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Transitioning Coal to Geothermal

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ABSTRACT

More than 50,000 MW of aging coal fired power generation capacity will need to be either repowered or retired between now and 2030, much of it in the next 10 years. These plants can't meet today's emission standards or the new standards of the Clean Power Plan even with prohibitively expensive pollution control equipment. While low prices drive many of these plants to consider natural gas repowering as the solution to their continued operation, renewable portfolio standards and the lack of sufficient gas supply pipeline capacity prevents most from taking this option. Wind and solar can offset some of this power supply, but coal plants by their nature provide baseload power. Conventional geothermal energy is limited to places where we can find it. Only with EGS can we replace coal with geothermal in a wide variety of locations. Co-locating the geothermal project on land owned by the coal plant takes advantage of the grid connection, permitting and cooling system as well as a skilled workforce. Waste water stored in ponds at the site can be used for reservoir fill up. Costs remain the major issue for utility scale EGS power generation. EGS plants running in Europe have relied on feed-in-tariffs only available for small scale projects. We are studying the impact of scaling, learning-by doing and technology improvement on the LCOE for utility scale EGS power production. Other technologies such as wind and solar have seen very large decreases in LCOE and installed cost as more and larger facilities have been installed. Photovoltaic power in particular has seen a dramatic decrease in cost as more and more solar facilities have come on line. The question is: Can EGS see the same kind of cost decreases as seen in wind and solar and realize the goal of replacing coal with geothermal?

1. INTRODUCTION

Over the next ten years 50,000 MW (Table 1) of aging coal fired generation needs to be repowered or shut down because it can't meet current emissions standards (Figure 1). Repowering with natural gas doesn't solve the problem of greenhouse gas emissions and many of these plants need expensive gas pipelines to provide enough supply. While nuclear power is an option, it is an option out in the future. The only new nuclear plant projects started in the U.S.in last 10 years have been at the site of existing nuclear plants. While new technology and designs are in development they will need to be approved and licensed before they can be constructed. While solar and wind can certainly contribute to coal plant replacement, these are intermittent resources which can't replace fully the base load power that a coal plant provides. Conservation will also reduce the amount of coal power that needs to be replaced, but coal fired generation is baseload and can only be replaced by other baseload power sources. For many states with coal fired generation there are renewable portfolio standards that require these plants be replaced with renewables. The Clean Power Plan (now stayed by the Supreme Court) and the agreements that came out of the COP21 meetings in Paris put further pressure on coal fired generation to be replaced by renewables, not only in the U.S., but around the world.

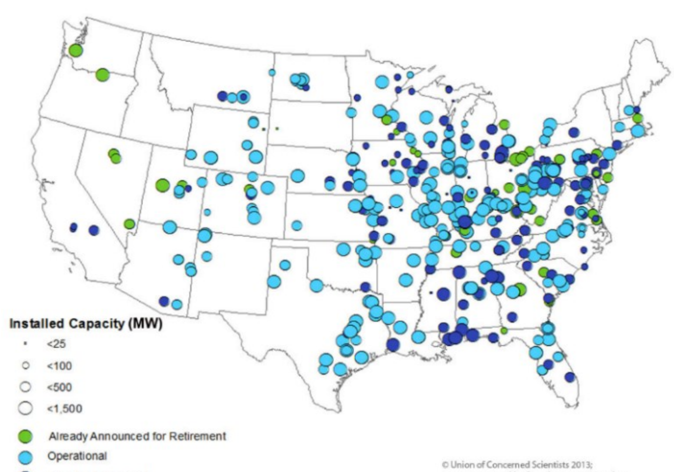


Figure 1 Coal fired power plants operating, retiring or ready for retirement in the U.S.

An Engineered Geothermal System (EGS) enables economic production of electricity using geothermal heat in geologic settings with little or no natural permeability rocks. The total extractable geothermal heat in the United States utilizing Engineered Geothermal Systems (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. 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.

Repowering retiring coal plants with EGS takes advantage of existing infrastructure, means zero emissions with very low cost to operate and keeps jobs and helps support communities that rely on these projects. Repowering with geothermal also accesses the enormous heat resource available across the U.S. and around the world.

2. BACKGROUND

In 2013 AltaRock Energy, Inc. undertook a study for the Electric Power Research Institute (EPRI) (Garrison, 2013) examining the potential for using waste water from coal fired power plants as the circulating fluid in an EGS project at the site of a coal fired power plant. The study found that at the best sites, in areas of the western U.S. with high temperature gradients, locating an EGS power plant at the site of a retiring coal plant resulted in power production at costs competitive with alternative baseload power production options.

Fifteen coal plants located in areas with geothermal gradients greater than 30°C per kilometer (2.6°F/ft) were identified in six different physiographic regions across the U.S. These locations were assessed based on key resource parameters and the quality of data available. Five sites were then retained for further analysis: Mountaineer Power Plant (West Virginia), North Valmy Generating Station (Nevada), Colstrip (Montana), Cayuga Generating Station (New York) and Danskammer Generating Station (New York). NREL's Geothermal Electricity Technology Evaluation Model (GETEM) was used to create site specific cost models based on key constraints: regional temperature gradient, reservoir injectivity (and thus its productivity), and water availability. These models were used to study improvement in the Levelized Cost of Electricity (LCOE) achieved both by reaching higher temperatures at greater depths and improving reservoir injectivity by stimulation.

During 2015 sustained low prices for oil and natural gas has forced drilling costs down significantly. Oil and gas operators have seen cost reductions as high as 30% for deep wells due to rig availability, reduced casing and cementing costs and technical innovation. (Klausen, 2015). Since 60%-80% of the cost of an EGS project is the wellfield, the cost reductions in drilling could contribute to a lower cost of power for EGS projects located at coal plants. Since low oil and gas prices are expected to continue for the foreseeable future, the reduction in drilling costs should persist. This reduced cost of drilling may afford an opportunity to begin the replacement of coal fired generation with geothermal power. The GETEM models reference above were therefore rerun using current reduced drilling costs from late 2015 to determine LCOE and cost per installed kW.

2. Coal to Geothermal

Over 1200 coal fired power plants generating more than 290,000 MW are over 30 years old. Over 540 coal plants generating over 49,000 MW are over 60 years old. (Table 1) While growth in renewable energy generation dropped following the 2008 economic crisis and has just in the last year begun to pick up again (**Error! Reference source not found.**), geothermal energy capacity continued to climb until the last couple of years (figure 3).

Table 1 Age of coal fired power plants in the US

Years Built	# of Units	Total Capacity (MW)
2005-2009	21	6,785
2000-2004	13	1,382
1995-1999	24	4,372
1990-1994	67	8,638
1985-1989	102	23,734
1980-1984	117	56,105
1975-1979	125	55,879
1970-1974	137	66,466
1965-1969	158	41,656
1960-1964	157	25,310
1955-1959	209	28,883
1950-1954	213	17,518
1940-1949	93	2,583
1930-1939	20	132
1920-1929	10	69

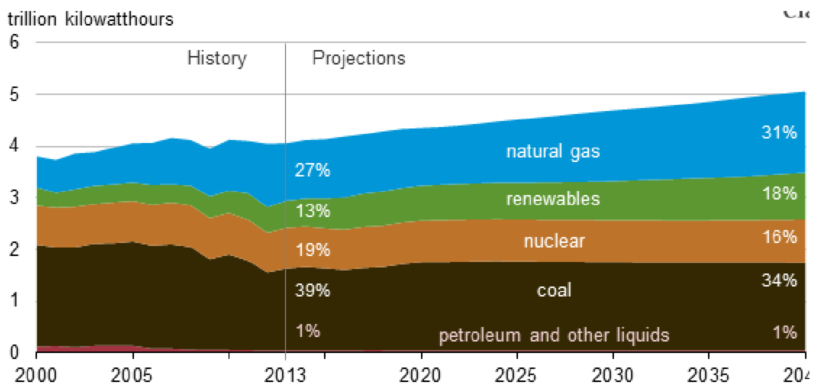


Figure 2 Electricity generation by fuel type in the AEO2015 Reference case, 2000-2040 (eia)

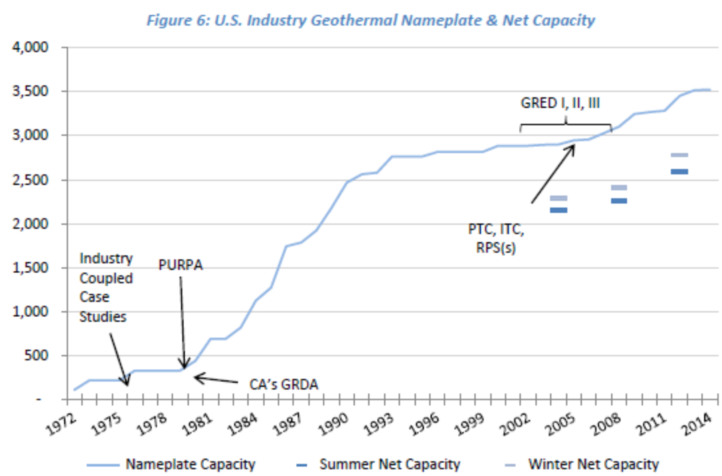


Figure 3 Installed and net geothermal capacity (GEA, 2015)

The possibilities for replacing coal fired power are limited. Utilities are concerned about supplying backing power for the growing intermittent solar and wind capacity already installed, never mind adding new wind and solar with the backing power or storage needed to replace coal. Biomass has been considered for some sites, but biomass supplies are often unreliable and can be costly. Natural gas is the primary source of potential coal power replacement. However, natural gas is still a carbon emitting fossil fuel which doesn't comply with many states renewable portfolio standards and many coal plants have no available gas pipeline or pipelines nearby don't have sufficient capacity to replace the coal plant. For plants in the west with high geothermal gradients, and for some sites in the east, using EGS technology can allow geothermal to scale to replace the capacity of the coal plant which is required for baseload demand. Replacing coal plants with geothermal using EGS can provide an expanded market for geothermal energy.

2.1 2013 EPRI Study

The AltaRock 2013 EPRI study (Garrison, et al., 2013) examined the economic implications of co-locating EGS with coal fired power plants as a means of mitigating process water disposal costs. These proposed developments address two objectives: consuming the entire wastewater stream, and generating geothermal electricity at minimal cost to replace the coal plant. Fifteen coal plants located in areas with geothermal gradients greater than 30 °C per kilometer (2.6 °F/ft) were identified in six different physiographic regions across the U.S. These locations were assessed based on key resource parameters and the quality of data available. Five sites were then retained for further analysis: Mountaineer Power Plant (West Virginia), North Valmey Generating Station (Nevada), Colstrip PPL (Montana), Cayuga Generating Station (New York) and Danskammer Generating Station (New York). NREL's Geothermal Electricity Technology Evaluation Model (GETEM) was used to create site specific cost models based on key constraints: regional temperature gradient, reservoir injectivity (and thus its productivity), and water availability. These models were used to study improvement in the Levelized Cost of Electricity (LCOE) achieved both by reaching higher temperatures at greater depths and improving reservoir injectivity by stimulation.

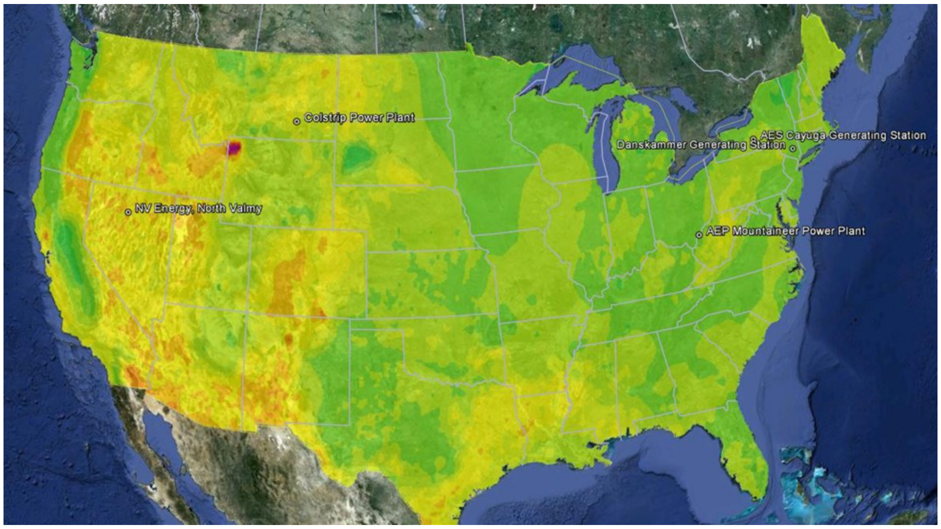


Figure 4 Temperature at 4.5km depth with 5 selected sites for 2013 EPRI study

Potential project sites for the 2013 EPRI 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. (**Figure 4**) The five selected sites were then assessed for EGS power potential using the methodology described in Future of Geothermal Energy, 2007. The selected sites are described below:

- **Colstrip, Montana**: operators at Colstrip have investigated underground disposal of process 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 process water supply of 1.1 million liters per day (mld, or 0.3 million gallons per day - 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 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 (23.0 °C/km) and a high process water discharge rate of 19 mld (5 mgd).
- **Cayuga, New York**: Central New York State has a noted elevated geothermal gradient that has garnered much interest from research scientists and engineers at Cornell University's College of Engineering [4], [15]. The site has a moderate geothermal gradient (25.2 °C/km) and a high process water discharge rate of 129 mld (34 mgd, sourced from the town of Ithaca). Any future EGS project work would find important support not only from Cornell's interest in geothermal, but also from the State government.
- **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 municipal waste water from the town of Newburgh of 26 mld (6.8 mgd). However, the site has a poor geothermal gradient (20.5 °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 process water (2.3 mld), 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 (64.5 °C/km), is considered to be at high end of the range of EGS resources studied.

LCOE was modeled at each site based upon the same theoretical EGS project type. EGS reservoir clusters consisting of 1 injector and 3 production wells each producing 275-830 kilopounds per hour (35 - 105 kilograms per second, kg/s) with projected temperature decline of less than 10°C over 30 years for the entire project. All of the binary projects were assumed to be drilled to a depth sufficient to produce 175°C based on regional temperature gradients around the coal plant studied. One high temperature site, the Valmy plant in northern Nevada, assumed a flash steam cycle with a resource temperature of 250°C. For the binary plants the production wells were assumed to be pumped while the flashed steam plant wells were assumed to self-flow. Site characteristics for each of the project sites in the EPRI study are shown in **Table 2**.

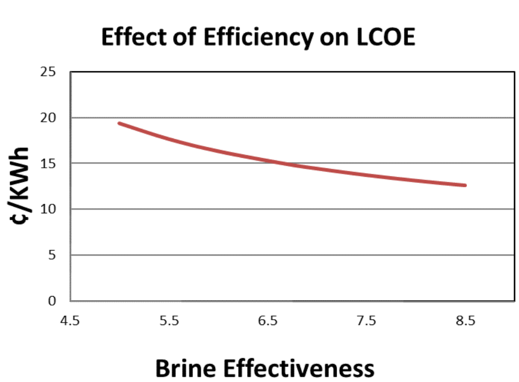
Table 2 Summary of site specific physical characteristics

Characteristic	Colstrip Power Plant, MT	AEP Mountaineer Power Plant, New Haven, WV	AES Cayuga 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	

The cost analysis assumed that there was no cost for transmission and that waste water from the coal plant would be used in filling and maintaining the geothermal reservoir and so water costs would be free. Site preparation costs were assumed to be minimal and a reduced permitting time was assumed due to the existing permits for the coal plant. This shortened the time to power generation from the start of the project. The projects were also sized to use all of the available waste water from the coal plant.

The EPRI study (Garrison, et al., 2013) looked at the sensitivity of cost to several factors, the most important of which were: Injectivity, temperature at depth, project scale, and power plant efficiency. While cost of drilling was considered a key factor, the depth to the temperature required for the project was viewed as dominating the drilling cost at the time of the study. A temperature of 175°C was used as the target for the four projects with low to moderate temperature gradients and air cooled binary conversion technology was assumed. The Valmy plant, in a very high temperature gradient area of Nevada was assumed to be a dual flash steam plant.

The sensitivity of LCOE at Mountaineer to both project scale and power plant efficiency as expressed by brine effectiveness in W-hr/lb of fluid was examined as an example for all four binary plants. (**Error! Reference source not found.**)



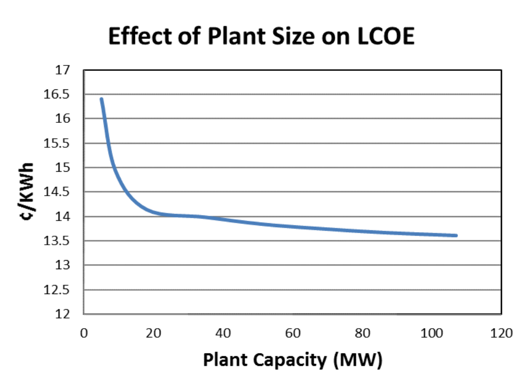


Figure 5 Sensitivity of LCOE to plant efficiency and capacity at Mountaineer, WV

As plant efficiency increases, costs steadily decrease so power plant efficiency is an important factor in cost reduction. Increasing plant efficiency by 20% decreases cost by 2.5¢/kWh. While plant scale is very important, rapidly decreasing LCOE for plants from 2 to 20 MW, the benefit of increasing size from 20MW to 100 MW only decreases cost by 0.5¢/kWh.

The variable with the highest impact on LCOE was found to be the injectivity of the injection well. This affects not only the pressure needed to inject the water which circulates through the system, but also impacts flow rate possible from each production well. Higher injectivity therefore reduces the total number of wells needed, particularly for a larger project. As an example Figure 6 shows the impact of injectivity in liters/minute/MPa on the injection flow rate and the number of wells needed at a 100MW EGS project at the Cayuga coal plant site in Lansing, New York.

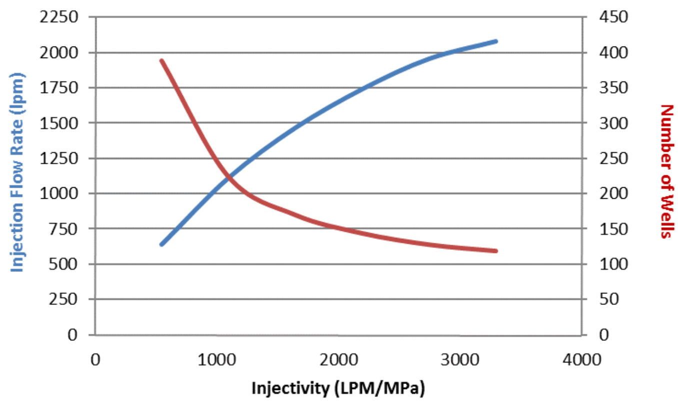


Figure 6 Modeled well field development as a function of injectivity at Cayuga EGS project

Since the completion of the original 2013 study, the drop in oil and gas prices has resulted in significant decreases in drilling cost, both for rig rental rates and for materials used in drilling, particularly for the deep wells with large casing sizes needed for EGS projects. Since well drilling is a significant cost factor in EGS projects, a revisit of the EPRI study was done to look at the impact of drilling cost reduction on LCOE and capital cost.

3. UPDATED COSTS FOR GEOTHERMAL POWER AT COAL PLANTS

The five sites included in the 2013 EPRI study were reviewed for inclusion in the update. Because the Danskammer plant near Newburgh, New York was converted to burn natural gas in 2014, this project is no longer a coal plant and so was not included in the update. The remaining 4 sites were updated using the same parameters as were used in the 2013 study but with reduced drilling costs and a uniform 100 MW power plant size. For the binary plants, a five module plant was assumed. For the flash plant, two 50 MW steam turbines were assumed.

3.1 Geothermal Potential at Coal Power Plants

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 distributed as a file type accessible through Google Earth™ In this study, SMU's resource potential map was overlain with the database published by the Carbon Monitoring for Action, which contains information about the carbon emissions of over 60,000 power plants worldwide. The temperature with depth data was used combined with the waste water flow from each plant to determine a resource potential and plant size that would use all of the waste water from the plant. This lead to a wide range of plant sizes from about 10 MW in the arid west to more than 300 MW for plants with higher water availability in the east.

Because the focus of this update is on the replacement of coal fired generation with geothermal using EGS technology the total resource potential that could be co-located at the coal plant site needed to be determined. In order for a coal plant to be replaced with geothermal power there has to be sufficient resource available under the surface area controlled by the coal plant operator. The 2013 study levelized the resource potential for all projects by assuming a uniform 40 km^2 of available land area.

For the update, the land area controlled by the plant operator was either determined by published data or by contacting the operator, or estimated using Google Earth satellite imagery. Then, the same method used for the original 2013 study was used to estimate the resource potential at each site using the entire land area. While a geothermal project would not take up very much more surface area than the existing coal plant, the geothermal rights to the subsurface would be needed in order to develop the resource. Table 3 shows the updated resource potential for each site.

Table 3 Resource potential for selected coal plant sites for 2015 update

Site	Coal Plant Capacity (MW)	Available Land Area (Acres)	Net Reservoir Thermal Potential (MW)	Recoverable Heat (MW)	Electricity Potential (MW)
Colstrip Power Plant	2094	56,000	2.69E+11	207,088	41,418
AEP Mountaineer Power Plant	1480	1700	1.02E+10	7,861	1,572
AES Cayuga Generating Station	306	1100	6.60E+09	5,086	1,017
Danskammer Point, Newburgh, NY	Converted to Natural Gas 2014	550	3.30E+09	2,543	509
NV Energy North Valmy Generating Station	522	10000	4.80E+10	36,980	7,396

3.2 Coal Plants Selected for Cost Update

Of the five sites selected for the 2013 EPRI study, four were updated for this study: Colstrip, Valmy, Cayuga and Mountaineer. While location may have an impact on the potential for cost reduction in drilling, large surpluses of material and rig availability combined with potential for favorable contracts possible when a large number of wells are drilled. For this reason, cost reductions of 30% were deemed reasonable for all projects. In some areas close to oil and gas operations, even larger cost reductions may be possible.

The four selected sites were reevaluated using 30% lower costs for well drilling for both producer and injector compared to costs used for the previous 2013 study. The injection well costs are higher than production well costs because three producers to each injector clusters were used. The higher injection rates needed to supply the production wells, means that the injection well needed larger casing diameter to accommodate the higher flow rate without excessive pressure drop.

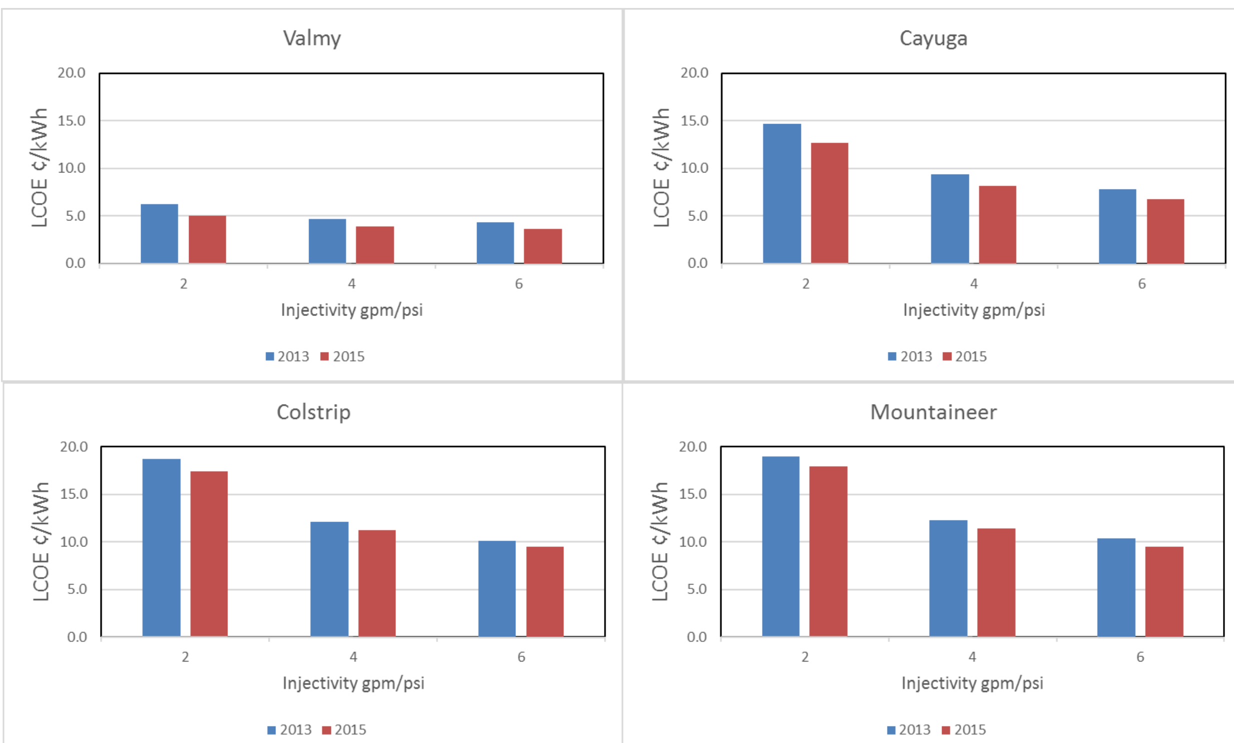


Figure 7 Comparison of LCOE for four selected sites using original 2013 costs with 30% reduction in drilling cost for 2015

The impact of 30% drilling cost reduction on LCOE is shown in Figure 7, while Figure 8 shows the impact on installed capital cost for these utility scale projects. The cost reduction ranged from 7% to 15% compared to the costs in the 2013 study. The impact of increased injectivity on project costs is clearly much greater than the impact of drilling cost reduction since improved injectivity can remove the cost of entire wells. Cost reductions due to increased injectivity ranged from 7% to 38% for projects with more and higher cost wells such as Mountainteer in West Virginia.

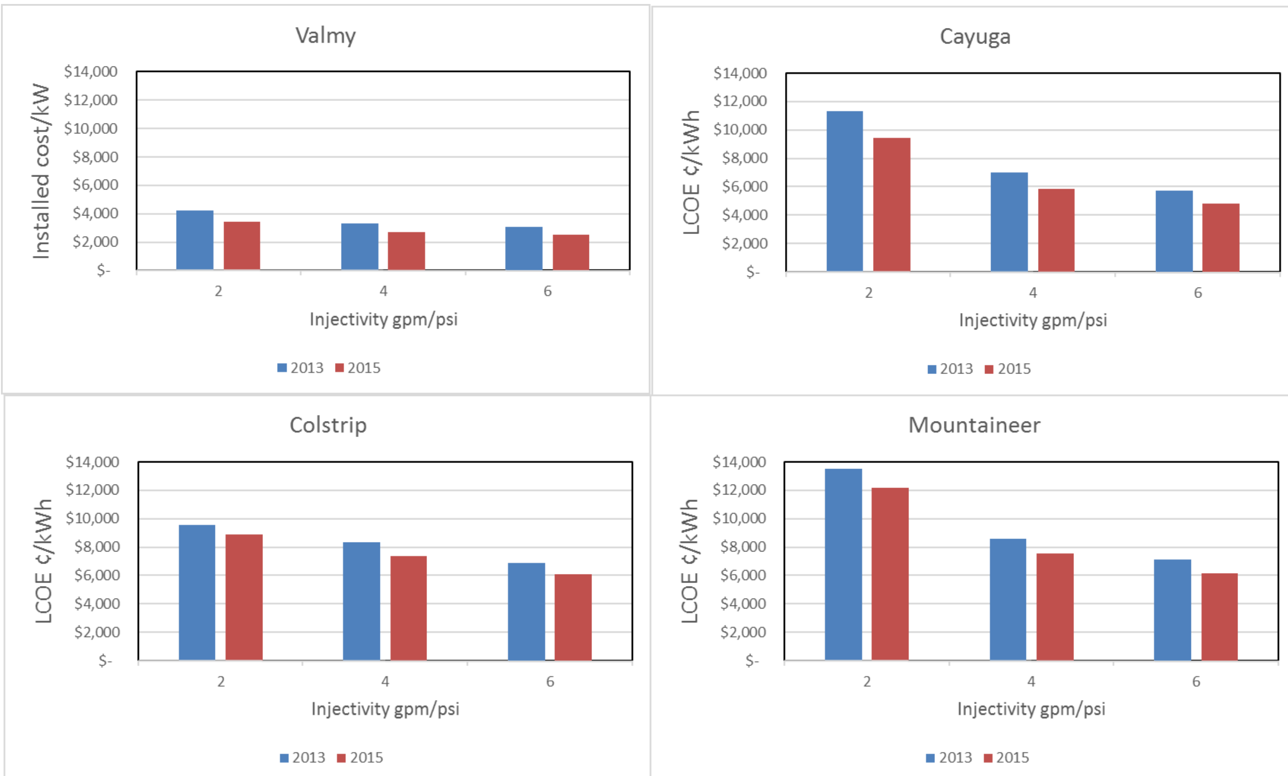


Figure 8 Comparison of 2013 capital cost per kW to 2015 costs with reduced drilling cost

Drilling cost reduction had the largest impact on capital cost for projects with deep wells such as Cayuga and Mountaineer (11% to 15% lower capital cost.) Injectivity remains the biggest single factor in determining project cost since this controls the injection pressure, the pressure drop through reservoir and the number of injectors and producers needed for the project.

4. CONCLUSION/FUTURE WORK

While reducing drilling cost remains an important target of most geothermal operators, for EGS projects a much larger factor in determining cost is the effectiveness of the stimulation at improving injectivity/productivity of wells while still providing good heat exchange for long term heat recovery without severe temperature decline. This is particularly true of utility scale projects where a large number of wells will be drilled and stimulated. Production well clusters around injection wells can reduce the total number of wells drilled in a large project. Learning by doing can also bring down project costs as the project develops.

The reduction in drilling costs does provide a very real opportunity to demonstrate EGS technology and benefit from learning by doing. The need to replace the baseload component of retiring coal fired power generation means that many coal plant sites have the potential to become geothermal power projects. The initial investment in this replacement effort will likely to be borne by investors rather than the coal plant owner/operator due the technology risk involved in early adoption of EGS. The example of the solar industry is useful here. As more and more solar installations of all sizes have been developed, costs have come down very rapidly. (Figure 9)

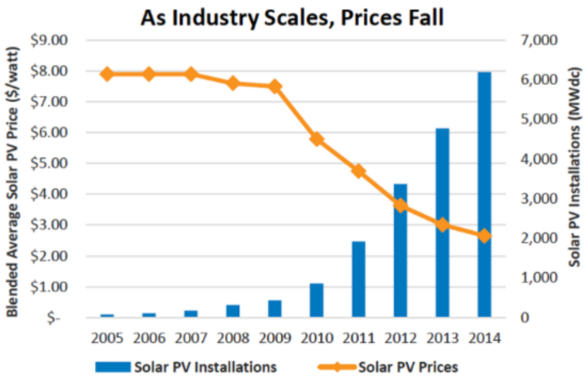


Figure 9 Drop in Solar PV prices as installations increase

While EGS costs at some coal plants in the western U.S. where high temperature gradients are found are likely to be very competitive with other renewables, for projects outside of the west with lower gradients the high capital cost for EGS will need regulatory frameworks that require renewables and give extra value for baseload renewable capacity. Even then, having example pilot projects operating at the site of coal plants will do more to convince utilities and coal plant operators that geothermal power is a viable option to replace their retiring plant.

Learning by doing by scaling a pilot EGS project to utility scale will not only reduce the cost of drilling, but also result in reliable and improving stimulation outcomes. So far, only a few EGS projects are in operation and those are small scale. High feed in tariffs for geothermal power in Europe has resulted in a number of projects coming on line in the past 8 years. However, these projects have not been scaled since the high power prices are only available for projects 5 MW and smaller. The benefits of repeating well drilling and stimulations in the same environment are only possible with utility scale projects.

Further research into stimulation best practices for EGS reservoir creation as well as strategies for improving near wellbore permeability will certainly be important. However, the biggest long term impact on EGS project cost will only come from installing large scale EGS projects in a variety of geologic settings. Replacing coal plants with geothermal using EGS technology provides that opportunity.

REFERENCES

Enhanced Geothermal Systems Potential Map of the Continental U.S. <http://www.google.org/egs/>, accessed September, 2012.

The Future of Geothermal Energy: The Future of Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century, An assessment by an MIT-led interdisciplinary panel. Prepared for the U.S. Department of Energy, Renewable Energy and Power Department Idaho National Laboratory, Contract DE-AC07-05ID14517, 358pp (2016).

Garrison, Geoffrey, Uddenberg, M., Cladouhos, T., Petty, S., Coleman, T.: An Assessment of Engineered Geothermal Systems for Water Management and Power Production, GRC Transactions, Vol. 37, 2013

Geothermal Electricity Technology Evaluation Model (GETEM), Version "Beta Version of GETEM 2012-08-29.xlsm." Maintained by United States Department of Energy (USDOE),

Google Earth (Version 7.0.3.8542) [Software]. Available from <http://www.google.com/earth/index.html> (2013).

Krauss, Clifford, "Drillers Answer Low Oil Prices With Cost-Saving Innovations", www.nytimes.com, The New York Times, May 11, 2015 web.Accessed Feb. 8, 2016. http://www.nytimes.com/2015/05/12/business/energy-environment/drillers-answer-low-oil-prices-with-cost-saving-innovations.html?_r=0

Matek, Benjamin: 2015 Annual U.S. & Global Geothermal Power Production Report, Geothermal Energy Association, 2015.

National Geothermal Database System (NGDS). http://geothermaldata.org/, accessed October, 2012.

Solar Energy Industries Association, Solar Industry Data: Solar Industry Breaks 20 GW Barrier, August, 2015, http://www.seia.org/research-resources/solar-industry-data

U.S. Energy Information Adminstration, Today in Energy, "Natural gas, renewables projected to provide larger shares of electricity generation", http://www.eia.gov/todayinenergy/detail.cfm?id=21072, May 4, 2015, Feb. 9, 2016.