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Supply Analysis of Geothermal District Heating and Cooling Application in United States

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ABSTRACT

This paper focuses on the approach to characterize the supply curve of geothermal energy for district heating and cooling system in the U.S. It estimates the thermal potential from identified, undiscovered hydrothermal resources, and near-hydro EGS resources. The thermal potential of the identified hydrothermal resources is estimated with a mean of 72,577 MW_{th}, with a lowest cost at 6.74 \$/MMBtu. That of the undiscovered hydrothermal resources is with a mean of 240,860 MW_{th}, with a lowest cost at 7.25 \$/MMBtu, and that of the near-hydrothermal EGS is 41,035 MW_{th}, with a lowest cost at 7.87 \$/MMBtu. An Excel-based model is developed to estimates the levelized cost of the geothermal district heating and cooling (GDHC) system corresponding to each resource. Several technical or economic inputs from the cost model are selected for sensitive analysis. The system's energy demand shows the most negative influence on the levelized cost, while the drilling cost shows the most positive influence. And increasing the energy demand is the most effective way to decrease the levelized cost. The supply curve indicates that the economical sites for the GDHC system are concentrated in western U.S. With over half of the low-cost identified hydrothermal energy has already been used for other applications such as geothermal power generation, it is worth considering the near-hydro EGS resources due to its acceptable levelized cost. Besides, there are another 150,000 MW_{th} of the undiscovered hydrothermal energy with levelized cost lower than 30 \$/MMBtu can also be used.

1. INTRODUCTION

The geothermal district heating and cooling (GDHC) system is defined to use a geothermal resource as a heat source to provide people with residential and commercial heating and cooling demand. The technologies in the GDHC systems, which including the subsurface reservoir design and the surface energy utilization and distribution, are mature and widely used. The GDHC systems uses an indigenous energy source that is insulated from changes in fuel price or supply, Thorsteinsson and Tester (2010), which makes it a high-capacity-factor system with stable cost. Also, it has the potential to significantly decrease mankind's dependence on hydrocarbon fuels and greenhouse gas emissions.

With all the promising advantages of the GDHC system, the development of it in the last decade has remained fairly constant, Lund et al. (2010). To the year of 2010, 21 GDHC systems are in operation with the installed capacity at 105 MW_{th} (data summed from Geo Heat Center, Oregon Institute of Technology). However, the estimated developable thermal capacity from hydrothermal geothermal energy is over 60,000 MW_{th}, Green and Nix (2006). There are barriers to implementing the GDHC systems, such as the competing natural gas price (system shut down in the Litchfield Correctional Facility in California, Lund et al. (2010)), general lack of public understanding of geothermal energy, high upfront investment, etc.

This paper focuses on the supply analysis of the GDHC systems, which answers the question about what is the potential of the technically and economically feasible geothermal energy for the GDHC systems, what is the levelized cost of energy by applying the system, and where are the most preferred locations for the GDHC systems. The two parts of studies are: estimation of the thermal potential, estimation of the levelized cost of the system.

2. PREVIOUS WORK

Previous works on supply analysis of geothermal energy have only been focused on the geothermal power generation, e.g. Petty et al. (1992), Petty and Porro (2007), Augustine (2011). The power potential and their cost summary from each report are listed in Table 1. The first geothermal supply analysis report was published in 1992 in which Petty identified 54 hydrothermal resources in the western U.S. by reviewing the USGS Circular 790, Muffler and Guffanti (1978), and the Bonneville Power Authority study, Bloomquist (1985). Due to the lack of exploration activities and insufficient data, the reservoir information such as temperature, depth, well flow, geology, and fluid chemistry was gathered based on the published reports, the state geothermal maps, personal knowledge, and contacts with the resource developers, Petty et al. (1992). The study used the IMGEO application developed by Entingh et al. (1988) to calculate the levelized cost as well as the capital cost of each resource. Petty and Porro (2007) updated the supply analysis of geothermal power generation with the new geothermal assessment data performed by Black Mountain Technology and a new costing model, GETEM developed by Princeton Energy Resources International, Entingh (2006). They also expanded their focus to the coproduced water from oil and gas wells, and a new geothermal category which is the enhanced geothermal system (EGS). In the latest supply analysis, Augustine (2011) reviewed any possible available reports and papers to estimate the power generation potential, in particular, the most recent geothermal assessment performed by USGS, Williams et al. (2008). For the cost estimation, the GETEM was still used, but with updated technical risk assessment, Young et al. (2010).

The supply analysis of other geothermal applications is currently blank, including the geothermal district heating and cooling system. There are case studies of specific GDHC or GDH systems, e.g. He and Anderson (2012), GHC (2005), Erdogmus et al. (2006), Yildirim et al. (2006), Ozgener et al. (2005), Valdimarsson (2008), but lack of a national-scale view of such application's supply characterization.

Table 1: Power potential and their cost summary from previous supply analysis studies

Source	Category	Power potential, MW_e	Power potential cheaper than ¢10/kWh, MW_e
Petty et al. (1992)	Identified hydrothermal	27,400	10,000
	Undiscovered hydrothermal	22,600	14,000
Petty and Porro (2007)	Hydrothermal and co-produced	71,600	71,600
	EGS	54,700	51,000
Augustine (2011)	Hydrothermal	36,400	25,000
	EGS	15,915,000	None*

**Levelized cost of EGS starts from ¢27/kWh.*

3. METHOD

This study includes two parts, 1) the estimation of the thermal potential and 2) the determination of the levelized cost of the system. The geothermal resources can be categorized into four types by the reservoir quality or water availability: identified hydro-geothermal, undiscovered hydro-geothermal, near hydro-thermal EGS and deep EGS resources. Because of the uncertainty currently associated with cost and achieved flow rates from green-field geothermal, this paper only focuses on the first three categories. The methods to estimate the potential of different resources are different, but the same levelized cost model is used for all the three categories.

3.1 Thermal potential estimation and reservoir characterization

3.1.1 Identified hydro-geothermal resources

The thermal potential estimate of this category has been discussed in the former supply analysis, He and Anderson (2013). It assumed the thermal potential to be the heat water can deliver to the surface, and calculated by Equation 1:

$$\dot{E} = \dot{m}_{WH} C_p (T_R - T_r) \tag{1}$$

The former report identified 251 moderate and high temperature geothermal resources in the western U.S., and retrieved the reservoirs' temperature and depth data from the USGS reports, e.g. White and Williams (1975), Muffler and Guffanti (1979), and Reed (1983). However, very little information about the reservoirs' flow rate was provided in the USGS reports.

This paper updates the method to estimate the available flow rate of each reservoir. It is derived from the volume method, which was used in the past USGS assessments for evaluating the power potential of geothermal energy, e.g. Nathenson (1975), Lovekin (2004). The volume method calculates the power capacity of each reservoir as a function of the reservoir temperature, flow rate, and other technical constant. So with available reservoir power capacity and temperature data, the flow rate is calculated by the use of GETEM as shown in Equation 2:

$$\dot{m}_{WH} = GETEM(\dot{W}_e, T_R) \tag{2}$$

For all the three categories, with the presence of possible values of reservoir temperature and mass flow rate, the Monte Carlo simulation will be used during the calculation. Therefore the thermal potential and the cost results will be in the form of possible values.

3.1.2 Undiscovered hydro-geothermal resources

Due to the uncertainty of the potential and location of undiscovered hydrothermal resources, there is not a way to target such kind of resource one by one and give estimation of them. This paper uses an analogous method as used in the geothermal power generation supply analysis, as shown in Equation 3. The thermal potential of the undiscovered hydro-geothermal in one region is α times of that of the identified hydro-geothermal resources in the same region. The favorability factor α is derived from the quantified evidence layers which are directly related to the occurrence of a hydro-geothermal resource, such as young felsic magmatism, high underground heat flow, occurrence of the Quaternary faults, etc. Williams et al. (2009) selected 28 evidence layers, assigned strength values of each layer based on the relation between the indicator and the geothermal resources, overlapped and analyzed these layers and gave estimation of the favorability factor of the hydrothermal resources in the Western U.S.

$$\dot{E}' = \alpha \dot{E} \tag{3}$$

As for the reservoir characteristics, a single reservoir depth, temperature, and mass flow rate will be assigned to all undiscovered resources for each state. For each state, the undiscovered resources are assumed to be more similar to the large identified resources than the small ones in reservoir characteristics. So the reservoir depth, temperature, and mass flow rate is measured by calculating the mean-thermal-capacity-weighted average of these parameters of the identified resources, as shown in Equations 4, 5, 6, and 7:

$$\beta_i = \dot{E}_i / \sum \dot{E}_i \tag{4}$$

$$d' = \sum (d_i \beta_i) \tag{5}$$

$$T'_R = \sum (T_{Ri} \beta_i) \tag{6}$$

$$\dot{m}'_{WH} = \sum(\dot{m}_{WHi}\beta_i) \tag{7}$$

3.1.3 Near-hydrothermal EGS resources

The near-hydrothermal EGS is defined as the geothermal resource around the hydrothermal site but lack of sufficient permeability to let water through. Because of the increased certainty surrounding the geologic environment and the potential for leveraging existing infrastructure, it is the least expensive EGS resource, and should be exploited first.

To the best of our knowledge, there is not a formal assessment of near-hydrothermal EGS resources. Therefore, an estimation of its thermal potential is preliminary and based on many assumptions. In this study, the reservoir temperature of near-hydrothermal resource is assumed as the same temperature with that hydrothermal resource which is in the nearby vicinity. The thermal potential of each near-hydrothermal EGS is assumed to be the difference between the mean and high-end estimates of thermal potential of its corresponding hydrothermal resources, shown in Equation 8:

$$\dot{E}_{near} = \dot{E}_{95percentile} - \dot{E}_{50percentile} \tag{8}$$

As for estimation of the mass flow rate, Darcy's Law describes the flow rate through a porous medium is determined by the permeability, the viscosity, the pressure gradient, and the drainage cross section. With absence of exploration data, it is hard to estimate such geologic data, therefore the flow rate for every resource. So in this paper, regardless of the subsurface characteristics, the mass flow rate is assumed as the available flow rate at the well head, and is directly set as possible values, as 40 kg/s, 60 kg/s, 80 kg/s, representing the current achieved rate and the increased rate because of the technology improvement in the future.

3.2 The GDHC system's cost model

A Microsoft-Excel based techno-economic analysis tool for GDHC system is developed. Its primary output is the levelized cost of thermal energy, but it can also provide other information such as capital cost, drilling cost of geothermal wells, operation and maintenance cost of the wells or the surface equipment, etc.

The design of the GDHC system considers not only the geothermal reservoir's availability of thermal output, which is solved by reservoir characterization, but also considers the integration of a well-designed surface heating and cooling facility, and the energy distribution network. The surface heating and cooling design is well discussed in the previous studies, He and Anderson (2012), (2014). The heating unit consists of an indoor radiator and an outdoor heat exchanger for each energy consumer, as shown in Figure 1. The cooling is provided by chilled water from a centralized absorption chiller. The size of the equipment is based on the maximum energy demand of each location from historical consumption data. By changing the mass flow rate of the production hot water, the system' energy output is therefore changed to fit the energy market due to the local ambient temperature change. The system will ensure no extra hot water is produced to prevent energy wasting and quick reservoir depletion. The GDHC system is not like geothermal power generation. The power grid will transmit any electricity that is generated. The design of the GDHC must be consistent with the energy demand. As a result, locations with dense population are preferred for a GDHC system.

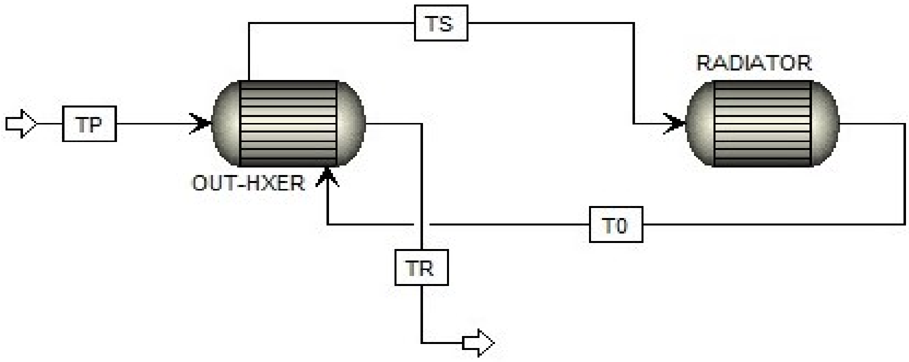

Figure 1: Schematic of a basic geothermal heating unit, which consists of a radiator and a heat exchanger.

The number of connections also plays an important role when designing the distribution network. A distribution model was discussed and a mathematic relation was developed between the total pipeline length and the connection node and distribution area in previous study, He and Anderson (2013), as shown in Equation 9:

$$L = 0.4 \times A^{0.5} N^{0.54} \tag{9}$$

For the other aspects of the cost model, the drilling cost follows a polynomial function of the drilling depth, which is developed by a cooperating research group from Cornell University, Beckers et al. (2013). The economic analysis follows Turton et al. (2008) procedure on the capital cost, and operation and maintenance cost. The levelized cost is calculated by Equation 10:

$$LC = \frac{\sum\left\{(I_t + M_t + F_t)/(1+r)^t\right\}}{\sum\left\{H_t/(1+r)^t\right\}} \tag{10}$$

4. RESULT AND DISCUSSION

4.1 Identified hydro-geothermal resources

With the reservoir characterization, the thermal potential will be estimated for each reservoir in each category. Then the GDHC cost model is used for economic analysis for each reservoir. Since some of the parameters contain probability distribution, the Monte Carlo simulation is used in this study. The iteration is set at 1000 times, and the simulations are processed by Excel @Risk add-in.

The total thermal potential of the 251 identified hydrothermal resources has a mean of 72,577 MW_{th}, and with a 95% probability of only 33,250 MW_{th} and a 5% probability of up to 113,535 MW_{th}. Identified resources are concentrated in the state of California, Nevada, and Alaska. Since quite a few numbers of resources have already been under development or in operation, mainly for geothermal power generation and space heating, the existing energy applications should be subtracted from the total thermal potential. The existing power generation capacity is 2,479 MW_e, Augustine (2011), and that of individual and district heating is around 215 MW_{th}, Lund et al. (2010). If assuming an overall 10% efficiency of thermal energy to electricity, the available thermal potential from identified hydro-geothermal resources is with a mean total of 47,566 MW_{th}.

As stated before, the GDHC system must be built at a populated location, so that the geothermal hot water can be consumed without much loss of energy. There are some of the geothermal resources with very few people living near them. Based on the levelized cost model, the levelized cost at such locations are extremely high, at more than $150/MMBtu. In the following analysis, those locations with unreasonably high levelized cost will be neglected. The levelized cost of the identified hydro-geothermal resources is estimated on a site-by-site basis. The supply curve can be plotted with the x-axis as the accumulative thermal potential and y-axis as the corresponding levelized cost (LCOH). Here the supply curve will be truncated to show the first 60 GW_{th} of thermal potential to emphasize the resources with lowest levelized cost, which are likely to be developed first, as shown in Figure 2. It also emphasizes the part of the supply curve with levelized cost lower than $40/MMBtu, as shown in Figure 3. Among all the resources, the Weiser area (Idaho) is with the lowest levelized cost, a mean of $6.74/MMBtu. Comparing to the current cost of residential heating by natural gas, which is $9.2/MMBtu, EIA (2013), most of the identified resources are above that cost. All the resources with competitive levelized cost can be characterized as with median or high reservoir temperature, median or low drilling depth, and the most importantly, with high energy demand. Figure 3 also tells that there are more than 8 GW_{th} of thermal energy can be utilized under $40/MMBtu with 10% of confidence, and more than 4 GW_{th} of thermal energy can be utilized under $40/MMBtu with 90% of confidence.

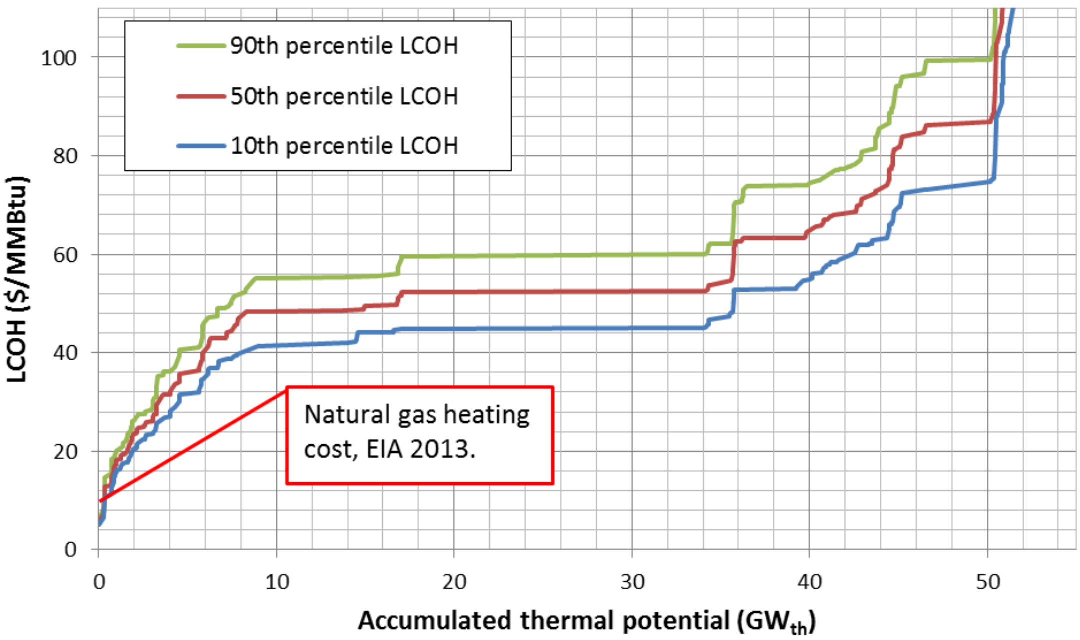

Figure 2: Supply curve of the identified hydrothermal resources, truncated at 60 GW_{th}, in comparison with the current cost of heating by natural gas, which is $9.2/MMBtu.

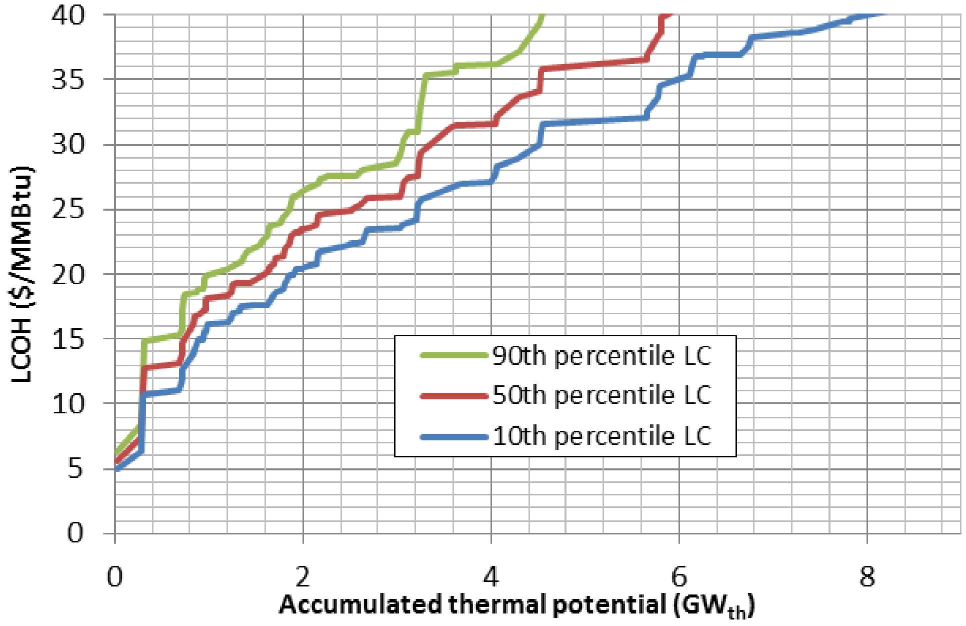

Figure 3: Partial enlargement of the identified hydrothermal resources' supply curve, with levelized cost lower than $40/MMBtu.

To determine the sensitivity of the model, seven technical or economic inputs from the model are selected. They are the system's energy demand, reservoir temperature, drilling cost, project lifetime, discount rate, pipeline capital, and heating and cooling facility capital. For each simulation, only one factor will be varied, while others remain constant. Several simulations will be run to ensure each factor varies -50%, -25%, +25%, and +50%, and the levelized cost result is recorded. The results of the sensitive analysis are shown in Figure 4. The energy demand has the most negative influence and the drilling cost has the most positive influence on levelized cost. Increasing the energy demand is the most effective way to decrease the levelized cost.

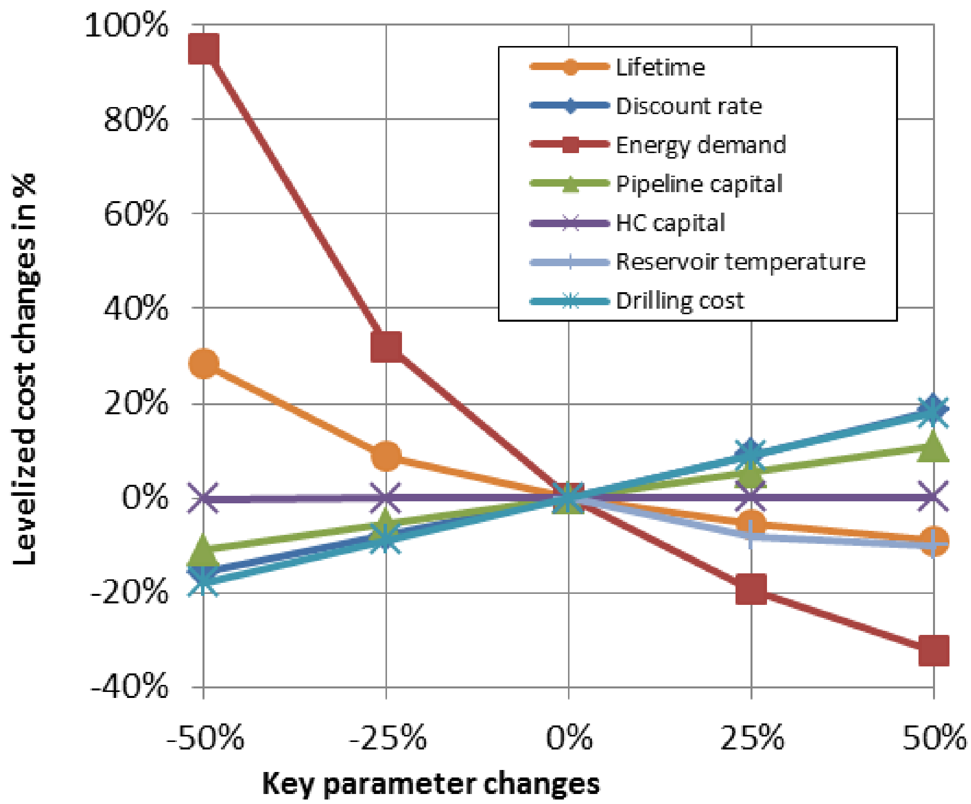

Figure 4: Sensitivity analysis of the levelized cost model with the identified hydrothermal resources data.

To further identify the relation between the levelized cost and the system's energy demand, the population data (*P*) of each location versus the corresponding levelized cost (*LC*) is plotted, as shown in Figure 5 in blue. With the least absolute error regression analysis of the population and the levelized cost data, the relation can be expressed in Equation 11, as shown in Figure 5 in red:

$$LC = 10202 \times P^{-0.7495} + 1.6469 \quad (11)$$

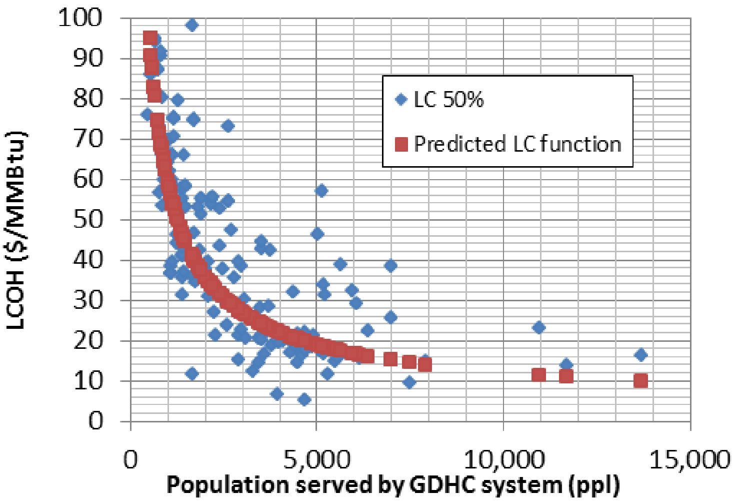

Figure 5: The population data at each geothermal reservoir versus the calculated levelized cost is plotted in blue. The levelized cost function derived by regression analysis is plotted in red.

4.2 Undiscovered hydro-geothermal resources

The favorability of hydrothermal resources presents the ratio of the undiscovered hydrothermal resources' occurrence to the discovered hydrothermal resources' occurrence. It is a statistical result derived from quantifying the preferable geologic conditions of hydrothermal resources, such as quaternary magmatic activity, heat flow, seismicity, etc. In this paper, several reports e.g. Augustine (2011), Williams et al. (2009), Williams and DeAngelo (2008) are consulted to estimate the favorability of hydrothermal resources for each state. The results of the favorability data are shown in Table 2:

Table 2: Favorability data of different geothermal regions.

Region	5% favorability	50% favorability	95% favorability
Alaska	2.28	2.64	3.13
Hawaii	9.78	13.45	17.00
Others	1.60	3.6	6.70

Based on Equation 3, the thermal potential of the undiscovered hydrothermal resources is calculated, with a mean total of 240,860 MW_{th}, and with a 95% probability of only 48,930 MW_{th} and a 5% probability of up to 579,660 MW_{th}. The distribution of the undiscovered hydrothermal resources' thermal potential of each state is shown in Figure 6.

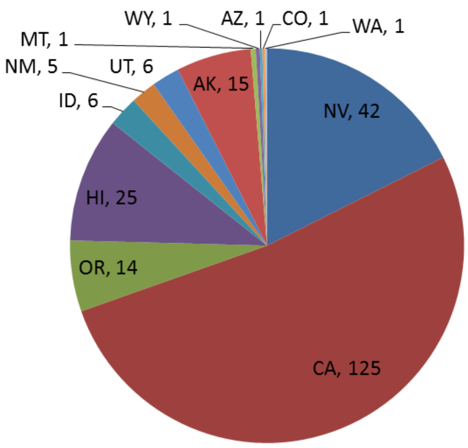

Figure 6: The total thermal potential of the undiscovered hydrothermal resources has a mean 241 GW_{th}. The distribution in each state is shown above.

As stated before, the reservoir characteristics of each state are calculated by a mean thermal potential weighted average. Thus the reservoir characteristics are more like the large identified geothermal reservoir in each state. But populated place not necessarily locates near the large identified geothermal resource in every state. In this paper, for each state's undiscovered hydrothermal resource, the GDHC system's energy demand is assumed to be the largest energy demand in that state. The supply curve is shown in Figure 7. The undiscovered resource with lowest levelized cost is the resource under 150°C in California, at $7.25/MMBtu with 50% of confidence.

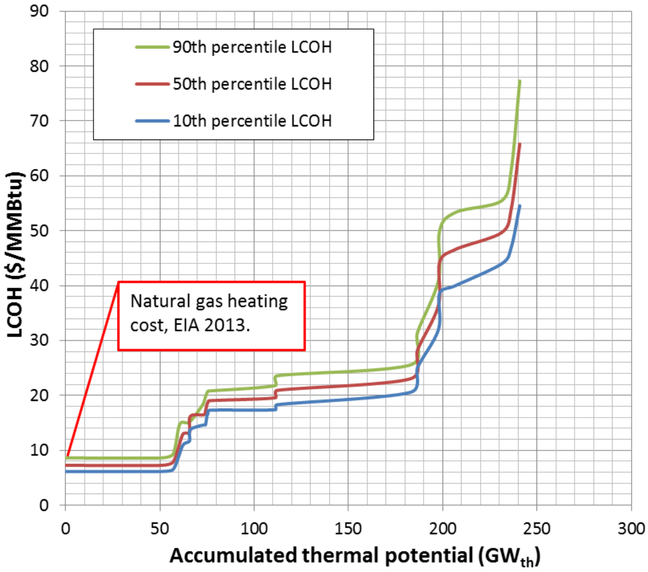

Figure 7: Supply curve of the undiscovered hydrothermal resources, in comparison with the current cost of heating by natural gas, which is $9.2/MMBtu.

Since the same model is used to calculate the levelized cost, the sensitive analysis for both the identified and the undiscovered hydrothermal resources are the same. For undiscovered resources, the energy demand still has the most negative influence and the drilling cost still has the most positive influence on levelized cost. And increasing the energy demand is still the most effective way to decrease the levelized cost.

4.3 Near-hydrothermal EGS resources

The near-hydrothermal EGS has the same reservoir depth and temperature with the hydrothermal reservoir which it is close to. The availability for water pathway is the difference between these two categories. Based on Equation 8, and the thermal potential estimation of the identified hydrothermal resources, the total thermal potential of near-hydrothermal EGS is 41,035 MW_{th}. The top five resources with the most thermal potential are all in California, which are Salton See area (8,555 MW_{th}), Geysers area (3,416 MW_{th}), Brawley (1,646 MW_{th}), Coso area (1,448 MW_{th}), and the Medicine Lake (1,393 MW_{th}).

With the uncertainty of the mass flow rate of each EGS reservoir, 40 kg/s, 60 kg/s, 80 kg/s is used as flow rate inputs for each case. The supply curve is shown in Figure 8. Among all the resources, the Weiser area (Idaho) is still with the lowest levelized cost, at $7.87/MMBtu. The cost increase is mainly due to the cost of hydro-fracture stimulation to create the EGS reservoir. Theoretically, with increased mass flow rate, the levelized cost will decrease because of the decreased number of production well. The several resources at the left end of the supply curve in Figure 8 do perform such character. The levelized cost of the 80 kg/s scenario is the lowest, while that of the 40 kg/s scenario is the highest. But for the other resources in Figure 8, most locations are with small energy demand, usually below 10 MW_{th}. As a result, one production well with 40 kg/s water flow rate is sufficient to provide the energy demand. Increase in mass flow rate will not efficiently decrease the number of the production well, therefore the levelized cost. That's the reason in Figure 8 the supply curves for three different mass flow rate scenarios overlap for the most parts.

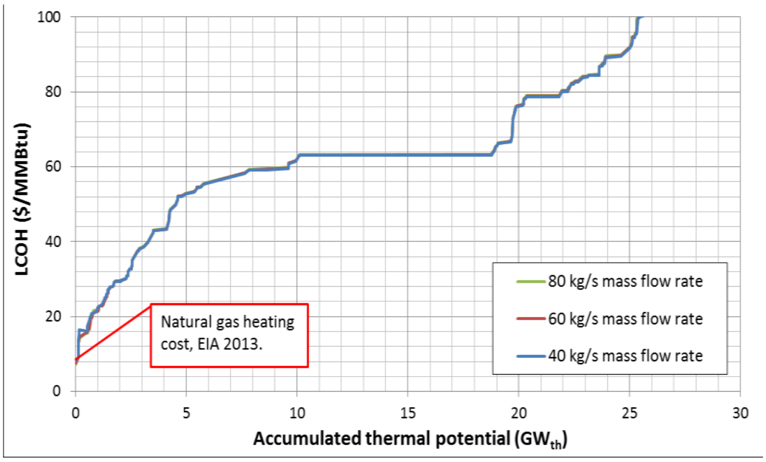

Figure 8: Supply curve of the near-hydrothermal EGS resources, with levelized cost lower than $100/MMBtu, in comparison with the current cost of heating by natural gas, which is $9.2/MMBtu.

At last, Figure 9 shows the supply curve which integrates all the three categories of geothermal resources. Figure 10 is a partial enlargement to show the thermal potential with acceptable levelized cost. The combined supply curve shows the order in which resource should be developed first based on the calculated levelized cost. Figure 9 tells over 80% of the thermal potential is with a levelized cost lower than $80/MMBtu. In Figure 10, except the starting point is the identified hydrothermal resource (Weiser area, ID) and its corresponding near-hydro EGS, over 50,000 MW_{th} of potential is undiscovered, with lower cost than the natural gas based heating. Besides, there are another 100,000 MW_{th} of the undiscovered hydrothermal resources with levelized cost between \$20 and \$30/MMBtu. The near-hydro EGS is the least expensive type of EGS resource. The levelized cost of near-hydro EGS is a little higher than its corresponding identified hydrothermal resources. Thus in the supply curve, the near-hydro EGS and the identified hydrothermal resource are usually together. In fact, there is not much thermal potential available from identified hydrothermal resources. From Figure 2, there is only 45,000 MW_{th} of potential with levelized cost lower than \$80/MMBtu, while the existing geothermal application has consumed over half of such potential, which is also the potential with lowest levelized cost. As a result, the near-hydrothermal EGS corresponding to those most competitive identified hydrothermal resources may be a good choice for expanding the existing system.

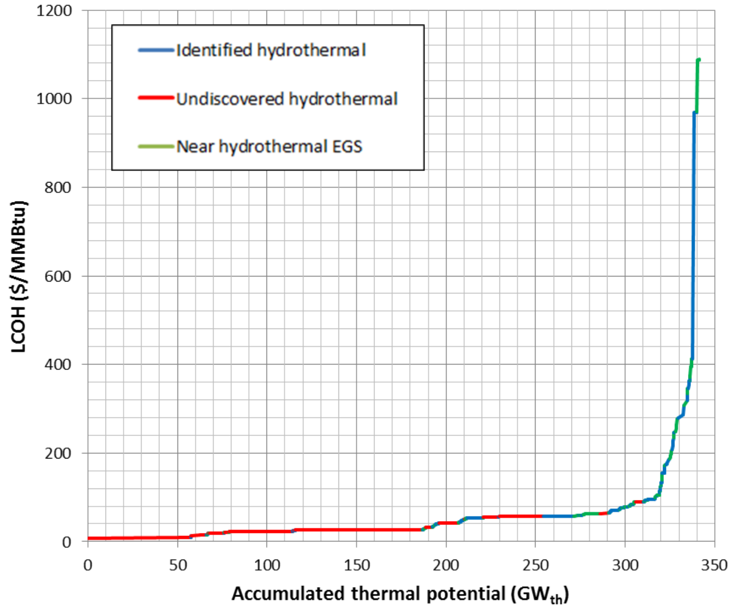

Figure 9: Supply curve integrated with three categories of geothermal resources.

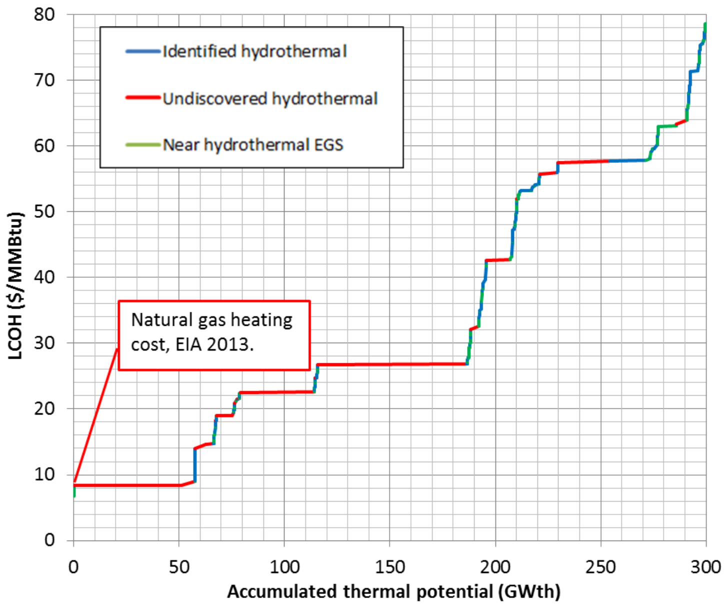

Figure 10: Partial enlargement of the integrated supply curve, in comparison with the current cost of heating by natural gas, which is \$9.2/MMBtu.

5. CONCLUSION

This paper focuses on the supply analysis of geothermal district heating and cooling systems (GDHC). This study categorizes the geothermal resources into four types: identified hydro-geothermal resources, undiscovered hydro-geothermal resources, near-hydro EGS and deep EGS. The thermal potential of the first three categories is estimated in this study. The thermal potential of the 251 identified hydrothermal resources is with a mean of 72,577 MW_{th}, and with a 95% probability of only 33,250 MW_{th} and a 5% probability of up to 113,535 MW_{th}. The thermal potential of the undiscovered hydrothermal resources is with a mean of 240,860 MW_{th}, and with a 95% probability of only 48,930 MW_{th} and a 5% probability of up to 579,660 MW_{th}. The thermal potential of the near-hydrothermal EGS resources is about 41,035 MW_{th}.

This paper also describes a Microsoft-Excel based techno-economic analysis tool for the GDHC system. The cost of near-hydrothermal EGS is usually higher than the hydrothermal resources, due to the hydro-shear or stimulation processes. And the cost of the undiscovered resources is higher than the identified ones, due to the exploration cost. The resource with the lowest levelized cost is the Weiser area, in Idaho, for both identified hydrothermal or near-hydrothermal EGS. The levelized cost is $6.74/ MMBtu using identified hydrothermal resources, and $7.87/MMBtu using near-hydrothermal EGS resources. The undiscovered hydrothermal resources in California are the cheapest among all the undiscovered hydrothermal resources. The levelized cost is $7.25/MMBtu. According to the sensitivity analysis of the cost model, the energy demand of the GDHC system has the most decreasing influence and the drilling cost has the most increasing influence on levelized cost. Therefore, increasing the energy demand is the most effective way to decrease the levelized cost of a GDHC system. Further investigation reveals that the levelized cost follows a power function with the served population, which directly influences the energy demand.

The supply curves show the order in which resource should be first developed. Since currently over half of the competitive identified hydrothermal resources has been developed, the undiscovered hydrothermal and the near-hydrothermal EGS resources are noteworthy. There are over 150,000 MW_{th} of potential undiscovered with levelized cost lower than $30/MMBtu, about 30% of such resources are even cheaper than the natural gas for heating. And with a little higher cost, the near-hydrothermal EGS may also be a good choice to expand the existing system which is based on the hydrothermal resources.

6. ACKNOWLEDGEMENT

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8. NOMENCLATURE

A	target distribution area [km^2]
C_p	specific heat [kJ/kg/°C]
d	reservoir depth [m]
$\dot{E}$	thermal potential of identified resources [kW]
F	GDHC pumping cost [$/year]
H	overall heating and cooling consumption [MMBtu/year]
I	GDHC system capital annuity
L	length of the distribution pipe [km]
LC	Levelized cost of the GDHC system [$/MMBtu]
M	GDHC operation and maintenance cost [$/year]
$\dot{m}_{WH}$	mass flow at the well head [kg/s]
N	number of connections to the network
P	population served by the GDHC [ppl]
r	discount rate [%]
T_R	reservoir temperature [°C]
T_r	reinjection temperature [°C]
$\dot{W}_e$	power potential of geothermal resources [kW]

α favorability factor

β_i thermal weighted average factor

Superscript

$'$ reservoir characteristics of the undiscovered hydrothermal resources

Subscript

i geothermal resources index

t system operation year index