An Assessment of Engineered Geothermal Systems for Water Management and Power Production

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Keywords

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ABSTRACT

This study presents a methodology to assess the economics of co-locating Engineered Geothermal Systems (EGS) with existing coal fired electrical plants to mitigate process water management and produce additional power. Fifteen coal plants in areas with geothermal gradients greater than 86 °F per 100 feet (30 °C/km) were identified and assessed based on resources and data quality. Five sites were further analyzed: Mountaineer Power Plant (West Virginia), North Valmey Generating Station (Nevada), Colstrip PPL (Montana), Cayuga Generating Station (Cayuga, New York) and Danskammer Generating Station (Newburgh, New York). Using the Geothermal Electricity Technology Evaluation Model (GETEM), site specific cost models were based on key constraints: temperature gradient, reservoir injectivity, and water availability. A detailed description of the geology, reservoir conditions, and power production system designs used to calculate the cost models is attached as an Appendix. These models were used to study improvement of the Levelized Costs of Electricity (LCOE) achieved both by reaching higher temperatures at greater depths and improving reservoir injectivity by stimulation.

Project economics were best at coal plants in the western U.S. where higher geothermal gradients exist. However, these sites usually have limited water, which could limit the scale of geothermal developments possible. Sites in the eastern U.S. generally have larger amounts of process water and could support larger scale developments, but they also would have larger associated well field development costs. Technologies to improve binary plant efficiency and reduce drilling costs would make eastern U.S. sites more competitive within the current electricity market. The study illustrates that developing EGS to produce cost competitive electricity and mitigate process water effluence is feasible in most locations given favorable stimulation results.

Introduction and Background

An Engineered Geothermal System (EGS) enables economic production of electricity using geothermal heat in geologic settings with little or no natural permeability rocks. Management and disposal of process water at existing coal-fired power plants and coal mines is an ongoing challenge for many energy companies. This report presents a feasibility study assessing the use of waste water produced via traditional power production to create, charge, and operate an EGS resevoir. The goal of this process would be improved waste water disposal while generating baseload renewable energy.

Accessibility to water is often one of the larger cost issues when developing an EGS. At The Geysers geothermal fields in California, one of the largest geothermal regions in the world, municipal wastewater is already being injected into a conventional geothermal reservoir to great effect, stabilizing production decline that had been caused by insufficient fluid recharge. Presently, coal mines and coal fired power plants produce large amounts of water which may require treatment. These wastewaters may be an economic impediment to the continued operation of coal fired power plants across the country. Given the right regional temperatures at depth, these process waters could be transformed from an economic and environmental liability to a renewable energy source.

For example, the coal-fired power project and associated mining operation at Colstrip, Montana generates between 80-120 million gallons per year of waste water from emissions-controlling wet scrubber operations, mine dewatering, and surface run-off. This process water is stored in ponds and disposed of through evaporation. However, not all the annual waste water produced can be evaporated in some years, resulting in net accumulation of the excess water. The evaporation process also leaves a concentrated brine and sludge that also requires disposal. In high rainfall or low evaporation years, the disposal system may be stretched far beyond its capacity. Exploratory drilling near Colstrip found a temperature of 210 °F (97 °C) near 8900 feet below ground surface (bgs). This temperature gradient of about 1.85 1 ft (33.7 °C/km) is higher than commercial EGS projects now being developed in Europe.

Therefore, Colstrip appears to be a location where EGS-based electricity might be developed with produced water while both safely disposing the process water and providing additional baseload power. This study sought to identify additional sites where waste water might be used to develop EGS, critically assess the conditions needed to produce that power, and determine a Levelized Cost of Electricity (LCOE) for that renewable power. The goal of the study is to assess the feasibility of developing EGS as a cost-effective waste water disposal method that could also generate revenue for traditional industries with excess waste water.

Study Objectives and Scope

The total extractable geothermal heat in the United States utilizing EGS has been estimated to be over 200,000 exajoules (EJ) – about 2,000 times the primary energy consumption in the United States in 2005 (MIT, 2006). In electrical terms this amounts to roughly 1 terawatt (TW) of baseload generation operating for 1000 years. Demonstrating the ability to cost effectively access this heat in various geologic settings is the key to unlocking this disruptive fuel source. Another barrier is the quantity of water needed to initially stimulate and charge the resource (estimated at 20-100 million gallons per 6-18 MW), and additionally the makeup water needed for ongoing operation of the EGS system (1-5% per year). Process water management could provide a business driver to encourage EGS development.

The objective of this study is to test the technical and economic feasibility of using EGS to manage waste water while generating power. The study's tasks are:

- Identify locations where there is a confluence of produced water sources with elevated average thermal gradient areas of the United States.
- Select the 5 best locations in diversified geographic and geologic settings.
- At each selected site determine the size of an EGS system that would be needed to completely dispose of the excess waste water, putting it to a beneficial use.
- Estimate the LCOE and total cost of a combined waste water based EGS and binary power plant in locations with favorable conditions.

Methods

Resource Identification

The Geothermal Laboratory at Southern Methodist University (SMU) has documented geothermal resource potential across the United States based on a database of bottom-hole temperature data (BHT) from thousands of wells to depths up to 10 km below the ground surface. This data has been mapped as a .KMZ file which is accessible through Google Earth™ (Google, 2013a, 2013b). In this study, SMU's resource potential map was overlain with the database published by the Carbon Monitoring for Action (CARMA, 2013), which contains information about the carbon emissions of over 60,000 power plants worldwide. Potential project sites for this study were then identified by combining these tools and locating power plants in areas with an elevated geothermal gradient. A list of locations was then narrowed based on a scoring system and ultimately five project sites were chosen.

Site Selection

Potential project locations were consider using a suite of site characteristics in three categories:

- **Resource quality**
  - o Geothermal gradient
  - o Depth to EGS resource
  - o Temperature at depth
  - o Regional tectonic stress regime
  - o Geology
  - o Joint distribution
  - o Nature and distance of faulting
  - o Existing permeability
  - o Proximity to known geothermal resources
- **Site suitability**
  - o Days to fill EGS reservoir
  - o Current annual water disposal costs
  - o Proximity to known geothermal field
  - o Waste water quality/need for treatment
  - o Availability of wells of opportunity
  - o Nature of the local power market
  - o Transmission Capacity
  - o Land ownership and availability
- **Quality of existing data**
  - o BHT data availability
  - o Geologic maps
  - o Seismic reflection surveys
  - o Resistivity data

Sites were ranked, and five were selected for further study and assessment, and more detailed site specific information was gathered.

Bottom Hole Temperature (BHT) Data

Regional bottom hole temperature data (BHT) were collected through the National Geothermal Database System (NGDS, 2012) and the U.S. Geoscience Information Network (USGIN, 2012). These data are typically raw uncorrected temperatures collected at the time of drilling, which means these data were not collected at a point when the boreholes were in thermal equilibrium with the surrounding rock. Subsequently, these raw data have been cor-

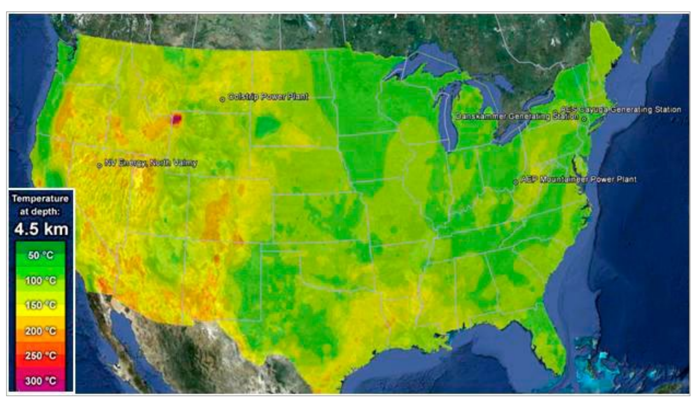


Figure 1. Example of the SMU database tool. BHTs are contoured at 4.5 km depth across the U.S.

rected using the techniques of Harrison et al. (1983) and Gallardo and Blackwell (1999), which employ a second order polynomial correction that correlates the BHT measurement to depth below surface given in Equation (1):

$$\Delta\ °C = -16.5 + 0.0183 \cdot z - 0.00000234 \cdot z^2 \tag{1}$$

where z = depth in meters, and Δ °C is the temperature correction (in Celsius) as a function of depth.

Resource Quantification

The size of an EGS reservoir needed to manage the waste water at each location was determined based on: 1) the water volume needed to stimulate and charge the EGS reservoir; and 2) volume of water that must be disposed of annually. Total annual water loss in an EGS is a function of both leakage out of the EGS reservoir and evaporative cooling to the atmosphere from the power plant. This study assumed a standard 0.8 km^3, three level cylindrical EGS reservoir with a fluid volume of 21 million gallons. EGS field size and number of wells needed were thus calculated as a function of waste water disposal rate and EGS field water consumption.

Next, the magnitude of heat that could be extracted (i.e., Recoverable Heat) over a 30 year period from an EGS reservoir at each candidate site was calculated as a direct function of the geothermal gradient and the geophysical properties of the heat reservoir. The magnitude of Recoverable Heat was modeled using the same approach undertaken as part of the 2007 MIT EGS study. Once the candidate sites were selected, geothermal temperature data was gathered from publically available resources for the areas around each location.

Theoretical Project Description

LCOE was modeled at each site based upon the same theoretical EGS project type. EGS reservoir clusters consist of 1 injector and 3 production wells each producing 400-950 kilopounds per hour (50 - 120 kilograms per second, kg/s) with projected temperature decline of less than 10 °C over 30 years. Each cluster would produce between 2 and 5 MW depending on the temperature and flow rate of the produced fluid. Leakage from an EGS reservoir is generally less than 5%; although this is not well supported due to the sample size of operating EGS projects being under 10 and relatively short operating histories. In order to dispose of the waste water generated each year by the power plant, new reservoirs with additional power generation would need to be added each year.

Economic Estimation

Total project costs and cost per kilowatt were calculated over a 30 year project life span using the Microsoft Excel®-based Geothermal Electricity Technology Evaluation Model (GETEM; USDOE, 2012). The model provides representative estimates of cost and performance for geothermal power produced from defined scenarios. The current version of GETEM does not include production stimulation costs, only injection stimulation costs. Therefore, costs of injection well stimulation was set as a function of the total number of wells drilled so that the total stimulation cost was $500,000 per well.

LCOE is the primary metric used for comparison of different projects in this study. Using LCOE allows comparison of electrical production by EGS with that of coal. Conventional assessment of costs on a dollar per power-unit-installed basis (i.e., ¢/kWhr) doesn't include the cost of fuel used over a project lifetime, and thus LCOE provides an equitable comparison. LCOE is defined as the average marginal cost on a per kilowatt hour basis for the life of the project, per Equation (2):

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{\left(1+r\right)^t}}{\sum_{t=1}^{n} \frac{E_t}{\left(1+r\right)^t}} \tag{2}$$

I_t = Investment expenditures in year t ($)
M_t = Operations expenditures in year t ($)
F_t = Fuel expenditures in year t ($)
E_t = Electricity generation in year t ($)
R = Discount rate (%)
N = Life of system (years)

The model was evaluated under different resource scenarios to determine potential costs associated with site specific conditions. This is essentially sampling from a surface defined as $z_{a,b} = f(x,y)$ where x is temperature, y is injectivity, z is LCOE, and subscripts a and b indicate position in the sample matrix (Table 1). This surface was sampled in 18 different points with equal spacing.

Table 1. Sample matrix used to calculate the surface of LCOE values as a function of injection pressure and temperature.

	1 gpm/ psi	2 gpm/ psi	3 gpm/ psi	4 gpm/ psi	5 gpm/ psi	6 gpm/ psi
257 °F (125 °C)	$z_{1,1}$	$z_{2,1}$	$z_{3,1}$	$z_{4,1}$	$z_{5,1}$	$z_{6,1}$
302 °F (150 °C)	$z_{1,2}$	$z_{2,2}$	$z_{3,2}$	$z_{4,2}$	$z_{5,2}$	$z_{6,2}$
347 °F (175 °C)	$z_{1,3}$	$z_{3,2}$	$z_{3,3}$	$z_{4,3}$	$z_{5,3}$	$z_{6,3}$

The sampled values were used to create a matrix of LCOE values using a regression function in the MATLAB® numerical computing environment. These matrices were used to produce the graphs of LCOE as a function of temperature and injectivity presented in Section 5. These graphs create site specific maps of cost given different resource scenarios.

Model Parameters

Models were defined by two main objectives; 1) eventual full use of the process water supply; and 2) identified conditions to make LCOE market competitive. The process includes a cost minimization process, the Excel® Solver Tool, to optimize LCOE given a defined set of constraints. The model varies both resource parameters and the power facility size to minimize LCOE. Optimization considers three components:

- decision variables: chosen by the user;
- project variables: controlled by the Excel® Solver Tool (a generalized reduced gradient; non-linear optimization code) to minimize or maximize certain model values; and
- constraints: hard boundaries on the project variables (i.e., known technical limitations).

Decision Variables

The decision variables were chosen as those which most affect project cost risk (Table 2).

Table 2. Decision Variable values used to model potential project LCOEs in GETEM.

Decision Variable	Value Ranges Used
Injectivity (gpm/psi)	1 to 6
Productivity (referred to as "Hydraulic Drawdown" in GETEM) (psi-h/1000lb)	= [(Injectivity)/(8.35 lb/gallon)/60(min/hr) •1000 lb]•2
Temperature	257-527 °F (125 - 275 °C)
Depth	Site specific dependent upon geothermal gradient

Project Variables

Variables controlled by the Solver Tool algorithm consist of:

- Production flow rate (kg/s);
- Number of wells;
- Injection flow rate (kg/s);
- Ratio of injection wells to production wells; and
- Number of power producing units.

Lower temperature resources with binary systems control production rate by pumping, which is constrained by economic considerations because pumping requires power. The number of wells is allowed to develop within the model based on the power demand and technical constraints. Injection rate is defined by the production rate divided by the Injection/Production ratio, which is the ratio of injection wells to production wells (1:3 in this study). The number of power units is defined by the assumption that an additional unit is needed per 50 MW increase in power plant size; for resources with a temperature of 175 ˚C an additional power unit is needed for every additional 100 MW.

Constraints

Waste water supply rates (Table 3) were constrained based on public data at each site and potential variables to that rate, and a water loss level of 5% for binary power plants (Shevenell, 2011). Production and injection flow rates are constrained based upon industry practicalities; injection rates are constrained at a higher value because cooler temperatures allow increased flow rates. Injection pressure is limited to 1000 psi to prevent tensile failure in the wells. Productivity is set as half of the given injectivity, which agrees with results from the EGS demonstration in Soultz, France (Ledésert and Hébert, 2012).

Table 3. Constraint variable values used to model potential project LCOEs in GETEM.

Constraint	Limit Value
Make up water (gpm)	50% to 105% of waste water supply
Production Flow Rate (gpm)	Up to 2500
Injection Flow Rate (gpm)	Up to 3000
Injection Pressure (psi)	Up to 1000
Productivity (psi/gpm)	= 1/(Injectivity x 1/2)

Economic Parameters

GETEM includes economic market parameters in determining LCOE (Table 4). Conservative values were chosen to accommodate for unknown investor perception of financial risk. Make up water supply costs can be included in GETEM as a negative value to show value added for waste water mitigation. However, waste water treatment costs are site specific, highly variable, and proprietary; the requests for information from individual power producers were unanswered. Therefore, no water cost values were entered, and the potential improvement to LCOE based on water treatment costs is only speculated upon.

Table 4. Financial parameter values used to model potential project LCOEs in GETEM.

Financial Parameter	Value
Effective Tax Rate	27.1%
Well Field Development Discount Rate	7%
Plant Construction and Start Up Discount Rate	4%
Contingency	10%
Water Costs	$ 0.0 per acre foot

Site Selection

Six regions were identified where geothermal gradients were elevated and coal fired power plants were operating (Table 5). These regions were also chosen to provide a variety of geologic and physiographic regions within the USA.

Table 5. Regions with active coal power plants and elevated geothermal gradients.

Region	Physiographic Province
Central West Virginia	Appalachian Highlands, Central Appalachian Plateau
Southeast Texas	Atlantic Plain, West Gulf Coastal
East Central Wyoming	Interior Plains, Great Plains Province
Central New York	Appalachian Highlands, Northern Appalachian Plateau
North Central Nevada/ Utah	Intermontane Plateau, Basin And Range Province
West Central Arizona	Mexican Highland, Basin And Range Province

Source: USGS, 2011

Power plants that were identified in these regions and some of the characteristics at each plant are summarized below in Table 6.

The list of sites in Table 6 was narrowed based on regional location, site conditions, regional geology, and resource quality. The sites carried forward have geothermal gradients exceeding 1.1 °F per 100 feet (20 °C/km), and they match a variety of conditions:

- **Colstrip, Montana**: operators at Colstrip have investigated underground disposal of waste water previously and documented an elevated thermal resource at depth directly beneath the site. The site has a moderately elevated geothermal gradient, but a low waste water supply (0.3 mgd).
- **AEP Mountaineer, New Haven, West Virginia**: AEP was the only operator to provide this study with information beyond what was available publicly. AEP also operated a

Table 6. List of potential power plant locations where an EGS system could be co-located.

Plant Name	Location	1st Yr of Operation	Operator	Gross Nameplate Rating (MW)	Waste Water Discharge Rate (mgd)	Waste Treatment
Mountaineer Power Plant	New Haven, WV	1980	AEP	1300	5.0	Surface Discharge
North Valmy Generating Station	Valmy, NV	1981, 1985	NV Energy	522	0.6	Evaporation Ponds
Colstrip PPL	Colstrip, MT	1975, 1976, 1984, 1986	Colstrip PPL	2094	0.3	Evaporation Ponds
Cayuga Generating Station	Lansing, NY	1955	AES	323	6.8	Surface Discharge
Danskammer Generating Station	Newburgh, NY	1951, 1954, 1959, 1967, 1967	Dynegy	537	9.0	Surface Discharge
Intermountain Power Project	Delta, UT	1986, 1987	Intermountain PA	950	NR	Injection Wells
Fort Martin Power Station	Fort Martin, WV	1967, 1968	Allegheny	1107	NR	NR
Hatfields Ferry Power Station	Hatfields Ferry, WV	1969, 1970, 1971	Allegheny	1710	NR	NR
John Amos	West Virginia	1971, 1972	AEP	2933	NR	NR
Harrison Power Station	Haywood, WV	1972, 1973, 1974	Allegheny	2000	NR	NR
Martin Lake Steam Station	Tatum, TX	1977, 1978, 1979	Luminant Power	2380	NR	NR
Dolet Hills Power Station	Dolet Hills, TX	1986	Cleco Power	721	NR	NR
Rodemacher Power Station	Rodemacher, TX	1975, 1982, 2010	Cleco Power	1623	NR	NR
H. Wilson Sundt Generating Station	Sundt, AZ	1967	Tucson Electric	173	NR	NR
Springerville Generating Station	Springerville, AZ	1985, 2006, 2009	Tucson Electric	1560	NR	NR

NR – Not researched, mgd – million gallons per day

successful underground CO_2 sequestration pilot project at the site between 2009 and 2011, and the geology at the site is very well understood. The site has a moderate geothermal gradient (1.84 °F/100 ft; 33.6 °C/km) and a high waste water discharge rate (5 mgd).

- **AES Cayuga, New York**: Central New York State has a noted elevated geothermal that has garnered much interest from research scientists and engineers at Cornell University's College of Engineering (Tester, 2006). The site has a moderate geothermal gradient (1.46 °F/ 100 ft; 26.6 °C/km) and a high waste water discharge rate (9 mgd, sourced from the town of Ithaca). Any future EGS project work would find important support not only from Cornell's long running interest in geothermal, but also from the State government.

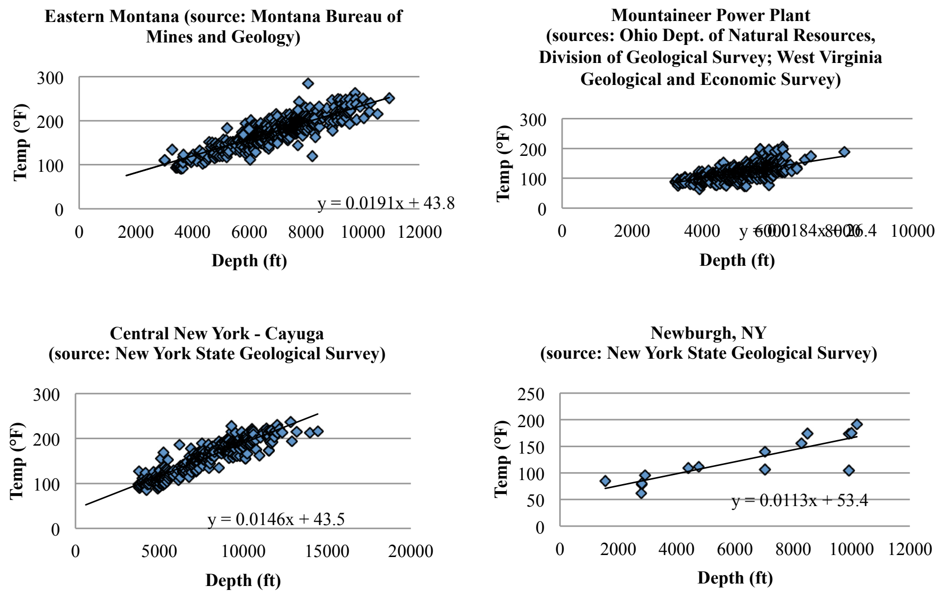
Table 7. Summary of site specific physical characteristics.

Characteristic	Colstrip Power Plant, MT	AEP Mountaineer Power Plant, New Haven, WV	AES Cayuga Generation Plant, Tompkins, NY	Danskammer Generating Station, Newburgh, NY	NV Energy North Valmy Generating Station	
Lease Area (Acres)	10,000	10,000	10,000	10,000	10,000	Reservoir Characteristics
Gradient (°F/100 ft)	1.91	1.84	1.46	1.13	3.3	
Surface Temperature (°F)	45	44	44	49	65	
Depth to Resource (ft)	13,574	14,268	14,692	21,746	12,814	
Reservoir Thickness (ft)	3,281	3,281	3,281	3,281	3,281	
Total well depth (ft)	15,951	16,757	17,254	25,614	14,197	
Thickness of sedimentary drilling (ft)	2,700	9,000	9,840	9,840	8,200	
Thickness of crystalline drilling (ft)	12,514	6,908	6,492	13,546	6,254	
Rock Density (lb/ft^3)	168.5	168.5	168.5	168.5	168.5	
Rock Specific Heat (J/g-°C)	0.8	0.8	0.8	0.8	0.8	
Fluid Density (lb/ft^3)	57.41	57.41	57.41	57.41	57.41	
Water Specific Heat (J/g-°C)	4.186	4.186	4.186	4.186	4.186	
Porosity (%)	15	15	15	15	15	
Reservoir Temperature (°F)	302	302	302	302	482	
Heat Extraction (°F)	68	68	68	68	68	
Life Cycle (yr)	30	30	30	30	30	Plant Characteristics
Power Production (MW)	2,094	1,300	323	0	522	
Waste Water Supply Rate (mgy)	100	1,825	2,482	3,285	210	
Waste Water Supply Rate (mgd)	0.3	5.0	2.3	9.0	0.6	
CAPEX for water treatment ($M; 1$M per 1 mgd treated)	$ 0.27	$ 5.00	$ 6.80	$ 9.00	$0.58	

mgy – million gallons per year, CAPEX – capital expenditures

- **Danskammer Point, New York**: The Danskammer power plant was shut down in 2012 following damage from Superstorm Sandy, and the plant will be demolished. The loss of the power plant represents an unfulfilled demand for power in the area, and there is an ample supply of waste water from the town of Newburgh, NY (6.8 mgd). However, the site has a poor geothermal gradient (1.13 °F/100 ft; 20.6 °C/km), is considered at the low end of the range of EGS resources studied in this report.

- **NV Energy, North Valmy, Nevada**: Located in northern Nevada, this power plant is in a region with significant geothermal energy production and high potential for further production. The site has a limited supply of waste water (0.6 mgd), but the need to dispose of the water in evaporative surface ponds makes other means of mitigation economically more desirable. The site has a high geothermal gradient (3.3 °F/100 ft; 60.3 °C/km), is considered to be at high end of the range of EGS resources studied.



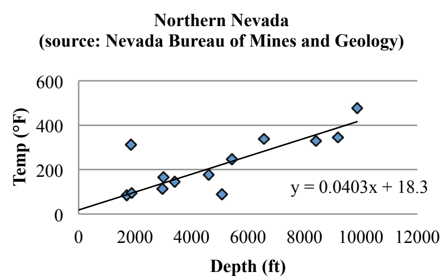


Figure 2. Site Specific Corrected Bottom Hole Temperatures and Geothermal Gradients.

Site Characteristics

Table 7 summarizes the characteristics used to generate predicted LCOE values in GETEM at each of the sites selected. Data are grouped into three categories: Reservoir Characteristics

Table 8. EGS reservoir heat capacity and potential electrical generation capacity.

Site	Lease Area (Acres)	Net Thermal Potential (MW)	Recoverable Heat (MW)	Electricity Potential (MW)
Colstrip Power Plant, MT	50,000	2.4×10^9	1,849	203
AEP Mountaineer Power Plant, New Haven, WV	50,000	3.0×10^9	2,312	254
AES Cayuga Generating Station, Tompkins, New York	50,000	3.0×10^9	2,312	254
Danskammer Point, Newburgh, NY	50,000	3.0×10^9	2,312	254
NV Energy North Valmy Generating Station, Valmy , NV	50,000	2.4×10^9	1,849	296

list the physical qualities of the EGS reservoir; Recoverable Heat Calculator inputs are the values used to determine the magnitude of the heat resources which are listed in Table 8; and Plant Characteristics list the characteristics of each power plant. The Potential Electrical Generation Capacities listed in Table 8 were used to verify that each EGS reservoir was of sufficient capacity to use the waste water available at each site.

Model Results

The corrected BHT data, data sources, and geothermal gradients determined for each of the power plant locations are shown in Figure 2. The Appendix details the geology and geothermal reservoir conditions at each location.

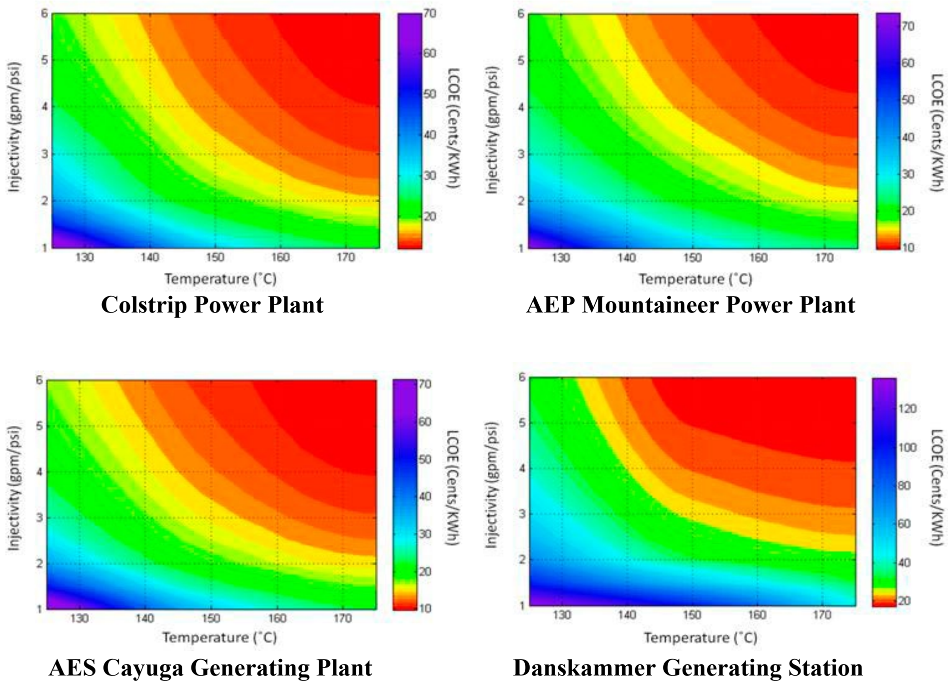
Figure 3 presents the LCOEs calculated as a function of temperature and injectivity the five sites studied. The reservoir conditions and power production facilities used to model the LOCEs are described in detail for each site in the Appendix.

Summary and Conclusions

This study developed a robust EGS feasibility assessment methodology. The modeling technique uses the cost estimation ability of GETEM to optimize a project as a function of the variables which have the greatest effect on project risk – injectivity and temperature. If the temperature and injectivity values needed to be competitive are known before starting an EGS project, much of the project risk is removed. Using this method, EGS project potential for any site could be adequately assessed by completing and stimulating one exploration well. Therefore, the technical and economic feasibility of developing EGS projects was assessed at five existing coal plants.

A range of predicted LCOE values were calculated as a function of injectivity, temperature, and resource depth. Model parameters were optimized within constraints to find the minimum LCOE value under certain conditions. Results, summarized in Table 9, indicate that EGS-based power can be competitive with new coal on the basis of LCOE over a project lifetime of 30 years.

Coal fired power plants east of the Mississippi River, where surface water resources are more abundant, can be typified as having lower EGS resource potential but more abundant supply



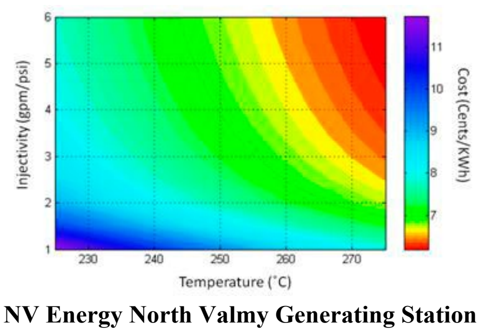


Figure 3. Contour graphs of LCOE associated with the development of EGS resources at each of the power plants assessed in this study.

of process water. Plants west of the Mississippi, where water resource supply is much more limited, typically have greater EGS resource potential and a lower water supply. By reducing project risk uncertainties (e.g., temperature, depth, and injectivity) and optimizing project parameters to site conditions, geothermal energy can be competitive within the traditional electricity market. New coal fired power plants have an LCOE of 10-12¢/kWhr (USEIA, 2012). In many of the scenarios modeled in this study, EGS co-located with existing coal power could be on par with new coal power. Additionally, the federal production tax credit and the revenue accrued through process water disposal have not been accounted for in these models. If these additional revenue streams are included, this specific resource is likely competitive within today's market. Furthermore, because there is no fuel cost, operating expenses (OPEX) will be low. Once developed these resources are low risk assets and may provide a suitable hedge against future fuel price volatility. Co-locating an EGS project with an existing coal fired power plant would provide a dedicated source of water, while such an EGS project would add value to by mitigating process water disposal and providing renewable power.

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Table 9. Summary of calculated water, power generation, and modeled LCOEs.

Site	Type of Plant	Number of Wells	Power Generated (MW)[1]	Injection Rates (gpm)	Well Field Costs ($M)	Stimulation Costs ($M)	Plant Costs ($M)	LCOE (¢/kW-h)[2]
Colstrip Power Plant, MT	binary	6 - 21	10.2 - 10.9	560 - 1673	4.8 - 15.8	0.2 - 0.6	4.7 - 6.1	10.8 - 71.2
AEP Mountaineer Power Plant, New Haven, WV	binary	90 - 98	145 - 189	610 - 2050	72 - 236	4.7 - 15.7	76 - 91	9.6 - 38.6
AES Cayuga Generating Station, Tompkins, New York	binary	55 - 180	89 - 120	640 - 2080	160 - 1590	29 - 94	522 - 570	9.8 - 72.5
Danskammer Point, Newburgh, NY	binary	141 - 303	89 - 300	530 - 2330	241 - 566	3.4 - 8.0	40 - 148	17.3 - 138.6
NV Energy North Valmy Generating Station, Valmy , NV	flash	2	5.8 - 7.6	1808	1.45	0.1	1.9	6.1 - 11.8

[1]Power produced to consume the process water supply based on the conditions specified.

[2]LCOEs are calculated without considering either tax development incentives or value added due to handling process water management.

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APPENDIX: Site Specific Results

This Appendix provides a detailed description of the geology, reservoir conditions, and power production system designs used to calculate the modeled LCOE surfaces presented in Figure 3.

Colstrip Power Plant, Southeastern Montana

The Colstrip Power Plant operates four coal-fired generating units capable of producing a total of up to 2,094 MW of electricity. The facility generates 80 to 120 mgy of process water primarily from wet emissions scrubbing but also mine dewatering and surface runoff and is stored in ponds and disposed by evaporation. Annual process water production cannot always be evaporated. Accumulation of excess water stresses the disposal system beyond its capacity in high rainfall years. Evaporation leaves concentrated brine and eventually a sludge that is either disposed of or left in place requiring new pond construction.

Colstrip's unique distinction is that temperatures have been measured at depth directly below the plant. An exploration well was drilled by Western Energy to test the Madison Limestone aquifer, and a temperature of 207 °F (97 °C) was reached at approximately 8000 ft (2700 m) below ground surface (Sonderegger-Bergantino, 1981). This is equivalent to a temperature gradient of about 1.91°F/100 ft (34 °C/km), which is consistent with the thermal gradients observed regionally (see below).

Regional Geology and Geothermal Gradient

The depth of sedimentary units in this region of Montana is not well constrained, but it's assumed that at the required depths for EGS development the rock type is likely crystalline basement and granitic in composition. Regional BHT data were collected from the northeastern part of Montana. Most of this data has been collected in association with development of the Williston Basin for oil and gas, thus the localization of the data points shown in **Error! Reference source not found.**. Eleven additional BHT data are available within 50 km of the Colstrip site. The gradient data proximal to Colstrip are consistent with the data collected farther afield. The corrected BHT data and geothermal gradient are shown as a function of depth in **Error! Reference source not found.**

EGS Project Conditions

Colstrip has a relatively limited amount of process water supply when compared to the other locations studied. Based on water supply and geothermal gradient, an air-cooled binary power plant and resource temperature of 300 °F were identified as the best options for economic success. The number of wells needed to consume the process water supply is relatively low, 6 to 21 wells depending on the depth, resource temperature, and productivity of the EGS reservoir. The resultant power plant isn't very large, approximately 10 MW compared to 50 MW for more typical geothermal projects. A larger facility would require obtaining additional make up water.

Predicted LCOE for EGS Geothermal

Error! Reference source not found. presents LCOE as a function of temperature and injectivity for a proposed plant at the Colstrip Plant. Temperature is calculated as a function of depth and thermal gradient. Water at about 100 ºC could be used for power production, and in fact slightly lower temperature fluid from the Madison Limestone was used to generate power at the Rocky Mountain Oilfield Test Center (RMOTC) in Wyoming (USDOE, 2010). However, LCOE is drastically reduced by using fluids at 150 °C in a binary power generator because increased power generation efficiency more than offsets the increased capital cost of drilling to greater depths, as illustrated in **Error! Reference source not found.** Under favorable conditions the LCOE of a geothermal development at Colstrip is approximately 12 ¢/kWhr.

AEP Mountaineer Power Plant, New Haven, West Virginia

The Mountaineer Power Plant is a 1480 MW (gross nameplate) coal-fired power plant outside New Haven, West Virginia. The site produces a high volume of process water, averaging 5 mgd according to the plant's NPDES permit (Stone and Webster, 2005). Process water is treated and discharged to the Ohio River.

Regional Geology and Geothermal Gradient

In this region of West Virginia, sediments reach a depth of exceeding 9000 ft and are defined by alternating sandstone, shale and limestone (USGS, 2009). An economic depth for EGS is below 14,000 ft bgs, which is assumed to be in the granitic and gneissic basement rocks of the Grenville province (USGS, 2009). The corrected BHT data and geothermal gradient are shown as a function of depth in **Error! Reference source not found.**

EGS Project Conditions

Mountaineer has an abundant process water supply. Based on water supply and geothermal gradient, a wet-cooled binary power plant and resource temperature of 300 °F were identified as the best options for economic success. However, almost all binary power systems are air cooled, and GETEM bases binary plant power efficiency on an air-cooled system. A well field on the order of 100 km^2 with a significant power generation capacity (>140 MW) would consume all of the process water currently being discharged into the Ohio River using an air-cooled binary system. On the other hand, a wet-cooled system with evaporative cooling towers could reduce the number of EGS wells needed by as much as half, with an equivalent reduction in EGS power capacity.

Predicted LCOE for EGS Geothermal

Error! Reference source not found. presents LCOE as a function of temperature and injectivity for a proposed plant at the Mountaineer Power Plant. Temperature is calculated as a function of depth as described by the regional gradient. Below an injectivity of three the LCOE is very sensitive to injectivity values. The average injectivity value reached by a well, within the proposed project, has a significant effect on the number of wells that need to be drilled in order to economically consume the power plant process water (**Error! Reference source not found.**). Given constraints specific to the site, a LCOE of approximately 10 ¢ can be reached if favorable resource conditions are found or created.

AES Cayuga Generation Plant, Central New York

The AES Cayuga Generation Plant is a coal power plant operated by the AES Corporation, formerly known as Milliken Station. The plant is located on the east shore of Cayuga Lake near the town of Tompkins in central New York State. The station operates in the Town of Lansing, on the east shore of Cayuga Lake. This coal-fired plant uses Cayuga Lake as a cooling source. The plant is allowed to discharge 245 mgd back into the lake, 2.32 mgd of which are treated process waters, and the rest of which is cooling water discharge (NYSDEC, 2004).

Regional Geology and Geothermal Gradient

The geology at the Cayuga site can be characterized as the northern extension of the Appalachian Basin. This basin is characterized by shales alternating with limestone and dolomite with occasional beds of sandstone. Economic development of this resource would require drilling to depths of around 13,000 ft. This depth is below the range of sedimentary strata which extend a depth of 9,000-10,000 ft within this area (Shope et al., 2012). Development would occur in the basement, which is likely either gneissic or granite. The corrected BHT data and geothermal gradient are shown as a function of depth in **Error! Reference source not found.**

EGS Project Conditions

Like other sites east of the Mississippi river, Cayuga has an abundant supply of process water. Based on water supply and geothermal gradient, a wet-cooled binary power plant and resource temperature of 300 °F were identified as the best options for economic success. However, almost all binary power systems are air cooled, and GETEM bases binary plant power efficiency on an air-cooled system. The conditions at this site are similar to those at Mountaineer and would support a comparable EGS reservoir; a 100 km^2 well field could support 100+ MW of EGS produced power. A wet-cooled system with evaporative cooling towers would reduce the number of EGS wells needed as much as half, with an equivalent reduction in EGS power capacity.

Predicted LCOE for EGS Geothermal

Error! Reference source not found. presents LCOE as a function of temperature and injectivity for a proposed plant at Cayuga Generating Station. Temperature is calculated as a function of depth and thermal gradient. Given constraints specific to the site, a LCOE of approximately 10 ¢ can be reached if favorable resource conditions are found or created. Further reduction of LCOE values could come from design measures not implemented in the model. What is clear from **Error! Reference source not found.** is that injectivity has a greater influence on the LCOE than the temperature of the resource. The reason for this is that the proposed facility has been designed to consume all the process water AES Cayuga Generating Station produces. If water consumption constraints were relaxed there would be less parasitic power losses from injection pumping and the LCOE values for different scenarios would come down. This could be done by evaporating extra water or using water cooled binary turbine systems which are both more efficient and consume more water.

Danskammer Generating Station, Newburgh, New York

Danskammer Generating Station is located on the shore of the Hudson River in the Town of Newburgh, New York. Danskammer was rendered inoperable as a result of Superstorm Sandy in late October 2012 and the facility will be retired and demolished (Dynegy, 2012). The process water supply for a potential EGS project was taken as the municipal process water produced at the town of Newburgh, New York – approximately 9 mgd (STS, 2011).

Regional Geology and Geothermal Gradient

The geology of this region of New York is not well characterized at the depths needed for economical geothermal development. It is therefore assumed that reservoir rocks will be similar to the basement rock in the area, which is defined as granitic or gneissic rocks. The corrected BHT data and geothermal gradient are shown as a function of depth in **Error! Reference source not found.**

EGS Project Conditions

The City of Newburgh has an abundant process water supply. Based on water supply and geothermal gradient, a wet-cooled binary power plant and resource temperature of 300 °F were identified as the best options for economic success. The local regional geothermal gradient is the lowest of all the locations studied in this report, and would require the most wells per process water volume to manage the process water supply.

Predicted LCOE for EGS Geothermal

Error! Reference source not found. presents LCOE as a function of temperature and injectivity for a proposed plant at Danskammer Generating Station. Temperature is calculated as a function of depth and thermal gradient. Modeling LCOE for a project at Danskammer is instructive because it clearly illustrates that resources with a gradient of 1.14 (°F /100 ft) will likely never be economic unless significant improvement to binary plant efficiency can be made. Given favorable conditions the LCOE of developing a facility at Danskammer is approximately 20 ¢/kWhr.

NV Energy, North Generating Station, Valmy, Nevada

The North Valmy Generating Station is a coal-fired steam-electric generating plant with two operating units. Operating water is supplied from the Valmy groundwater well field and the Lone Tree Mine dewatering project. This cooling water is recirculated, and the plant discharges 0.6 mgd into five 25 acre lined evaporative discharge ponds (NDEP, 2004).

Regional Geology and Geothermal Gradient

Geology at Valmy, Nevada is characterized by alluvial deposits at shallow depths and metasediments at deeper depths. The Meta-Sediment believed to be underlying the younger alluvial deposits is called the Harmony formation. This formation is Cambrian in age. At the depth of proposed development rocks are likely characterized by granodiorite, which is exposed nearby on Buffalo Mountain (Willden, 1964). The corrected BHT data and geothermal gradient are shown as a function of depth in **Error! Reference source not found.**

EGS Project Conditions

The North Valmy plant has a relatively limited amount of process water supply when compared to other locations. Based on water supply and geothermal gradient, a flash steam power plant and resource temperature of 480 °F were identified as the best options for economic success.

Predicted LCOE for EGS Geothermal

Error! Reference source not found. presents LCOE as a function of temperature and injectivity for a proposed plant at Valmy Generating Station. Temperature is calculated as a function of depth and thermal gradient. The relatively elevated geothermal gradient 3.3 (°F /100 ft) and use of a flash steam power plant produced LCOE values that were the lowest among all the locations studied. Valmy is the most cost competitive project analyzed in this study. Given favorable resource values, projected LCOE for a project at Valmy is approximately 6 (¢/kWhr). This project is constrained by a lack of available process water; a further reduction in the LCOE could be accomplished by accessing more water and scaling up plant capacity.