	**~ 14,200**

* Thermal energy of co-produced fluids is not included in these resource estimates—see Tester.[2]

But the challenge of making productive, economic use of geothermal energy lies in its site-specific recoverability—or lack thereof. By contrast, we are bathed in our renewable wind and solar resources—"access" to those resources is not a problem. The economic challenges of using solar and wind resources lie with their conversion and storage technologies.

Economic challenges for geothermal energy differ substantially. The technologies for converting thermal energy to electricity are long proven, and energy storage is not an issue—in fact, the energy is already in storage awaiting extraction. The challenge for competitive, commercial scale geothermal energy recovery for power generation lies in the risks related to access and extraction from remote resources within the earth's crust. Although reaching depths of interest does not pose a technical limitation using conventional drilling methods, there is significant technical and economic uncertainty surrounding site-specific reservoir properties (permeabilities, porosities, in-situ stresses, etc.), and the challenges of stimulating sufficiently large and productive reservoirs and connecting them to a set of injection and production wells. Resolving these challenges will in large part determine the amounts of the vast quantity of earth's stored thermal energy that can be economically recovered. Given the large potential of geothermal, the proportional payback for research and development (R&D) gains is huge.

To illustrate the magnitude of this opportunity, Figure 2 shows a geographically averaged distribution of potentially recoverable thermal energy stored in EGS resources at particular depth intervals to 10 km.[2] This is a depth-wise integration of heat stored in the earth, as represented for a single depth slice to 6 km shown in Figure 1. The nonlinear behavior reflects the fact that temperature, a measure of thermal energy content, increases with depth. Considering the geographic dispersal of temperature gradients shown in Figure 1, this demonstrates a broad variability of site-specific depths at which cost-effective resource temperatures will occur. Energy content in reservoirs shallower than 3 kilometers is a small fraction of the 14 million quads estimated to lie between 3 and 10 kilometers.

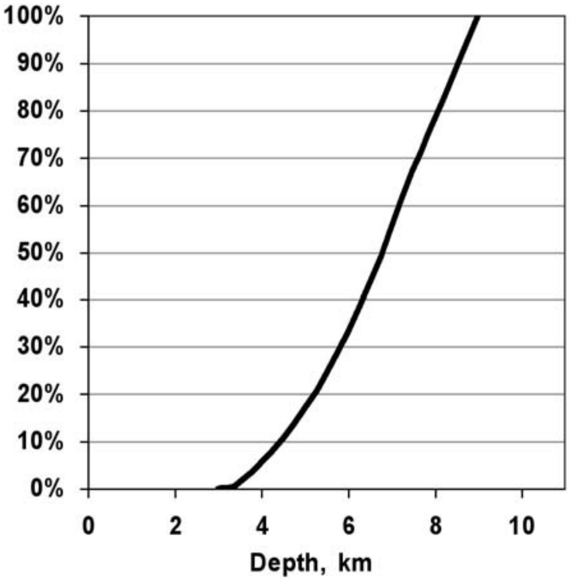

Fig 2: Recoverable EGS Energy Distribution with Depth

As listed in Table 1, less than 0.1% of the total geothermal energy lies in these typically shallow hydrothermal systems. Although these hydrothermal systems are not discernable on the scale used in Figure 2, they are often characterized by sufficiently high permeability and water content values that allow economic heat recovery in today's energy markets. Nearly 99% of the heat-in-place across the 3 to 10 kilometer horizon resides in reservoirs characterized as sedimentary and basement EGS resources that require stimulation to be productive. Some EGS reservoirs will be relatively more economic than others, depending on local reservoir productivities and capital costs for drilling, stimulation, and energy conversion. By definition, though, they will require some technological advances to be competitive. Additionally, the integrated heat content represented in Figure 2 spans a range of temperatures from which only a part of the available energy would be economically convertible to electricity. This is a function of depth. Thus, drilling to depths greater than 3 kilometers is an inevitable factor in determining site-specific power feasibility.

DOE research into advances needed to foster EGS development assigns goals that fall into four categories, in order of potential impact—reservoir stimulation techniques to produce heat from large volumes of rock; drilling technology to access difficult geothermal zones; energy conversion efficiencies; and exploration. Success of research toward technology development is essential in all four areas to bring large new resources into economic play.

R&D is likely to yield several advantages. First, advances in exploration technology can reduce the risk of positively identifying resources of commercial temperatures and recoverability characteristics. Second, drilling advances will make it possible to access resource temperatures at greater depths and in tougher conditions than are economically competitive today. Third, stimulation is a key technique for enhancing reservoir productivity and lifetime, by increasing connectivity between sets of production and injection wells. This amounts to structurally increasing reservoir permeabilities on a large scale to raise fluid flow rates and heat recovery values. Fourth, conversion advances will use resources more efficiently and at reduced production temperatures, which will both raise thermodynamic efficiency and allow fewer and shallower wells to be used. Combined gains in all four improvement areas will result in fewer, shallower, or cheaper wells than current technology, reducing capital and operating costs per megawatt (MW) of generation.

Stimulation is conceptually and mechanically simple. First apply pressure to wells in low-permeability rock formations to induce rock fracturing, then optionally introduce corrosive chemicals and proppants (materials that hold open cracks) to "prop" open new flow paths. A combination of stress and chemical etching may preferentially open flow paths connecting sets of multiple wells. Then a fluid for carrying heat from the reservoir—water—can be pumped down injection wells and withdrawn from production wells, moving heat to the surface for energy conversion.

Hydraulic stimulation has long been successfully demonstrated in oil and gas production systems. But it is not yet proven for geothermal systems in long-term applications at commercially high flow rates and heat recoveries.

The energy content stored at 3 to 10 km depths in U.S. geothermal resources is vastly greater than the national annual energy demand.

Potential for Power Production

A group of 17 geothermal technology specialists recently performed a study of the potential of enhanced geothermal systems on behalf of the DOE Geothermal Technology Program (the Program). That work occurred under the auspices of the Massachusetts Institute of Technology (MIT).[2] A pending report on the work updates data on EGS resources in the United States and provides contemporary estimates of technology performance and economics.

The U.S. geothermal power industry operates power plants predominantly in the West, with a nominal installed capacity of about 2,800 MW.[6] The industry uses hydrothermal resources. Geothermal power systems are best suited to base load operation. They can operate over a modest range of turndown, but as with most technologies that rely on large thermal mass throughput other than internal combustion engines, geothermal plant economics favor steady-state operation at near-full-load.

Significantly, the pending DOE report estimates that 2% of the energy in U.S. Enhanced Geothermal Systems (EGS) reservoirs could be recovered as electricity with current stimulation, drilling, and energy conversion technologies. However, the technologies do require advances to cut costs. The study updated estimates of available work and power potential. The in-place energy estimates are integrated from spatial temperature and depth distributions across the U.S.[4] At the 2% recovery level, the study projects that 2.4 terawatts might be generated over a long-term timeframe.

For a mid-term range of four to five decades, the study concludes that a recovery rate of 100 gigawatts (GW) may become feasible. The 2% recovery factor was derived from a starting estimate of 40% thermal energy recovery as a theoretical limit. As a conservative measure, that estimate was reduced to account for practical problems of implementation consistent with field development experience seen not only in the geothermal field, but also in the oil and gas industry. In practice, recovery will be reduced by factors including (but not limited to) flow channeling in a reservoir; failures to maintain initial permeability gains; and long-term changes in flow patterns affecting flow and heat recovery. All such effects would limit heat recovery, though with time and experience they may be overcome. These conservative assumptions are needed to account for cost impacts of uncertainties that are inherent to EGS stimulation technology as an immature discipline.

Temperature differentiates geothermal resources, and energy conversion options play a significant role in power economics as a function of temperature. At temperatures below about 200oC, binary power systems are favored for relative cost effectiveness. The term "binary" connotes dual-fluid systems, wherein hot geothermal brine is pumped through a heat exchange network to transfer its energy to a working fluid driving a power train. The power train is a closed-loop system that transfers heat from the geothermal brine to the working fluid, then adiabatically evaporates and expands the fluid by mechanical energy recovery (driving a turbine/generator set) and re-condenses the fluid by rejecting waste heat outside the system. The working fluid can be from a family of hydrocarbons—a homologous series including butanes through heptanes, for example. Ammonia has also been tested as a working fluid. A key goal of research in binary systems is to increase conversion efficiencies and improve conditions at which the waste heat can be rejected. In general, above about 200oC, the economics of energy conversion begin to favor flashing geothermal fluids to produce steam, and directly driving turbine/generator sets with the steam.

WGA Estimates of Short-Term Power Production Potential

The Western Governors’ Association (WGA) sponsored a recent study entitled "The Clean and Diversified Energy Initiative."[1] The study addresses growth scenarios for renewable energy sources, as specifically affected by economics and policy. It views renewable energy sources both in competition with and as complementary sources to advanced fossil fuel sources.

A task force of specialists in geothermal power evaluated geothermal power prospects for a 13-state region of the western U.S. over the next 20 years, with a target milestone in 2015. The geothermal task force reported industry-based estimates of prospective power projects in the WGA states. They project that there could be about 5,600 MW of new geothermal capacity within ten years, at wholesale power costs of up to about 8 cents per kilowatt-hour (kWh). Energy costs were estimated as "busbar" values and given as 15-year levelized cost of energy (LCOE) figures.

The WGA task force considered only hydrothermal systems, and they estimated commercialization costs assuming the use of current technologies. The WGA projection assumed that most of the target systems would use binary energy conversion systems.

Table 2 lists the respective state capacities for new hydrothermal power development by 2015. The task force developed a supply curve shown in Figure 3 to illustrate these potentials. It categorizes a range of short-term potential increases in geothermal generating capacity as a function of energy cost, both with and without an incentive of a production tax credit as included in the Energy Policy Act of 2005 (EPACT 2005). The costs are levelized constant-dollar values for the financing terms listed on the chart.

Finally, the geothermal task force considered additional conventional hydrothermal potential that members estimated might also be developed, either in the next 20 years or sooner if market power prices rise. This 20-year potential could bring the total geothermal growth to about 13,000 MW. This is consistent with historic resource estimates for known hydrothermal systems, predominantly in the West.

Table 2:
Projected New Hydrothermal Power Capacities in the Western U.S. through 2015 (1)

States	Capacities (Megawatts)	Sites
Alaska	20	3
Arizona	20	2
Colorado	20	9
California	2,400	25
Hawaii	70	3
Idaho	860	6
Nevada	1,500	63
New Mexico	80	6
Oregon	380	11
Utah	230	5
Washington	50	5
TOTAL	**5,630**	**138**

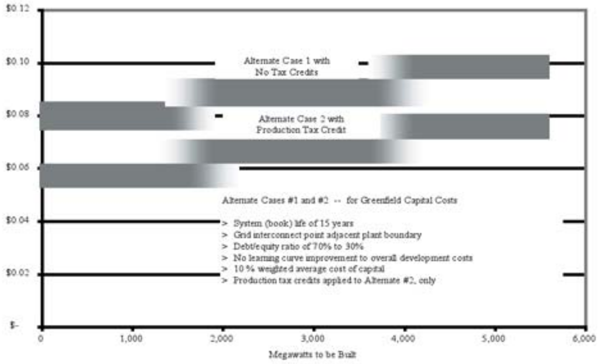

Figure 3: WGA Supply Curve for Geothermal Power Generation, Alternate Cases, LCOE versus Cumulative Generating Capacity, 2005 real dollar basis

Table 3 summarizes DOE estimates [7] of current and future greenfield (i.e., new sites and resources) geothermal power project costs from the Multi-Year Program Plan. The economics of geothermal technologies spans disciplines ranging from geologic exploration to reservoir development, to well drilling and wellfield construction to thermal energy conversion. Present-day LCOE estimates range from 8.5 to 29 ¢/kWh, assuming current binary energy conversion technology is used in hydrothermal and EGS developments. The progressive reductions in LCOE values listed in Table 3 reflect DOE's estimates of impacts of the R&D achievements of the Geothermal Technologies Program.

Table 3:
Estimated Generation Costs from 2005 MYPP Reference Cases (6) (2005 U.S. Constant Dollars)

	Hydrothermal Binary	EGS Binary
Reference Case Bases		
Reservoir Temperature ºC	150	200
Well Depths, feet	5,000	13,000
LCOE as ¢ per kWh		
LCOE -- as of 2005	8.5	29
LCOE -- as of 2010	4.9	
LCOE -- as of 2040		5.5

U.S. geothermal power capacity is dominated by systems using relatively shallow hydrothermal reservoirs and producing steam or flashing brine for energy conversion. DOE research focuses on technology opportunities in exploration, reservoir stimulation, drilling, and energy conversion. Research advances in these areas will empower industry to transition toward a larger pool of resources. The improvements will yield performance gains, improved reliability, and ultimately, reduced unit costs.

The R&D goals aim toward using binary conversion systems at temperatures down to 125 to 150ºC in conjunction with well depths to 4 km (13,000 feet). The goal of the combined temperature and depth values is to expand the resource base for power generation. By comparison, binary systems in use now generally have well depths of a few thousand feet, and they accommodate temperatures marginally below about 200ºC. As shown in Table 3, R&D goals address hydrothermal systems using binary conversion, approaching a Program goal of 5¢/kWh in a near-term of 2010, and in a longer-term timeframe for EGS binary systems around 2040.

The preceding observations describe DOE goals for technical and economic advances by their impacts on what it costs to generate electricity. This is in a context of resource development projects. How, then, do we relate this economic impact of research at the project level to a larger picture, for example, in terms of the U.S. energy economy?

Figure 4 is a current example of a supply curve that has been used to test in-market penetration computations using the National Energy Modeling System (NEMS). NEMS evaluates competing energy resource and technology development impacts in the national energy market. Assessments of resource characteristics and technology economics provide power supply curves as energy cost—LCOE— versus cumulative installed capacity.[7] The upper dashed curve in Figure 4 uses current-technology economics based on 2004 year-end values. The lower curve incorporates DOE research benefits in the form of advances to the technology status.

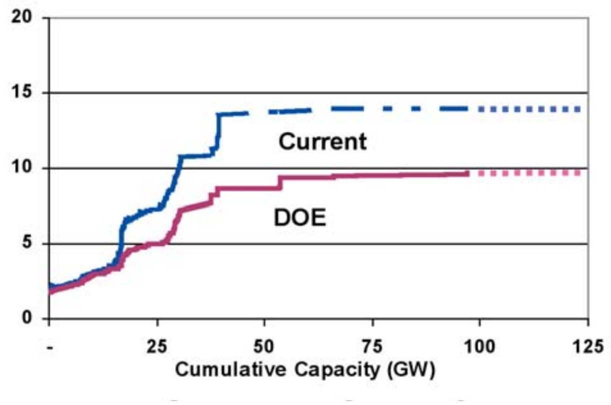

Figure 4. Geothermal Supply Curves

These supply curves were constructed as input to NEMS to provide energy costs for a pool of resources up to the 100 GW estimate that the MIT study [2] projected for development by 2050. NEMS estimates forward economic trends 25 years out. The resources total about 100 GW of new capacity distributed in four resource categories:

• Hydrothermal	27 GW
• Sedimentary EGS	25 GW
• Co-produced fluids	44 GW
• Basement EGS	4 GW

This calculation gives a basis for comparison with the NEMS calculations of potential market penetration, discussed below. As indicated by dashed lines at the right boundary of the plots in Figure 4, the resource capacities are estimated to be larger at the price thresholds indicated.

The hydrothermal resource estimate of 27 GW is consistent with a long-standing capacity originally published in the U.S. Geological Survey Circular 790 (1978). The sedimentary EGS category represents resources at the margins of known hydrothermal fields. They are expected to exhibit reduced permeabilities that will require stimulation to achieve economic productivity. Numerous references [2][7] cite oil and gas fields that generate "co-produced" water at temperatures sufficient for power generation with both state-of-the-art and improved conversion technologies. Basement EGS resources are assumed to have very low permeabilities and/or low water content. This category exemplifies resources with high degrees of uncertainty as to their economic viability. It is a small component in this case study but, in terms of both cost and quantity of recoverable energy, basement EGS is where stimulation and drilling research offer their greatest dividends.

Altogether, this input set of resource capacities is a very small fraction of the in-place geothermal potential. The resources are selected from a database, including those by Blackwell [3] and others, of temperature and depth information, and assigned estimates of potential productivities.[7] This provides best-cost prospects for a 100-GW resource pool used as a database for NEMS modeling.

The NEMS results project that success in the DOE research goals could result in a competitive, national geothermal power capacity of around 50 GW by the year 2030. Omitting the benefits of the DOE research program, geothermal power was projected at a level of 30 to 35 GW in that timeframe.

Therefore, one answer to the above question of what relationship DOE research goals have to the U.S. energy economy is that NEMS predicts that the economy will have a capacity and cost structure that would support 50 GW of new geothermal power generation by 2030, or half of the 100 GW projected for 2050 by Tester et al.[2] Furthermore, by contrasting cases that both discount and give credit for technology contributions by DOE research programs, NEMS shows that the benefits of DOE research gains may add 15 to 20 GW of energy development capacity in the 2030 timeframe.

Infrastructure Performance and Emissions Indicators

A large increase in geothermal power generated in the U.S. energy sector would proportionally offset fossil emissions. Here are data from the EIA that yield the estimates of emissions reduction on the next page.[4]

In 2004, total U.S. fossil fuel use for power generation plus combined heat and power (CHP) was stated as fuel consumption and net power output, as follows. The data suggest that the CHP component of the fossil demand is in a range of 5% to 10% of the total. (While the focus here is on geothermal power, a synergy of geothermal heat in CHP applications also offers major potential benefits to overall energy supply.)

• coal	1.0 billion tons per year 2.0 billion MWh (megawatt-hours)
• petroleum	210 million barrels per year 0.1 billion MWh
• natural gas	6.1 million MSCF (thousand standard cubic feet) per year 0.7 billion MWh
• other gases	190,000 MBtu (million British thermal units) per year 0.02 billion MWh
• total output	2.8 billion MWh per year

As context for the above values in terms of overall U.S. fossil fuel demand in 2004, EIA reports:

- total fossil fuel consumption—86 quads per year
- fossil use for power generation—28 quads per year or 33% of total fossil fuel use
- coal consumption for power generation accounted for generated power as 50% of total watt-hours and 70% of fossil-fueled watt-hours.
- coal-fired power plant capacity—335 GW (nameplate) with indicated 67% capacity factor.

Assuming a target capacity factor of 90% for geothermal power plants, [1] the coal-fired generating capacity could be replaced by geothermal plants with nominal capacities totaling about 250 GW. This evolution could offset fossil fuel demand by about 20 quads, accounting for 23% of the 2004 U.S. total fossil fuel consumption.

Robb Williamson/NREL

Interior of geothermally heated greenhouse in New Mexico with radiant floor heating, flood irrigation, and overhead curtain for light control.

EIA also reports emissions resulting from fossil fuel combustion for electric power and combined heat and power systems for 2004, as follows:

- 2300 Mt of CO_2 (carbon dioxide) (equivalent to 620 MtC) of which 82% was from coal
- 10 Mt of SO_2 (sulfur dioxide)
- 4 Mt of NOx (nitrogen oxides)

The levels of emissions from geothermal power plants are striking when compared to fossil combustion systems. Table 4 lists information from the Geothermal Energy Association [5] that compares the relative rates of discharge in what?? per MW of capacity for flashed-steam geothermal power and fossil power plants.

Table 4:
Relative Flashed-Steam Power Plant Emissions[5] per megawatt of capacity

	CO_2	NOx	SOx
Fossil	24	4,000	11,000
Geothermal	1	1	1

Flashed-steam systems vent a noncondensable gas stream from their condenser systems. That stream will typically comprise most of the gases naturally occurring in geothermal fluids (except for hydrogen sulfide, which is aggressively scrubbed from the emissions). Carbon dioxide is usually the dominant gas in geothermal fluids, and it is the principal combustion product of fossil power plants. Steam-driven geothermal power systems will typically exhaust about 4% of the CO_2 mass flow of a fossil plant, per equivalent MW of power output.

Significantly, binary systems achieve almost 100% elimination of the gas emissions because the plant systems are closed-loop processes, returning all geothermal fluids—gas and liquid—to the resource.

Figure 5 depicts annual carbon emissions offsets if geothermal power were to progressively displace fossil fuels used for electrical power generation systems, up to the 50 GW capacity that NEMS projects could be competitive by 2030. The upper, solid line represents a CO_2 reduction equivalent to replacing coal-fired power sources. This is reasonable as a replacement fuel basis because both geothermal and coal-fired power plants are optimally designated as base load power generators. The comparison uses capacity factors of 67% per the EIA [5] and 90% per the WGA report [1] for coal and geothermal systems, respectively.

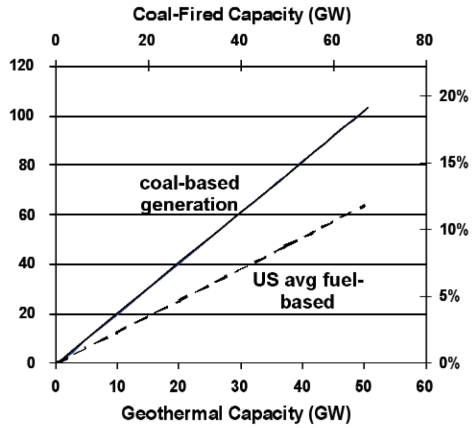

Figure 6. Carbon Emissions Displaced by Geothermal Power

Alternatively, to apply a common fuel basis to compare CO_2 emissions reductions by geothermal sources with other renewable energy technologies, the lower, dashed curve in Figure 5 is based on the U.S. national average fossil fuel heating values and carbon content for power generation. While this fuel equivalence puts the renewable energy sources on a common emissions reference basis, it is more suitable to non-baseloading energy technologies such as solar and wind power systems. These two technologies are likely to offset a higher proportion of peaking-power sources, driven by lower-carbon fuels such as natural gas, than would geothermal sources.

The projected 50 GW geothermal capacity is roughly equivalent to 70 GW of coal-fired power plants, per the EIA database. This CO_2 reduction assumes using binary conversion systems with near-zero carbon emissions. If the equivalent fossil displacement were achieved by flashed-steam geothermal systems, average carbon reductions would be about 96% of the values in Figure 5. As noted in the preceding section, in 2004 there were 335 GW of coal-fired generating capacity in the United States. If geothermal energy achieves still higher, long-term offsets of coal-fired power capacity, that would further reduce carbon emissions in direct proportion.

Challenges and Opportunities

Even among those who work in the geothermal industry, these positive technical and economic assessments of energy recovery and power generation potentials leave us faced with a key question—"Why isn't there already more development of geothermal resources for large-scale power generation?" Not unsurprisingly then, people outside the geothermal community would undervalue or even ignore its potential.

There are many elements that provide answers to this important question. And they all underscore the need for intensive and long-term research to improve the four key technology areas cited above—exploration, reservoir creation via stimulation, drilling, and energy conversion.

Risk is a most basic, common hurdle to geothermal power growth in the U.S. energy sector. Risk is both a simple, real technical factor in regard to finding a cost-effective resource to develop, and it is a management barrier to commitment of funding at a predictable and competitive return on investment. This simple statement belies the complexity of risk-based limits on funding for resource exploration, engineering development, market (buyer) commitment, and commitment before-the-fact to installing transmission capacity for new power plants to access their prospective markets.

A number of focused technical issues contribute to the real and perceived risks.

Lack of formation water. Geothermal resources are most economical in geologic formations of high permeability that favor flow of water. A worst-case reservoir scenario is absence of water or just very low flow rates. Exploration and development are done to target productive geologies, and to build out from proven productive zones by following trends of permeability and/or enhancing permeability by stimulation. This exemplifies how EGS technology will work in practice. Risk is reduced by starting at productive sites and expanding to bring less productive zones into play. Lack of naturally contained formation water is not a primary barrier. In practice it will be reduced or eliminated by applying EGS stimulation technologies.

Loss of water via cooling. Thermal fluid-driven power systems, such as geothermal technology and most fossil-fueled systems, will work most efficiently using evaporative water cooling. In the arid western U.S. that is a disadvantage because of relatively high rates of evaporation there. For geothermal systems deployed in the arid west, it is a dual problem, because cooling water is hard to come by, both economically and environmentally. And failure to return all or most of the groundwater produced for geothermal power will often lead to production decline.

Using dry cooling systems can mitigate evaporative water losses, but they are typically more costly to build and operate than evaporative systems, and they reduce energy conversion efficiency. This is an area of ongoing development, both in industry and DOE research programs.

Elimination of water as a prime mover fluid to recover heat from geologic formations could be an answer to both lack of formation water and cooling system water losses. A potential solution now in early stages of investigation might substitute supercritical carbon dioxide for water as a reservoir heat transfer fluid. Similar to the circulation of water through the reservoir, CO_2 could be compressed and liquefied at the earth's surface and pumped into a geothermal reservoir for heat recovery. The CO_2 could be returned in a supercritical state to the surface via production wells, where it could drive energy conversion systems. This is a long-term development prospect, with significant practical and economic challenges. If it proves physically possible to sustain this application, it could have ramifications in CO_2 sequestration, providing a significant technological synergy with combustion systems.

Induced seismicity. Injecting and producing geothermal water or steam from hydrothermal and other geologic formations frequently is accompanied by microseismic events. Monitoring and managing seismic activity would be required to ensure stable long-term operation. Predicting and detecting seismic behavior falls under the technology of exploration and reservoir assessment and necessitates gathering and evaluating data from producing geothermal systems.

Drilling and reservoir stimulation. As shown in Figure 2, energy stored in the earth increases with depth, and permeability is widely variable. The costs of wells make up a major component of the cost of geothermal power. Therefore, the economics of risk can be directly tackled by focusing development R&D on improving the technologies of drilling and stimulating geologic permeability.

Expanded geothermal development clearly carries high potential and a set of challenges. Addressing these challenges is tractable but will require a modest investment to support research and early deployment to reduce risk and uncertainty to acceptable levels. Such investment parallels that needed for other types of renewable energy sources.

Why isn't there already more development of geothermal resources for large-scale power generation?

Conclusions

Resource capacities, technologies, and environmental benefits of geothermal energy are expected to advance markedly in coming decades. In a near-term timeframe of about 2015, up to 5.6 GW of new electric generating capacity may be developed using high-grade hydrothermal resources in the western United States, based on current technologies and anticipated busbar costs of up to 8 cents per kilowatt-hour (¢/kWh). Up to 13 GW is projected for development within 20 years, or sooner if market energy prices rise.

Research sponsored by the U.S. Department of Energy (DOE) seeks to greatly expand the competitive potential of geothermal power generation. A long-term goal is to develop EGS for energy recovery. EGS resources may become economically viable, depending largely on the success of engineered enhancements to reservoir productivity and drilling advances. An independent assessment of EGS technology funded by DOE [2] studies the potential for EGS technology to add 100 GW of U.S. generating capacity by 2050 (100,000 megawatts [MW] or 0.1 terawatt [TW]). The study presents a tractable approach to achieve this goal with R&D and deployment support from government and private sectors. Based on the methodology presented in that study, an ultimate sustainable potential of 2.4 TW is technically possible, using conservative heat recovery factors. In that range of capacities, long-term geothermal energy development could offset a significant fraction of fossil-fueled power generation in the U.S. Therefore, adopting geothermal power on this larger scale could also displace much of the 2.3+ billion metric tons per year of carbon dioxide emitted by conventional fossil-fired power sources in the U.S. today.

Finally, in a third estimate by the National Renewable Energy Laboratory (NREL) using supply curve data by Petty [3] in the NEMS, the U.S. electric sector was projected to call for geothermal power generating capacity of up to 50 GW by 2030.

Including geothermal as an option for base load electricity for the U.S. complements other renewable sources such as wind and solar as well as nuclear alternatives to fossil fuels and can contribute to mitigating climate change.

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The conclusions presented in this work are the authors' and do not necessarily reflect DOE or NREL policy.

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Resource and economic information cited here reflect historic sources, industry projections, and ongoing studies under the Geothermal Technology Program of the DOE.

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