Introducing the GeoRePORT Resource Size Tool: Reporting on Geothermal Resource Size Estimations Using the Geothermal Resource Portfolio Optimization and Reporting Technique (GeoRePORT)

Preprint

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1 National Renewable Energy Laboratory
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Introducing the GeoRePORT Resource Size Tool:

Reporting on Geothermal Resource Size Estimations Using the Geothermal Resource Portfolio Optimization and Reporting Technique (GeoRePORT)

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ABSTRACT

The Geothermal Resource Portfolio Optimization and Reporting Technique (GeoRePORT) was developed with funding from the U.S. Department of Energy (DOE) Geothermal Technologies Office (GTO) to assist in identifying and pursuing long-term investment strategies through the development of a resource reporting protocol. The assessment protocols used in GeoRePORT allow for comparison of project attributes across locations and geological settings to understand the feasibility of geothermal development. This work introduces the Resource Size Tool, a new feature within the GeoRePORT package that compiles two independent methods for estimating geothermal resource size in terms of energy capacity in MW. Energy production potential for 23 case studies was estimated with the Resource Size Tool in order to: (1) generate a reasonable range of resource size estimates for a particular geothermal field; (2) illustrate the advantages and limitations of each methodology (such as data input requirements, estimate accuracy and precision, and the appropriate circumstances of use); and (3) test the ability of the resource size tool to provide useful and accurate information for geothermal stakeholders. The tool employs two methods widely used in the geothermal industry: (1) USGS Volumetric and (2) Power Density. Results from our case studies show general overlap between these two methods in terms of resource size estimates; however, they also reveal key differences between the two approaches that should be considered when using such estimates to drive development. First, the two methods rely on different input parameters and therefore one method may be more appropriate and/or accurate for a given project than the other. Second, the Power Density method was found to generate wider ranges of resource size predictions, more consistently aligning with actual power production of the field but with larger scales of error, whereas the USGS Volumetric method predicts narrower ranges but tends to overestimate when compared to current MW production. Future work will refine variables used in the methods with input data from other sections of GeoRePORT and modify uncertainty levels based on the particular datasets used for a given project.

1. INTRODUCTION

The Geothermal Resource Portfolio Optimization and Reporting Technique (GeoRePORT) system was developed to address the needs of the U.S. Department of Energy (DOE) Geothermal Technology Office (GTO) effectively measure the impact of its research, development, and deployment funding for geothermal projects (Young et al. 2016a). GeoRePORT is designed to provide a uniform assessment criterion for geothermal resource grades and developmental phases of geothermal resource exploration and development. GeoRePORT provides scientists and nonscientists a comprehensive and quantitative means of reporting: (1) features intrinsic to geothermal sites (project grade) and (2) maturity of the development (project readiness). Because geothermal feasibility is not determined by any single factor (e.g., temperature, permeability, permitting), a site's project grade and readiness are evaluated on 12 attributes pertaining to geological, technical, or socio-economic feasibility. GeoRePORT was developed to provide consistency among the user community in *reporting*; it is neither a prescription for conducting exploration and field development nor a replacement for expertise and conceptual or reservoir models.

The GeoRePORT protocol was designed to distill massive amounts of geothermal project data into a concise, communicable summary that can be understood by project experts (e.g., geochemists, permitting experts) and by those in management. It can be used to establish country baseline information, for project-specific reporting, or for summarizing project development portfolios. Previous publications (Kolker et al. 2019; Young et al. 2016a; Badgett et al. 2015) have discussed the aims of GeoRePORT and presented applications of the tool. (Full details about GeoRePORT and the protocols can be found on https://openei.org/wiki/GeoRePORT.) This paper provides an introduction to the resource size tool that was recently developed as part of the GeoRePORT package, outlining its development and testing its usefulness by applying it to a number of geothermal case studies.

The resource size tool is an essential addition to GeoRePORT due to the economic and legal context of geothermal development. In order to utilize a geothermal resource, a competitive Power Purchase Agreement (PPA) must be obtained, for which the resource's power capacity must be demonstrated. However, proving the existence and size of a geothermal resource is comparatively expensive and risky relative to other renewable technologies; it can cost developers 5 to 10 million USD to demonstrate a financially viable geothermal resource (Young et al. 2017). GeoRePORT aims to address this barrier to development by providing a clear assessment of resource quality and certainty. The resource size tool will enable GeoRePORT users to not only qualitatively report on a given a resource, but also to compare methodologies for quantifying a potential power output for a plant.

Multiple methods exist for estimating energy capacity of a reservoir. The two relevant to this study will be introduced briefly below. For further information, refer to Sanyal and Sarmiento, 2005 and Franco and Donatini, 2017.

Absent from these is the more robust method of numerical simulation and modeling, which provides the most realistic estimate of potential resource size but requires parameters that may be unavailable to GeoRePORT users such as rock porosity and permeability, fluid flow, and reservoir shape (gleaned through production, injection, and flow data from already-drilled wells). Similarly, lumped-parameter models and decline-curve analyses require production data from an already-installed power plant. Because GeoRePORT is used for the assessment of both undeveloped and developed resources, these tools for power estimation are not in the scope of the resource size tool.

Another method for geothermal reservoir estimation is the Heat Loss Method (Wisian et al. 2001). This method uses the flow of heat out of a reservoir to calculate potential MW production. Because neither heat flow nor the parameters used to calculate heat flow are reported in GeoRePORT this method was excluded as well.

2. REVIEW OF EXISTING METHODS FOR RESOURCE SIZE ESTIMATION

2.1 Volumetric Method (Heat-in-Place)

The USGS Volumetric or Heat-in-Place method has been commonly used to calculate geothermal power reserves since its conceptualization in the 1970s. It provides a simple method for estimating resource potential by breaking down the reservoir into its volume of rock, the heat energy in that rock, and how much of it will be extracted over the lifetime of the plant. The basic equation is:

$$Q_T = A \bullet h \bullet (T_r - T_a) \bullet C$$

where Q_T is the total available heat resources of the geothermal system, A is the area of the reservoir (m^2), h is the reservoir thickness (m), T_r is the initial temperature of the reservoir (°C), T_a is the abandonment temperature of the power plant (°C), and C is the heat capacity of the reservoir (kJ/kg°C).

This method has seen critique over the past several decades because it has tended to overestimate the amount of energy in a reservoir (Grant 2014; Garg 2010; Garg and Combs 2015). These overestimates stem from the lack of consideration for the heat lost in resource utilization, as well as an overestimation of certain parameters.

The more detailed equation utilized for this analysis is summarized by Pocasangre and Fujimitsu in their 2018 paper regarding the Python program GPPeval, developed to estimate resource size using an updated version of the volumetric method. It breaks down total heat into two components: heat from the rock and heat from the fluid within the rock.

$$Q_T = Q_R + Q_W \tag{1}$$

Where Q_r is the thermal energy found in the rock and Q_w is the thermal energy found in the water contained in the reservoir.

$$Q_R = A \bullet h \bullet [\rho_r \bullet C_r \bullet (1 - \phi) \bullet (T_r - T_a)] \tag{2}$$

Where A is the area of the reservoir (m^2), h is the average thickness of the reservoir (m), ρ is the rock density (kg/m^3), C_r is the rock specific heat at reservoir conditions (kJ/kg-°C), and ϕ is the porosity of the reservoir (%).

$$Q_w = A \bullet h \bullet [\rho_w \bullet C_w \bullet \phi \bullet (T_r - T_a)] \tag{3}$$

Where ρ_w is the fluid density (kg/m^3) and C_w is the fluid specific heat at reservoir conditions (kJ/kg-°C).

Together, these equations yield a value representing total heat stored in the reservoir. To determine the amount of energy which could be extracted by power plants, another equation is used:

$$P = (Q_T \bullet RF \bullet C_e) / (PF \bullet t) \tag{4}$$

Where RF is the recovery factor of the reservoir (the fraction of heat that can actually be recovered to the surface to be used), C_e is the conversion efficiency of the plant being used to capture the energy, PF is the plant factor or the percentage of time a plant can be used to generate electricity throughout the year, and t is the economic life of the plant (years).

Two corrections to values within the volumetric equation have been applied in order to curb overestimation. The first is narrowing the range of recovery factors. Original USGS studies generally assumed a value of 0.25; however, this factor was found to be too high in most cases (Grant 2014). Adjusted ranges assume a rectangular distribution of more conservative values of 0.08 to 0.20 (Garg and Combs 2015). Another adjustment applied to the volumetric equation was the choice of abandonment temperature. USGS originally used an abandonment temperature of 15^{o} C, an assumption of the ambient air temperature; however, the temperature at which a fluid is no longer usable is actually dependent upon the design of the power plant, not the temperature of the air. Accordingly, it is recommended that the saturation temperature corresponding to saturator pressure be used for flash plants, generally 151.831^{o}C for flash plants. The abandonment temperature of a binary plant is its pinch-point temperature, which depends on the working fluid used (Garg and Combs 2015).

Many of the variables used in the Heat-in-Place equation have ranges of values, with certain values within the range having higher probability or confidence. It is therefore generally recommended that a Monte Carlo stochastic analysis be performed on the data, giving a probability distribution of power capacities of the reservoir. The mode of the distribution can then be taken as the most likely resource size value. The tool presented herein conducts such Monte Carlo simulations and reports the probability distribution of various energy reserve estimates.

A few drawbacks must be considered when using the Volumetric method. Reservoir volume estimates are uncertain, as reservoir surface area is not easy to delineate accurately and the depth to the top and bottom of the reservoir varies across a geothermal field. The recovery factor also continues to present issues, as the value is not calculated from empirical data, and is simply conjecture. This "heuristic fudge factor" (Grant 2014) is assumed to take on the same range in all cases. The use of porosity in the equation also faces similar issues, as it is categorically assumed to be 0.05 without any resource-specific variation.

2.2 Power Density Method

Due to the limitations of the Volumetric Method, many geothermal professionals prefer to use power density for first-order estimates of resource capacity, usually expressed in terms of MW/km2.

While many geothermal professionals make resource capacity estimates using power density, historically, there have been only a few publications which describe how to assess power density and how it might vary as a function of resource type and temperature. Grant (2000) suggested that power density increases with reservoir temperature, indicated 10-20 MW/km^2 was a suitable range in early exploration, and observed that "…power density for most fields ranges from 8 MW/km^2 at 230°C to up to 30 MW/km^2 at 300°C." Grant and Bixley (2011), Atkinson (2012), Bertani (2005), Sarmiento and Björnsson (2007), and Benoit (2013) have all investigated and made alternative suggestions for power density relationships.

Wilmarth and Stimac (2014) surveyed power density of 53 high-temperature (>200°C) geothermal fields around the world with more than 15 MW net output and at least 10 years of production history and concluded that power density increases with average reservoir temperature in a manner similar to that proposed by Grant (2000). Wilmarth and Stimac (2015) expanded the study to lower temperature systems (>130°C), to smaller fields with more than 10 MW net output and to younger fields with at least 5 years of production history. They found that power density generally increases with increasing reservoir temperature, but that tectonic setting strongly controls power density as well. In particular, volcanic arc-hosted systems have a bimodal distribution of power densities, such that roughly half of the volcanic arc-hosted operating geothermal fields in the world lie on "The Main Sequence"—the main trend of increasing power density with reservoir temperature (Figure 1)—while the other half of this group of geothermal fields demonstrate a constant power density of ~10 MW/km2 independent of increasing reservoir temperature. The suggestion was that these systems ("Constant Power Arcs") tend to be in more purely compressional structural settings where reservoir permeability is limited and not preserved.

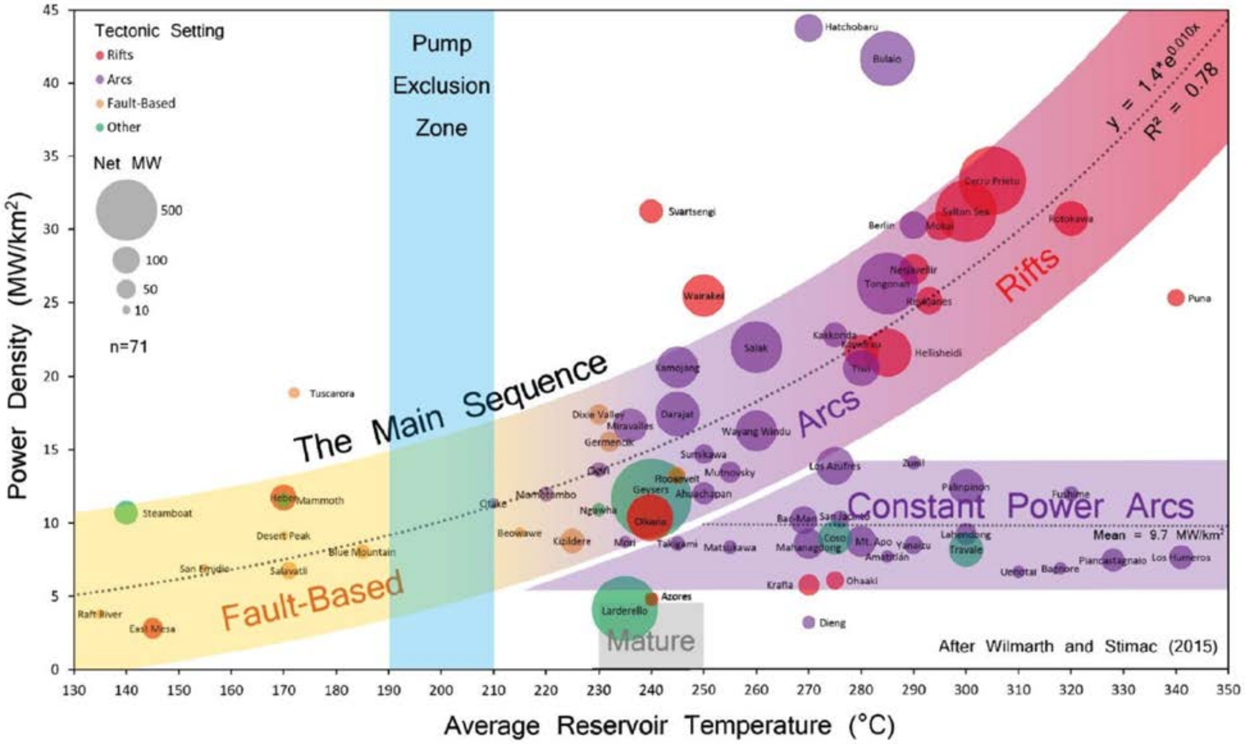

Figure 1: Power density vs. temperature for 71 geothermal fields with interpreted affiliations. After Wilmarth and Stimac (2015). (This plot is frequently updated, and those that wish to use it are encouraged to contact its authors for the most recent version).

A key source of uncertainty in this approach is the definition of area of a system (in m^2). A 500-m buffer around production wells is a common metric in the industry; other workers would include unproduced area known to contain reservoir fluids. Wilmarth and Stimac (2015) explain that their 500-m^2 area definition allows for a baseline comparison across fields and pairs actual production wells with the MWs produced by those wells. Reservoir temperature is always a range, and the use of average reservoir temperature is a simplification. Net power output was used rather than gross because these values are much more commonly available, but this means power plant efficiencies were not considered. Fields that had been producing for more than 5 years but had only recently expanded may have had an unsustainable power output.

3. METHODOLOGY

The Resource Size Tool consists of several tabs in the GeoRePORT Excel worksheet, which pull user input data about a reservoir from the main GeoRePORT interface and estimate resource potential via the Volumetric and Power Density Methods. To accommodate these methods, a "master tab" was created to allow inputs for variables not present within the previous iterations of GeoRePORT.

In this study, the Volumetric method was conducted using a prototype of the Resource Size Tool, which calls the Python program GPPeval. In this version, the Volumetric Method tab is formatted to output a comma-separated-value file to GPPeval containing all necessary parameters. The tool has since been updated to solely utilize Excel-based programming, and no longer requires the user to download or run GPPeval and its associated packages.

The tool asks the user to report the minimum, mean, and maximum measured temperatures of the resource. It also requires the ranges for either the volume of the reservoir or the area and depth, depending on which parameters were measured. The reference/abandonment temperature varies based on the temperature of the reservoir, and, thus, the type of power plant which is most likely to be used. If the user has reported Temperature Difference grades (under the Power Conversion tab of GeoRePORT) of A or B, signifying a flash plant, then the abandonment temperature in the input file is set at 151.831 ℃, based on the saturation temperature of a flash-steam plant (Garg and Combs 2015). If the user reported grades of C or D, indicative of a reservoir temperature appropriate for a binary power plant, then an abandonment temperature of 105.36 ℃ is used (Garg and Combs, 2015). Likewise, conversion efficiency at grades of A or B is assumed to be .4, based on average efficiencies of flash-steam power plants. For binary plants, at grades C or D, conversion efficiency, is assumed to be 0.25 (Garg and Combs 2015).

A cell for reporting reservoir rock type was added to the GeoRePORT spreadsheet. Rock specific heat capacity and density are then set in the input file based on this parameter, with values taken from USGS reports and rock density tables (Robertson 1988; Jemmal et al. 2016; Hartlieb et al. 2015; Gilliam et al. 1987, Alden 2019). This is a more precise methodology than has been taken in many other studies, in which an average specific heat and density of reservoir rock was simply assumed, regardless of the actual bedrock type of the reservoir. (Klein et al. 2004). Specific heats and densities of fluid were taken from standard tables of water thermal properties by temperature

(Engineering ToolBox). Recovery factor is input as a range with uniform distribution between 0.08 and 0.2 (Garg and Combs 2015). Porosity is assumed to be 0.05 and constant across the reservoir, with a standard deviation of 0.02. Power Factor, or the plant's availability throughout the year, is considered as a range between 0.9 and 1, with a mean of .95.

These values were input into Pocasangre and Fujimitsu's Python model, which conducted Monte Carlo statistical simulation to determine the most probable values for resource size. 10,000 iterations were run for each case study. (The Resource Size Tool now performs these statistical calculations within its own Excel workbook).

Another tab in GeoRePORT performs the calculation of resource size using the Power Density method. It uses the minimum temperature reported by the user as the P10 value, the mean/most likely as P50, and the maximum as the P90 value. The user is also asked to report tectonic setting. Based on these values, the power density at these three confidence levels is calculated using the plot of power density versus reservoir temperature, grouped by geologic setting, after Cumming (2016). If tectonic setting is not a purely compressional arc, then the P10 power density is determined from the equation for the line of the lower boundary of the main sequence at the minimum temperature, P50 from the mean trendline at the mean temperature, and P90 from the upper boundary of the main sequence at the maximum temperature. These power density values are then multiplied by the total surface area of the reservoir that the GeoRePORT user has reported to determine total net power capacity of the reservoir.

These two methodologies were first evaluated with four case study reservoirs which have been run through the GeoRePORT framework already: the Coso Geothermal Field in California, Chena in Fairbanks, Alaska, White Sands Missile Range in New Mexico, and Dixie Valley in Nevada. Additional example fields were taken from sources listed in Appendix A. We intentionally chose case sites in semi-equal representation of each of the four tectonic settings shown in Figure 1.

In order to facilitate better analysis, previous estimates by the USGS were recorded and included to compare with the ranges found from the two methods (DeAngelo and Williams 2010). Additionally, actual production values, when available, are presented in order to compare the estimates to reality. Actual production values come from sources listed in Appendix A.

4. RESULTS

For each case study, the results of the Monte Carlo analysis of the Volumetric Method, as well as the results of the Power Density Method, were compiled and visualized in the figures below, along with any previous estimation data and the actual production data (if available). It should be noted that although data was added together if there were multiple geothermal generation plants on a given reservoir, the actual values do not necessarily reflect the maximum achievable power output from a field.

The results of each of the studies were then used to group the studies themselves into three graphs depending on MW output. The three groupings are low power (Less than 60 MW), medium power (60-160 MW), and high power (Greater than 160 MW).

For analytical purposes, mean temperature, mean surface area, and mean volume are displayed above the MW output graph for each site. The correlation of these parameters with resource size results can thus be investigated.

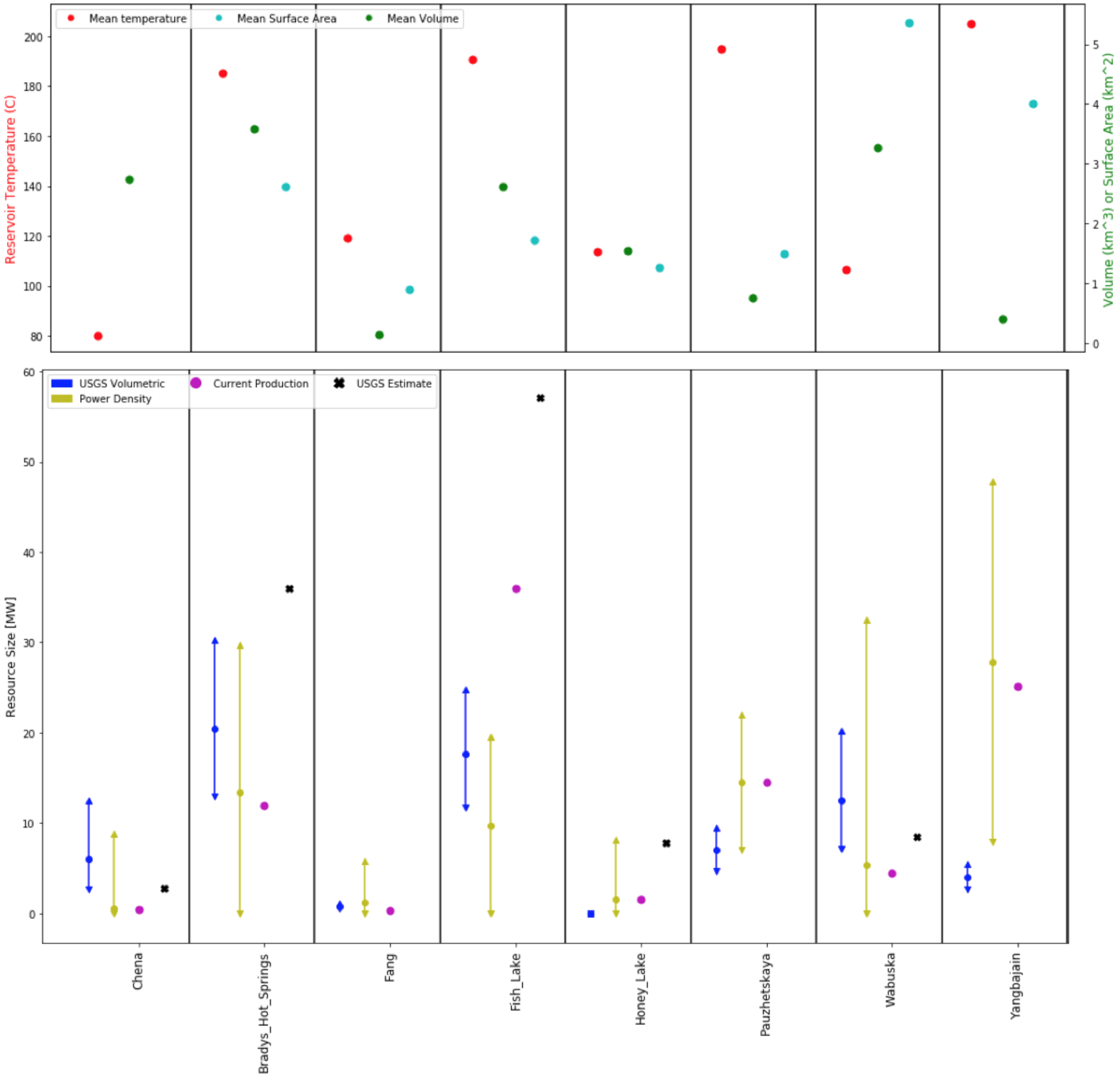

Figure 2: Temperature, surface area, volume, and predicted megawatt capacity of small-size (less than 60 MW) resources. On the USGS Volumetric and Power Density bars in the lower graph, the top arrow represents the method's estimate of P10, or the value at which the resource has 10% probability of being that size or larger. The bottom arrow represents P90, or the value at which there is 90% probability that the resource will be that size or larger. The round dot in the center of the line represents the prediction of P50.

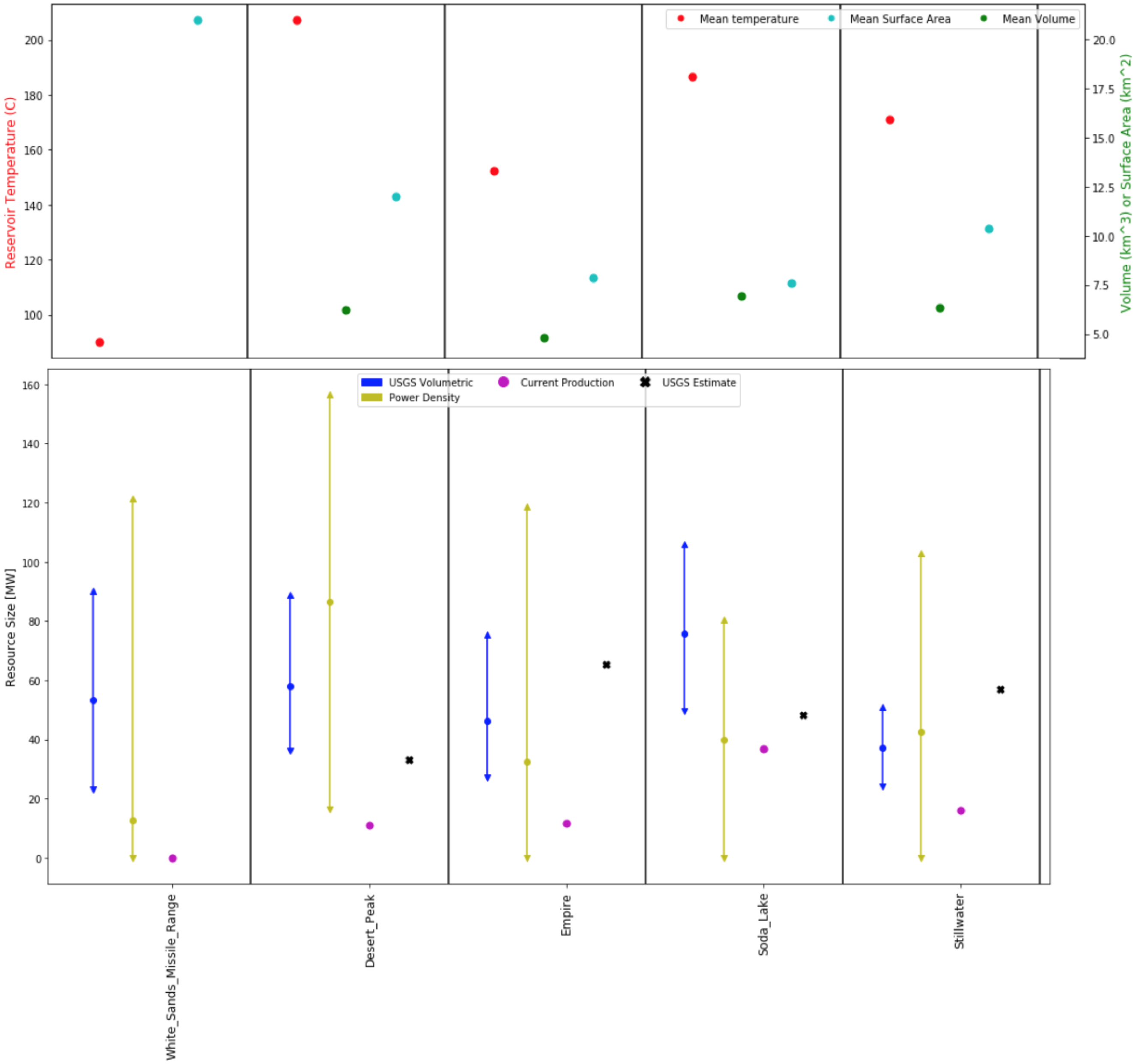

Figure 3: Temperature, surface area, volume, and predicted megawatt capacity of medium-size (less than 160 MW) resources. On the USGS Volumetric and Power Density bars in the lower graph, the top arrow represents the method's estimate of P10, or the value at which the resource has 10% probability of being that size or larger. The bottom arrow represents P90, or the value at which there is 90% probability that the resource will be that size or larger. The round dot in the center of the line represents the prediction of P50.

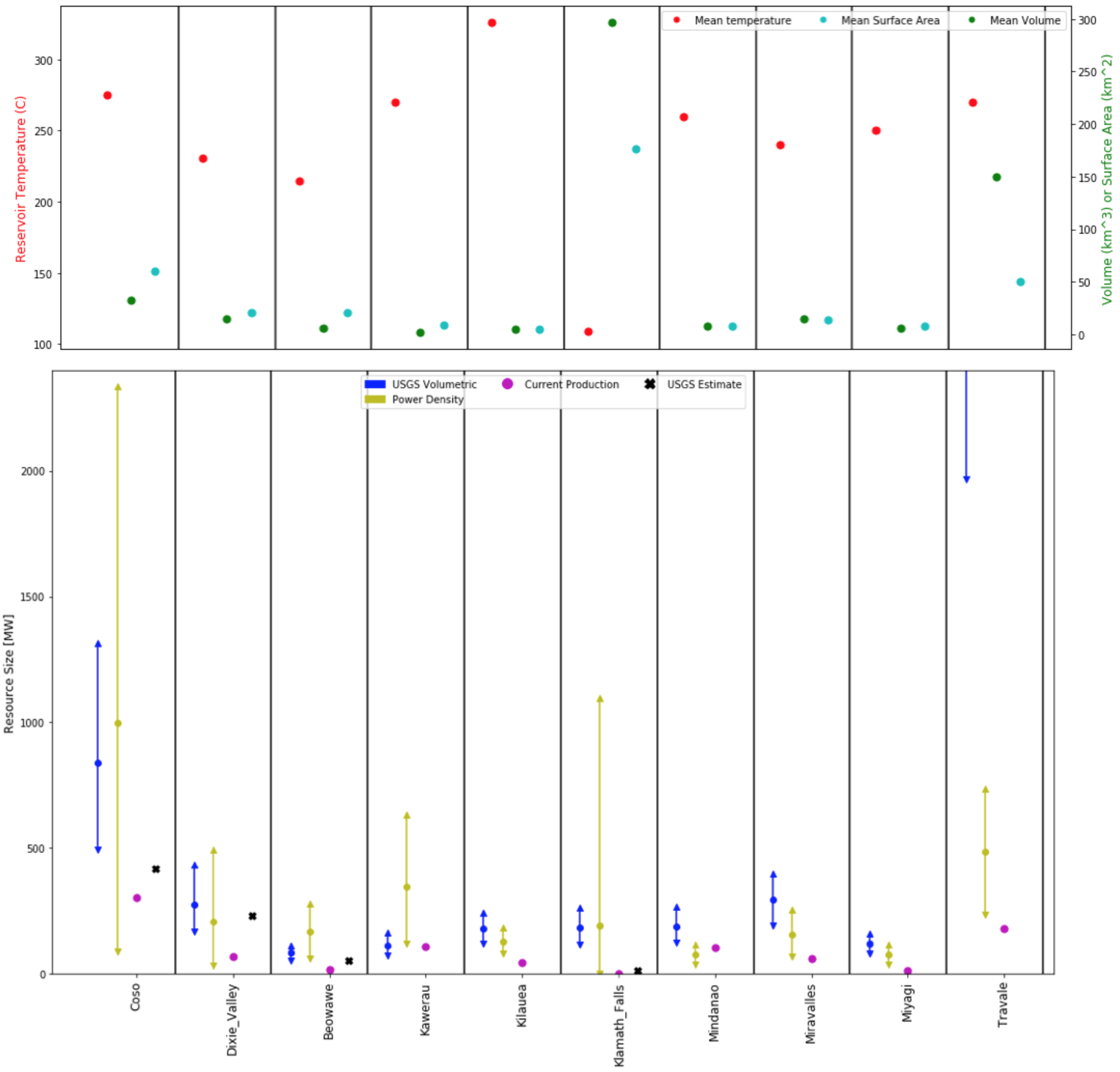

Figure 4: Temperature, surface area, volume, and predicted megawatt capacity of large-size (greater than 160 MW) resources. On the USGS Volumetric and Power Density bars in the lower graph, the top arrow represents the method's estimate of P10, or the value at which the resource has 10% probability of being that size or larger. The bottom arrow represents P90, or the value at which there is 90% probability that the resource will be that size or larger. The round dot in the center of the line represents the prediction of P50.

5. DISCUSSION

The USGS Volumetric and the Power Density methods do not differ drastically from one another in their prediction of resource size on the whole. For the majority of sites tested, the two methods predict overlapping ranges of resource size from P10 to P90. One method does not consistently predict a lower P50 value than the other; Power Density gives a lower P50 prediction for roughly half (13) of the case sites. But the Power Density method does predict a lower P90 value than the USGS Volumetric method in most instances. In 11 cases, the P90 for power density is predicted as 0 MW, which the Volumetric estimation only predicts for one site, Honey Lake. These results reflect both a strength and a weakness of the Power Density method.

If minimum reservoir temperatures are below ~170°C, the Power Density method returns a negative value for the P90 MW capacity of a reservoir. As evident in Figure 1, the lower error bar for the main sequence intersects with the temperature axis at about 170˚C; therefore, any reservoir with a minimum temperature below 170˚C would give a prediction of 90% probability of a reservoir which produced negative megawatts. We interpret this result as a 0-MW output to reflect the reality of potential outcomes.

Geothermal prospecting is an inherently risky endeavor, and a certain proportion of potential reservoirs will fail to produce sufficient energy to make a plant viable (Young et al. 2017). Thus, the fact that Power Density accounts for this potential of failed reservoir development may give the user a more realistic expectation of possible outcomes. The Volumetric method's negligence in predicting a possibility of zero-megawatt production has been debated in prior literature. Garg and Combs (2010; 2015) point out that if the difference between the reservoir and reference temperatures is nonzero, then the USGS equation will give a nonzero available work. They argue that to account for this departure from reality, the recovery factor should be taken as a range starting at zero in the Monte Carlo calculations. However, this caveat only applies in the exploration phase prior to well drilling and testing. Williams (2014) argues that if the existence of a permeable reservoir has been proven, then recovery factor cannot be zero. Because the primary interface of GeoRePORT itself reports the resource quality and level of certainty in that quality to the user, incorporating factors such as permeability and chemistry, we do not find it necessary to incorporate the possibility of a zero recovery factor into the volumetric estimate for the Resource Size Tool. The user will know if a permeable reservoir is proven before estimating resource size, and so the uncertainty of exploration will already be accounted for.

Power Density may be a more realistic method of resource size approximation for use in the exploration phase of a reservoir, before the site's viability has been confirmed. Because it does not account for the possibility of a failed venture, the Volumetric method with the parameters used in the GeoRePORT Resource Size Tool should only be used if the reservoir has been found viable with assurance. However, if desired, the lower limit for the range of the Recovery Factor could easily be changed to zero in the input spreadsheet for the Volumetric calculation, to more realistically give probability outcomes in the exploration phase of a reservoir.

Power Density's tendency to yield results of 0 MW or less is more likely attributed to the fact that it gives greater ranges in general. As evident in Figures 2-4, the Power Density method tends to estimate a greater difference between P90 and P50 than the Volumetric, as well as a greater range between P50 and P10. In some cases, this range is extraordinarily large. For example, the Power Density method estimates that Coso has the potential to produce as little as 89 MW, or as many as 2,336 MW (with a 10% probability of producing this much power or higher). The USGS Volumetric method, on the other hand, gives a much smaller (but still sizable) range, with a P90 of 494 MW and a P10 of 1,316 MW (Figure 4).

Values for current megawatt production of installed plants also tend to fall within the resource size range predicted by the Power Density method more often than within the USGS method. At first glance, this would indicate that Power Density is a more accurate method for predicting resource size than Volumetric; however, using current megawatt production as a definitive metric for actual resource size is problematic. The reservoirs in these case studies may not have been developed to their greatest capacities. In some cases, multiple plants may be necessary to exploit all of the power in a reservoir, or more efficient plants than are in current use. Because the Volumetric method assumes that all of the heat-in-place energy will be extracted, it is prone to overestimation when compared to actual production of the reservoir (Sanyal 2005). The estimation also does not account for factors such as a decrease in fluid enthalpy over time, cold water breakthrough, and the method of cooling. The Volumetric method estimates the best-case-scenario of power capacity of the reservoir, while the reality of power output is dependent upon both the size of the plant operations and the sustainability with which the reservoir is exploited.

The Power Density method calculates a much larger range of possible capacities than the USGS method. In some cases, this range is so large that it arguably defeats the purpose of calculating resource size. A Resource Size Tool is intended to facilitate new geothermal development by providing prospective developers with a sense of the power they could expect to generate from a given resource. However, if the predicted resource capacity is a range of 0-1,000 megawatts, the user is no more assured of the size of their resource than before. As such, the USGS Volumetric method, while consistently estimating higher values than the actual production numbers for our case sites, would generate useful data for GeoRePORT users by constraining the range of probable resource sizes more tightly. While the method generally reports all power that would be possible to extract from a reservoir, and does not take into account the extent to which a reservoir would realistically be utilized, it would still be informative to a developer to know the full extent of energy they could obtain from a resource.

It is also interesting to compare our resource size estimates with the P50 values calculated by USGS (DeAngelo and Williams 2010). The values for P50 output by the computer program are not identical to those calculated by USGS—in seven cases, they are lower, and in four higher (Figures 2-4). It is unclear what drives the disparities between these results—the USGS report does not go into detail as to their methods and the values they chose for variables in the equation. Differences in the Monte Carlo stochastic calculations may account for some discrepancies. Some parameters may have been given differently shaped distributions in their modeling versus ours. These divergences highlight the importance of choosing proper values for variables in the equation, as well as thoughtfully specifying the distributions in Monte Carlo analysis.

A few uncertainties inherent in our analysis should be considered. In lower-temperature reservoirs, optimal for the use of a binary power plant, we assume that the working fluid in such a plant is isobutane. This assumption means that the abandonment temperature for most resources under 150ºC is calculated as 105.36ºC (the boiling point of isobutane). In reality, the binary plant designer will select a working fluid optimal for the temperature of the reservoir so as to extract the most energy possible. Thus, for some low-temperature reservoirs, our volumetric calculations may have underestimated resource size.

Future work should aim to increase the accuracy of the porosity variable in the volumetric equation. With prior methods, porosity has been assumed equal to 0.05 and uniform across the reservoir. This generalization is overly simplistic, and, in many cases, inaccurate.

Porosity and permeability of a reservoir govern its thermodynamic characteristics and can greatly change its power output potential. Pinpointing a value for the porosity of each reservoir would increase the efficacy and certainty of the resource size calculation. GeoRePORT collects information about the reservoir's rock type and fracture dimensions (which dictate permeability). Methods with which to use these data to determine a more refined value for porosity, specific to the reservoir, will be investigated.

As discussed in Section 1, the main input parameters for both the USGS Volumetric Method and Power Density are uncertain. Estimating reservoir volume, depth, surface area, and even temperature is difficult, especially when extensive test wells have not been drilled. This resulted in different, or wider-ranging, values for temperature, volume, and surface area of reservoirs than the USGS, in some cases. For the majority of case sites, reservoir information was sourced from either OpenEI or papers. In many cases, links to sources on OpenEI were "broken" or certain data did not reference a source at all. The discrepancies between values for reservoir parameters between different sources was also evident. We recognize that the sparsity of data on most resources is a source of uncertainty in this study. It also highlights the need for more rigorous documentation in geothermal research, as well as the maintenance of databases. The current disorganization and inconsistencies in geothermal data repositories pose obstacles for future research. It also prevents reservoirs under exploration from being easily analogized to existing resources, an important component of creating conceptual models (Cumming 2016).

While uncertainty associated with measured and inferred reservoir parameters is noted throughout the literature, it has not been adequately quantified and incorporated into calculations as part of probability distributions or some measure of standard error. The uncertainty in measurements of reservoir parameters is dependent on the experimental method with which the data was obtained. For example, when measuring reservoir temperature, it is more reliable to use a downhole temperature probe than geothermometry; however, such intricacies in the method of data collection have not yet been explicitly incorporated into reported ranges of resource size with either the volumetric or power density methods. With future updates to the Resource Size Tool, we recommend more accurately quantifying the uncertainty of resource size estimates using the Activity and Execution fields in the main GeoRePORT interface. Users are asked to input the method with which they measured various reservoir parameters, such as temperature and volume. Consultation with reservoir and power plant engineers to determine the standard errors inherent in different field methods would allow for incorporation of these errors into the minimum and maximum values for the ranges of these parameters in the input spreadsheets for the two resource size calculation methods. Changing the distribution of these variables based on the activity and execution grades they are given from GeoRePORT will enable the Resource Size Tool to more accurately convey the uncertainty of its estimates due to the method in which data was gathered.

6. CONCLUSIONS

The Power Density and USGS Volumetric methods for calculating energy reserves both have strengths and weaknesses that should be considered in interpreting their predictions. Power Density more regularly predicts values for resource size consistent with values for current power plant production of that reservoir; however, the method tends to give undesirably large possible ranges of values for resource size. The Volumetric method predicts narrower ranges, allowing for greater confidence in a certain megawatt potential. Yet it tends to overestimate when compared to values for current production. This may reflect insufficient utilization, as opposed to inaccurate calculations of reservoir size.

Certain parameters in these methods can be refined to increase accuracy and more realistically represent uncertainty. If feasible, reservoir information input into GeoRePORT should be used to determine the porosity of the reservoir. Information about experimental methods, in the form of 'Activity' and 'Execution' grades, could also be incorporated into ranges for Monte Carlo calculations to better convey uncertainty.

The Resource Size tool will report results from both the USGS Volumetric method and the Power Density method. GeoRePORT is intended to assist developers in making informed decisions about a resource, and the results of both methods align with this purpose, so long as the benefits and drawbacks of each method are understood. Additional methods will be added if developed, and existing ones will be modified to increase accuracy, as long as their parameters remain within the scope of what is reported within GeoRePORT.

Future work should focus on optimizing the Resource Size Tool by running additional case studies. In order to fully rely on case study data, sources of information on geothermal reservoirs and operating power plants need to be trustworthy. Databases such as OpenEI require regular updating and maintenance to support the continued adding of geothermal-related research, as well as compilation of existing research. The current state of these databases is not sufficient to support accurate research. In order to not only facilitate the future development of this tool, but the future of all geothermal software as a whole, the development of an open, accurate, and easily accessible database is paramount.

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APPENDIX A: CASE SITE CHARACTERISTICS

	Minimum Area (km^2)	Mean Area (km^2)	Maximum Area (km^2)	Minimum Volume (km^3)	Mean Volume (km^3)	Maximum Volume (km^3)	Thickness (m)	Minimum reservoir temperature (deg. C)	Mean reservoir temperature (deg. C)	Maximum reservoir temperature (deg. C)	Rock Type	Geologic Setting (rift, faults, arc with faulting, purely compressional arc with no faulting)	Abandonment Temperature	Conversion Efficiency	Current Output (MW)	USGS/Other Estimated Output (MW)	OpenEI	Other Sources	Other Sources Cont.	
Beowawe Hot Springs Geothermal Area		21.255		5	6.04	7.08	3650	213		216	basalt	Basin and Range (fault, rift)	151.831	0.4	16.6	54.1	Beowawe Hot Springs Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Beowawe_Hot_Springs_Geothermal_Area	N. (2009, March 18). Online Nevada Encyclopedia. Retrieved from http://www.onlinenevada.org/articles/beowawe-geothermal-field	Garg, S. K., Pritchett, J. W., Wannamaker, P. E., & Combs, J. (2007). Characterization of geothermal reservoirs with electrical surveys: Beowawe geothermal field. Geothermics,36(6), 487-517. doi:10.1016/j.geothermics.2007.07.005	
Brady's Hot Springs	2.31218089	2.61487965	2.91757841	3.17	3.585	4	1371	171.111	185	198.889	metamorphic capped with basalt	Basin and Range (fault, rift)	151.831	0.4	12	36	Brady Hot Springs Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Brady_Hot_Springs_Geothermal_Area	Klein, C. W., Lovekin, J. W., & Sanyal, S. K. (2004). NEW GEOTHERMAL SITE IDENTIFICATION AND QUALIFICATION(Rep.). Richmond, CA: GeothermEx.		
Chena		1.37			2.74			74	80	121	granite	Fault	70	0.25	0.4	2.8	Chena Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Chena_Geothermal_Area	Erkan, K et al (2008). Understanding the Chena Hot Springs, Alaska, geothermal system using temperature and pressure data from exploration boreholes. Geothermics 37: 565-585.		
Coso		60		30	32.5	35		200	275	350	basalt	Basin and Range (fault, rift)	151.831	0.4	302	419.2	Coso Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Coso_Geothermal_Area	Wamalwa, Antony et al (2013). A joint geophysical analysis of the Coso geothermal field, south-eastern California. Physics of the Earth and Planetary Interiors 214: 25-34.	Klein, C. W., Lovekin, J. W., & Sanyal, S. K. (2004). NEW GEOTHERMAL SITE IDENTIFICATION AND QUALIFICATION(Rep.). Richmond, CA: GeothermEx.	Lees, J.M. (2002). Three-dimensional anatomy of a geothermal field, Coso, southeast-central California. Geological Society of America, Memoir 195.
Desert Peak	5.791505792	12.01737452	18.24324324	3	6.225	9.45	518	198.889	207.222	215	basalt/quartzite/metasedimentary	Basin and Range (fault, rift)	151.831	0.4	11	33	Desert Peak Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Desert_Peak_Geothermal_Area	Klein, C. W., Lovekin, J. W., & Sanyal, S. K. (2004). NEW GEOTHERMAL SITE IDENTIFICATION AND QUALIFICATION(Rep.). Richmond, CA: GeothermEx.		
Dixie Valley		21		11	15.275	19.55	1600	200	231	285	sedimentary	Basin and Range (fault, rift)	151.831	0.4	67.2	232.5	Dixie Valley Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Dixie_Valley_Geothermal_Area			
Empire	4.232283465	7.857611549	11.48293963	2.58	4.79	7	609.6	151.667	152.222	190	basalt/metasedimentary	Basin and Range (fault, rift)	105.36	0.25	11.8	65.2	San Emidio Desert Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/San_Emidio_Desert_Geothermal_Area	Klein, C. W., Lovekin, J. W., & Sanyal, S. K. (2004). NEW GEOTHERMAL SITE IDENTIFICATION AND QUALIFICATION(Rep.). Richmond, CA: GeothermEx.		
Fang Geothermal Area		0.9			0.1341		149	116		122	Granite	arc with faulting	70	0.25	0.3	2.8	Fang Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Fang_Geothermal_Area	Wood, S. H., Kaewsomwang, P., & Singharajwarapan, F. S. (2018). Geologic framework of the Fang Hot Springs area with emphasis on structure, hydrology, and geothermal development, Chiang Mai Province, northern Thailand. Geothermal Energy,6(1). doi:10.1186/s40517-017-0087-7	Amatyakul, P., Boonchaisuk, S., Rung-Arunwan, T., Vachiratienchai, C., Wood, S. H., Pirarai, K., . . . Siripunvaraporn, W. (2016). Exploring the shallow geothermal fluid reservoir of Fang geothermal system, Thailand via a 3-D magnetotelluric survey. Geothermics,64, 516-526. doi:10.1016/j.geothermics.2016.08.003	
Fish Lake Valley	1.476377953	1.722440945	1.968503937	2.25	2.625	3	1524	182.222	190.556	198.889		Basin and Range (fault, rift)	151.831	0.4	36	57.1	Fish Lake Valley Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Fish_Lake_Valley_Geothermal_Area	Klein, C. W., Lovekin, J. W., & Sanyal, S. K. (2004). NEW GEOTHERMAL SITE IDENTIFICATION AND QUALIFICATION(Rep.). Richmond, CA: GeothermEx.	https://www.energy.ca.gov/almanac/renewables_data/geothermal/geothermal_list.xls	
Honey Lake	0.8940288714	1.267224409	1.640419948	1.09	1.545	2	1219.2	106.111	113.889	121.111	granite	Basin and Range (fault, rift)	70	0.25	1.6	7.8	Amedee Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Amedee_Geothermal_Area	Klein, C. W., Lovekin, J. W., & Sanyal, S. K. (2004). NEW GEOTHERMAL SITE IDENTIFICATION AND QUALIFICATION(Rep.). Richmond, CA: GeothermEx.		
Kawerau		9	10		1.6		200	235	270	310	basalt	fault	151.831	0.4	108.3		Kawerau Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Kawerau_Geothermal_Area	Milich, S. D., Clark, J. P., Wong, C., & Askari, M. (2016). A review of the Kawerau Geothermal Field, New Zealand. Geothermics,59, 252-265. doi:https://doi.org/10.1016/j.geothermics.2015.06.012	Mercury NZ Limited, Ngati Tuwharetoa Geothermal Assets Limited, Geothermal Developments Ltd, & Te Ahi O Maui Partnership. (2018). KAWERAU GEOTHERMAL SYSTEM MANAGEMENT PLAN(Rep.).	
Kilauea, Hawaii	3.4	4.7	6	3.4	4.7	6	1000	302	326	350	basalt	rift	151.831	0.4	46	750	Kilauea East Rift Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Kilauea_East_Rift_Geothermal_Area	Kinslow, R., Hass, B., Maddi, P., & Bakane, P. (2012). Development Overview of Geothermal Resources in Kilauea East Rift Zone. GHC Bulletin,9-17.		
Kilauea, Hawaii	3.4	4.7	6	3.4	4.7	6	1000	302	326	350	basalt	rift	151.831	0.4	46	750	Kilauea East Rift Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Kilauea_East_Rift_Geothermal_Area	Kinslow, R., Hass, B., Maddi, P., & Bakane, P. (2012). Development Overview of Geothermal Resources in Kilauea East Rift Zone. GHC Bulletin,9-17.		
Klamath Falls	114	177	240	114	297	480	300	105		113	siltstone,sandstone, basalt	fault/extensional	70	0.25	1.8	11.5	Klamath Falls Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Klamath_Falls_Geothermal_Area	Lienau, P. J., Culver, G., Lund, J. W., & OIT Geo-Heat Center. (1989). Klamath Falls geothermal field, Oregon: Case history of assessment, development and utilization. Klamath Falls, Or.: Geo-Heat Center, Oregon Institute of Technology.		
Mindanao, Phillipines		8			8		1000		260			constant power arc	151.831	0.4	106	126	Mindanao Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Mindanao_Geothermal_Area	Trazona, R. G., Ma. G. Sambrano, B., & Esberto, M. B. (2002). RESERVOIR MANAGEMENT IN MINDANAO GEOTHERMAL PRODUCTION FIELD, PHILIPPINES. PROCEEDINGS,27.		
Miravalles, Costa Rica	13		15		15		1000	230	240	255	basalt	arc w faults	151.831	0.4	60	150	Miravalles Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Miravalles_Geothermal_Area	Gonzales-Vargas, C., Moya-Rojas, P., Sanchez-Rivera, E., Vallejios-Ruiz, O., & Yock-Fung, A. (2005). Evolution of the Miravalles Geothermal Field in Costa Rica after Ten Years of Exploitation. PROCEEDINGS.		
Miyagi, Japan		8			5.6		700		250		volcanics	constant power arc	151.831	0.4	12.5	25	Miyagi Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Miyagi_Geothermal_Area	Sustainability and Renewability of Geothermal Power Capacity. (2005). PROCEEDINGS. doi:10.1007/springerreference_310717		
Pauzhetskaya, Russia		1.5			0.75		500		195		tuff	constant power arc	151.831	0.4	14.5		Pauzhetskaya Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Pauzhetskaya_Geothermal_Area			
Soda Lake	5.468066492	7.567804024	9.667541557	5	6.92	8.84	914.4	182.222	186.667	190.556	basalt	Basin and Range (fault, rift)	105.36	0.25	37	48.1	Soda Lake Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Soda_Lake_Geothermal_Area	Klein, C. W., Lovekin, J. W., & Sanyal, S. K. (2004). NEW GEOTHERMAL SITE IDENTIFICATION AND QUALIFICATION(Rep.). Richmond, CA: GeothermEx.		
Stillwater	9.301181102	10.39206037	11.48293963	5.67	6.335	7	609.6	160	171.111	182.222	sandstone	Basin and Range (fault, rift)	105.36	0.25	16	57.1	Stillwater Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Stillwater_Geothermal_Area	Klein, C. W., Lovekin, J. W., & Sanyal, S. K. (2004). NEW GEOTHERMAL SITE IDENTIFICATION AND QUALIFICATION(Rep.). Richmond, CA: GeothermEx.		
Travale-Radicondoli, Italy		50			150		3000		270		dolostone, metamorphic basement	constant power arc	151.831	0.4	180		Travale-Radicondoli Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Travale-Radicondoli_Geothermal_Area			
Wabuska	1.640419948	5.364173228	9.087926509	1	3.27	5.54	609.6	104.444	106.667	108.333	unconsolidated sediment/metasediments	Basin and Range (fault, rift)	70	0.25	4.4	8.5	Wabuska Hot Springs Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Wabuska_Hot_Springs_Geothermal_Area	Klein, C. W., Lovekin, J. W., & Sanyal, S. K. (2004). NEW GEOTHERMAL SITE IDENTIFICATION AND QUALIFICATION(Rep.). Richmond, CA: GeothermEx.		
White Sands Missile Range (Tularosa Basin)		21					1600	70	90	98	granite	Basin and range (fault, rift)	70	0.25	0			Ruby Mountain Inc. and Energy and Geoscience Institute, University of Utah (2017). Innovative Play Fairway Modeling Applied to the Tularosa Basin: Phase 2 Project Report.	Land, Lewis, 2016, Overview of Fresh and Brackish Water Quality in New Mexico, New Mexico Bureau of Geology Mineral Resources, Open-file Report, v. 0583, pp. 55.	
Yangbajain		4			0.4		100		205		granite	fault	151.831	0.4	25.181	150	Yangbajain Geothermal Area. (n.d.). Retrieved from https://openei.org/wiki/Yangbajain_Geothermal_Area	Geography. (2004, March 1). Retrieved from http://ru.china-embassy.org/rus/ztbd/xzzt/xzjj/t69893.htm		