



**PROTOCOL VOLUME VI**

**RESOURCE SIZE ASSESSMENT TOOL**

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**Prepared for:**

*The U.S. Department of Energy, Geothermal Technologies Office*



# GeoRePORT Protocol Volume VI: Resource Size Assessment Tool

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## LIST OF ACRONYMS

GeoRePORT	Geothermal Resource Portfolio Optimization and Reporting Technique
LF	load factor
PF	power factor
RSAT	Resource Size Assessment Tool
USGS	U.S. Geological Survey

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## I. PRINCIPLES OF THE GEOREPORT PROTOCOL

The Geothermal Resource Portfolio Optimization and Reporting Technique (GeoRePORT) is based on the concept that a geothermal system can be described both in terms of the quality of the geothermal resource as it relates to the potential to extract heat (resource grade) and the progress of research and development over the lifetime of the project (project progress).

Resource grade and project progress are reported for three assessment categories: geologic, technical, and socioeconomic. Each category has specific criteria and guidelines for assessing both resource grade and project progress, as outlined in each of the following assessment tools (and associated colors):

- **Geological Assessment Tool** (representative color: red)
- **Technical Assessment Tool** (representative color: blue)
- **Socioeconomic Assessment Tool** (representative color: green)
- **International Socioeconomic Assessment Tool** (representative color: orange).

Additionally, users may need to estimate the project size (often reported in  $MW_e$  or  $MW_{th}$ ). The Resource Size Assessment Tool (RSAT) 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), or similar, often must be obtained, for which the resource's power capacity must be demonstrated. To determine that a geothermal heat or power project is worthy of development, investors or other funding mechanisms often require information on the anticipated heat and/or power potential of the reservoir. They might also be interested in the certainty of that estimate. 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 consistent and clear assessment of resource quality and certainty. The RSAT will enable GeoRePORT users to not only qualitatively report on a given a resource, but also to compare standard methodologies for quantitatively estimating a resource size in terms of potential heat and/or power output.

These assessment tools are written for industry professionals and **are not substitutes for detailed feasibility and engineering studies**. The estimates provided by the RSAT are simplified outcomes using published methods. They are neither certified nor guaranteed to be accurate. The reported results are not comparable to detailed resource analyses performed by engineering professionals, and not a substitute for detailed numerical reservoir modeling.

## II. THE RESOURCE SIZE ASSESSMENT TOOL

The tool presented herein estimates the quantity of recoverable heat for a geothermal resource—the resource size—both in terms of the amount of heat producible for a direct-use application and the amount of electricity that could be converted from available heat in a power plant. The user can therefore get a sense of the different potential applications for their resource, and the extent to which excess heat may be available for cascaded uses.

This document focuses on both the qualitative decisions that determine the certainty of the resource size estimations, meaning the choice of values incorporated in the estimations, as well as giving explicit instructions on using the spreadsheet itself.

There are multiple methods used to estimate resource size. The most robust involves numerical simulation and modeling, incorporating detailed reservoir characterization and geologic parameters. Models provide the most realistic estimate of potential resource size but require parameters that may be unavailable to GeoRePORT users such as rock porosity and permeability, fracture distribution, fluid flow, and reservoir shape (gleaned through production, injection, and flow data from already drilled wells). Similarly, lumped-parameter models, reservoir simulations, and decline-curve analyses require production data from an already installed power plant or extrapolation from aforementioned numerical models. Because GeoRePORT is used for the assessment of both undeveloped resources and developed resources, these tools for power estimation are not in the scope of the RSAT. Furthermore, modeling platforms already exist to assist developers in more stringently quantifying their resource once required data are available (see TOUGH, Leapfrog, ECLIPSE, HeatEx, etc.)

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.

To estimate the power capacity of the reservoir, the RSAT instead implements three commonly used methods: the U.S. Geological Survey's (USGS) volumetric heat-in-place method (Williams et al. 2008), the power density method (often used by geothermal companies) (Wilmarth and Stimac 2015), and estimation of the supplied heat from the fluid flow rate (Rafferty 2004). The heat-in-place, which can be used for direct-use applications, is also estimated with the volumetric and flow rate methods (power density has not yet been applied to direct-use resources), but with differing factors applied to the base equations to account for efficiency losses in conversion of heat to power or in heat exchangers.

### III. ESTIMATING RESOURCE SIZE

The information needed for accurate estimates of resource size requires a thorough understanding of the features of the geothermal resource—the main goal of the GeoRePORT Geological Assessment Tool. As described in the Geological Assessment Tool, a variety of different analytical techniques are available to estimate these parameters, which can then create multiple estimates of varying quality for a single measurement location. Multiple measurement locations are often necessary to fully capture the variability within a geothermal system or project.

The volumetric and the power density methods each have strengths and weaknesses for estimating resource size. The GeoRePORT RSAT thus estimates resource size of a site using both methods, and presents the results of the two side by side. A method for estimating resource size based on fluid flow rate is also provided, in the case that necessary data for the aforementioned methods are not available or if the project is at an advanced enough stage for flow rate to be known.

The tool simply reports these results, and it is up to the user to interpret them. Depending on the quality of each input parameter’s data, the various methods resource size estimations may differ by orders of magnitude. In order to facilitate more reliable predictions, the user should ensure their input parameters are as accurate as possible (see Section V: Input Values).

#### USGS VOLUMETRIC METHOD

The USGS volumetric method, also known as the “heat-in-place” method has been commonly used to estimate 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—assuming a uniformly porous and permeable rock.

This method has been criticized 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 such as reference temperature.

The refined volumetric equation utilized for this analysis is sourced from Pocasangre and Fujimitsu (2018). It breaks down total heat into two components: heat from the rock and heat from the fluid within the rock.

$$Q_T = Q_R + Q_W$$

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.

$$Q_R = A \cdot h \cdot [\rho_r \cdot c_r \cdot (1 - \phi) \cdot (T_{res} - T_{ref})]$$

Where  $A$  is the area of the reservoir ( $m^2$ ),  $h$  is the average thickness of the reservoir ( $m$ ),  $\rho$  is the rock density ( $kg/m^3$ ),  $c_r$  is the rock specific heat capacity at reservoir conditions ( $kJ/kg-^{\circ}C$ ), and  $\phi$  is the porosity of the reservoir (%).  $T_{res}$  is the average temperature of the reservoir ( $^{\circ}C$ ), and  $T_{ref}$  is the reference

temperature (in power applications, the abandonment temperature/rejection temperature of the power plant or direct use application) ( $^{\circ}\text{C}$ ).

$$Q_w = A \cdot h \cdot [\rho_w \cdot c_w \cdot \phi \cdot (T_r - T_{ref})]$$

Where  $\rho_w$  is the fluid density ( $\text{kg}/\text{m}^3$ ) and  $c_w$  is the fluid specific heat capacity at reservoir conditions ( $\text{kJ}/\text{kg}\cdot^{\circ}\text{C}$ ).

Together, these equations yield a value representing total heat stored in the reservoir. To determine the amount of energy that could be extracted by power plants, or the proportion of heat that can be utilized for direct use, GeoRePORT multiplies the total heat stored (or the “Accessible Resource Base”) by factors that account for the amount of heat that can be recovered at the wellhead, then subsequently the amount that can be converted to electricity or exchanged with the use process.

For estimating the amount of the accessible resource base that can be converted to **power**, the following equation is used (Pocasangre and Fujimitsu 2018):

$$P = (Q_T \cdot RF \cdot C_e) / (PF \cdot t \cdot 3.154 \cdot 10^{10})$$

Where  $P$  is the size of the power plant in  $\text{MW}_e$ ,  $RF$  is the recovery factor of the reservoir (the fraction of heat that can actually be recovered to be used at the surface),  $C_e$  is the conversion efficiency of the plant being used to capture the energy,  $PF$  is the power factor or the percentage of time a plant can be used to generate electricity throughout the year (capacity factor), and  $t$  is the economic life of the plant (years).

Values for the recovery factor, conversion efficiency, power factor, and plant lifetime are automatically given defaults by the spreadsheet based on the type of power plant used and standard assumptions made in the literature. For further information on these factors and selecting their values if the user wishes to change them, see Section V: Input Values.

For estimating the amount of the accessible resource base that can be utilized as **heat**, the following equation is used (adapted from Reed 1982):

$$H = (Q_T \cdot RF \cdot E_e) / (LF \cdot t \cdot 3.154 \cdot 10^{10})$$

Where  $H$  is the resource size in  $\text{MW}_{th}$ ,  $RF$  is the recovery factor of the reservoir (the fraction of heat that can actually be recovered to be used at the surface),  $E_e$  is the heat exchange efficiency when transferring heat from the geothermal brine to the end-use application,  $LF$  is the load factor (also known as the utilization efficiency) or the percentage of the year that the heat will be delivered/under demand, and  $t$  is the economic life of the plant (years).

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. 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 concerns as it is categorically assumed to be 0.05 without any resource-specific variation.

**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, expressed in terms of MW/km<sup>2</sup>. While the volumetric method attempts to estimate the heat in place by assuming the value of important reservoir characteristics such as the porosity and recovery factor, the power density method aims to approximate the heat-in-place with basic, early-project-stage data by assuming that such characteristics are inherent to or common across certain tectonic settings. This method draws a direct correlation between reservoir temperature and the MW density per surface area of the reservoir.

Wilmarth et al. (2021) have recently updated the method developed in Wilmarth and Stimac (2015) by surveying over 100 geothermal fields and generating an equation for the curve that relates these two parameters, as well as drawing a correlation with tectonic setting of the reservoir (see Figure 1). 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 consistently demonstrate a power density below 10 MW/km<sup>2</sup> independent of increasing reservoir temperature. These systems (“Hot Arcs”) tend to be in more purely compressional structural settings where reservoir permeability is limited and not preserved.

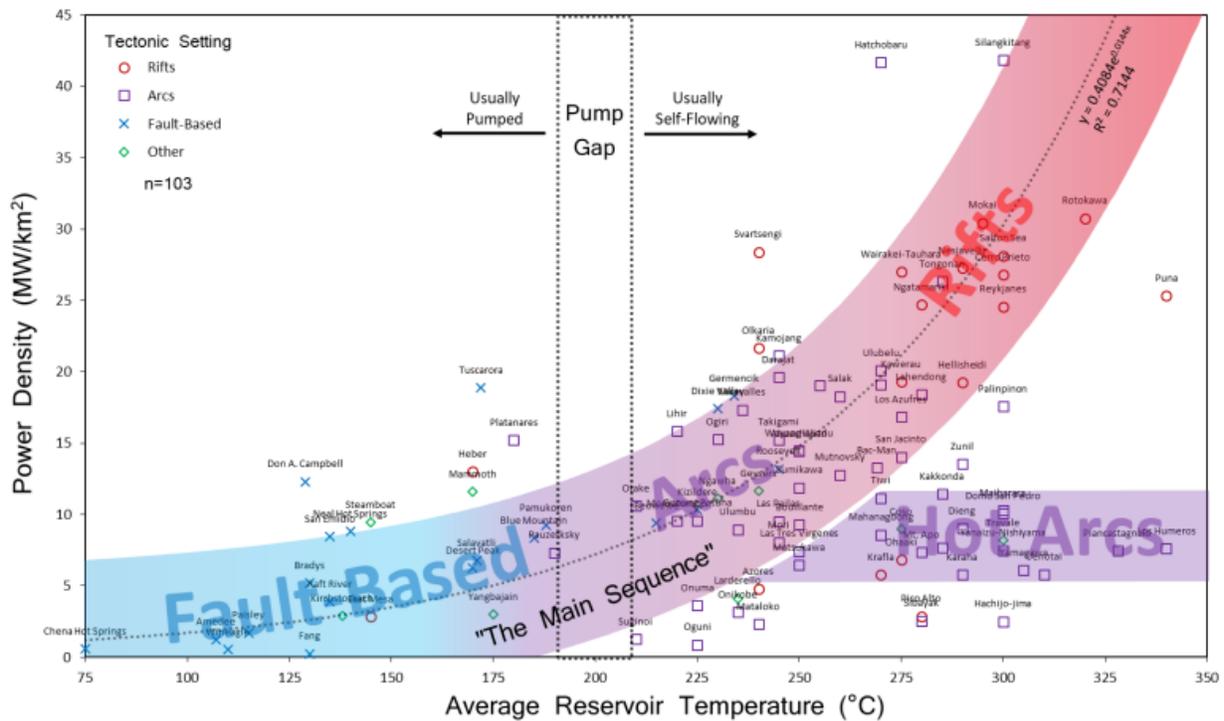


Figure 1. Power density vs. temperature for 103 geothermal fields with interpreted affiliations

Based on Wilmarth et al. (2021)

In the RSAT, reservoirs found on the Main Sequence are labeled “Rift,” “Extensional Regime (Normal Fault Based),” and “Large-scale arc setting with smaller-scale fault-based structures.”

The power found in these reservoirs is estimated using the following equation (Wilmarth et al. 2021):

$$P = 0.0484e^{0.0144T_{res}} \cdot A$$

Where  $P$  is the power in the geothermal resource in  $MW_e$ ,  $T_{res}$  is the average reservoir temperature in  $^{\circ}C$ , and  $A$  is the area of the reservoir ( $km^2$ ).

The Hot Arc reservoirs are labeled “Primarily compressional Arc-volcanic setting (Hot Arc)” in the RSAT. The power density of all Hot Arc systems is assumed to be constant at  $9.7 MW/km^2$  (Wilmarth and Stimac 2015), meaning the power is estimated using the following equation:

$$P = 9.7 \cdot A$$

## FLOW RATE METHOD

If conducting a third-party study of a geothermal project, it may be difficult to find easily accessible data on geological parameters of the site (e.g., area, thickness, rock type), which are necessary for estimation of resource size using the volumetric or power density methods. Furthermore, a project may be at an advanced enough stage that producing wells have already been drilled, tested, and produced. For such cases, a method of calculating resource size using the total well flow rate is included. ***This simplified estimation is not a substitute for detailed numerical reservoir modeling.***

As discussed above, the USGS volumetric method first estimates the *Accessible Resource Base*, or quantity of heat stored in the reservoir that is accessible for utilization. A secondary equation is then conducted which first multiplies the Accessible Resource Base by a recovery factor, which approximates the amount of the heated fluid that can be recovered or brought by wells to the surface. In the flow rate method, developed by this protocol, the flow rate of the wells is considered to be the real-world manifestation of the accessible resource base multiplied by the recovery factor, as it demonstrates the amount of heated fluid that is actually being recovered at the surface. As such, the flow rate method is considered more accurate than the USGS volumetric or power density methods, as the recovery factor is not an assumed value or approximated based on the reservoir setting.

The flow rate, in liters per second, is then multiplied by the fluid temperature (to calculate heat being delivered per second), and then all of the same factors that the USGS volumetric methods for power and heat incorporate in the tool are applied. These equations are adapted from Rafferty (2004).

The following equation is used to estimate the resource size for **power**, in  $MW_e$ :

$$P = (q \cdot (T_{res} - T_a) \cdot c_w \cdot C_e \cdot \rho_w) / (PF \cdot 10^9)$$

Where  $P$  is the resource size in  $MW_e$ ,  $q$  is the flow rate (L/s),  $T_{res}$  is the reservoir temperature,  $T_a$  is the abandonment temperature,  $c_w$  is the specific heat capacity of water (J/kg-K),  $C_e$  is the conversion efficiency of the plant being used to generate electricity,  $\rho_w$  is the fluid density ( $kg/m^3$ ), and  $PF$  is the plant factor or the percentage of time a plant can be used to generate electricity throughout the year.

The following equation is used to estimate the resource size for **direct use**, in  $MW_{th}$ :

$$H = (q \cdot (T_{res} - T_{ref}) \cdot c_w \cdot E_e \cdot \rho_w) / (LF \cdot 10^9)$$

Where  $H$  is the resource size in  $MW_{th}$ ,  $q$  is the flow rate (L/s),  $T_{res}$  is the reservoir temperature,  $T_{ref}$  is the reference temperature,  $c_w$  is the specific heat capacity of water (J/kg-K),  $E_e$  is the heat exchange efficiency when transferring heat from the geothermal brine to the end-use application,  $\rho_w$  is the fluid density ( $kg/m^3$ ), and  $LF$  is the load factor (also called utilization efficiency) or the percentage of the year that the heat will be delivered/under demand.

The terms  $PF$ , or power factor, and  $LF$ , or load factor, are included to reflect the fact that a resource will likely not be utilized at all times of the year due to a variety of factors (climate, demand, etc.). The total potential power or heat that could be generated from the reservoir with a given flow rate will be the equation with a  $PF$  or  $LF = 1$ .

## STATISTICAL TREATMENT OF METHODS

In resource methodologies, certainty has traditionally been determined in two ways:

- **Deterministic scenario:** a discrete estimate of the certainty of a single scenario within a range of possible outcomes determined by an analyst
- **Probabilistic distribution:** a wide range of confidence levels derived from iterations of varying scenarios.

Differences in deterministic scenarios are primarily based on the analysts' projections. The analysts determine whether currently available data correspond to separate, distinct scenarios in order to represent three situations: *reasonably certain*, *more likely than not*, and *unlikely*. An example is a single outcome of a decision tree. On the other hand, differences in probabilistic scenarios are based on repeated randomized sampling, such as from Monte Carlo simulation results.

The RSAT uses probabilistic calculations in order to determine the range of probable resource size results. Each equation discussed above is run through a Monte Carlo statistical analysis. To reflect the uncertainty inherent in many input values, each of the parameters in the equation is given a type of probability distribution (e.g., triangular, normal, log-normal, constant; with a minimum, mean, and maximum value, a mean with a standard deviation, or a single value that is constant across all cases) either selected by the user or as a spreadsheet default. Excel then randomly selects a number from within the given distribution, over the desired number of iterations (GeoRePORT calculates a default of 1,000 iterations). For each iteration, a value is chosen for each equation input, and then integrated into the relevant methods, so that by the end of the simulation resource size has been calculated as many times as the specified number of iterations. For more information on Monte Carlo simulations, see Harrison (2010).

Once a range of resource sizes has been calculated, these values can be treated as multiple data points and plotted as a histogram, showing the range of resource size predictions and which values are most prevalent. The distribution of results can therefore indicate the likelihood of a certain resource size.

The following table provides a suggested level of certainty associated with the confidence in estimates of geothermal resource potential.

**Table 1. Options to Describe Level of Certainty**

Certainty	Probabilistic Outcomes	Deterministic Scenarios
<b>Low</b>	<b>P<sub>10</sub>:</b> There is an estimated 10% probability that the correct answer will be P <sub>10</sub> or above	<b>Unlikely:</b> Low degree of confidence that actual value will be at least X amount
<b>Mean</b>	<b>P<sub>50</sub>:</b> There is an estimated 50% probability that the correct answer will lie above P <sub>50</sub>	<b>More likely than not:</b> Equal degree of confidence and uncertainty that actual value will be at least X amount
<b>High</b>	<b>P<sub>90</sub>:</b> There is an estimated 90% probability that the correct answer will lie above P <sub>90</sub>	<b>Reasonably certain:</b> High degree of confidence that actual value will be at least X amount

The RSAT reports the P10, P50, and P90 calculated from each method in the "Results" tab. It also plots the range of the probability distribution, from P10 to P90, of each method as a histogram.

## IV. USING THE RESOURCE SIZE ASSESSMENT TOOL SPREADSHEET

Once the RSAT Excel spreadsheet is opened, it may ask the user to “enable macros.” Please select the “enable” button so that the spreadsheet functions properly.

To navigate the GeoRePORT RSAT spreadsheet, use the tabs at the bottom of the page. The only tab that requires input by the user is the “Input Sheet.” The Input Sheet asks for reservoir and utilization parameters, which are likely known if the geological, technical, and socioeconomic tools in the primary GeoRePORT spreadsheet have been completed. No other tabs should be modified by the user as they provide inputs to the main data sheets or perform calculations.

### INPUT SHEET

The Input Sheet has three sections that delineate different components of the project. The “Reservoir Properties” section determines the estimation of the accessible resource base, or the total amount of heat stored in the reservoir. “Utilization” and “Demand Properties” determine the factors that the accessible resource base will be multiplied by to determine the beneficial heat, or the amount that can be recovered and used at the surface.

The only variables requiring input by the spreadsheet user are those under “Reservoir Properties” and, if calculating resource size in  $MW_{th}$  for direct use, the direct use under “Utilization Properties.” All other variables are given default values. If the user wishes to override the defaults, they may enter their own values under the “user input” column for that variable. All cells that the user has the option to populate are highlighted yellow. Rationale behind the defaults given is described in Section V: Input Values.

Reservoir Properties						
Site name:						
	Minimum	Most Likely/Mean	Maximum	Standard Deviation	Distribution type	Unit
Area	60	70	90		Triangular	km <sup>2</sup>
Volume		3		0.5	Lognormal	km <sup>3</sup>
Thickness	0.5	0.58	0.7		Triangular	km
Temperature		225		5	Normal	C
Total Mass Flow Rate		80			Constant	L/s
Primary Bedrock Composition	Granite					
Tectonic Setting	Large-scale arc setting with smaller-scale fault-based structures					
Number of Monte Carlo iterations	1000					

Figure 2. “Reservoir Properties” section of Input Sheet

Each calculation method requires different input parameters. The volumetric method requires the user to input temperature, area and thickness OR volume. The power density method requires user input on temperature, area, and tectonic setting. The flow rate method requires user input for temperature and mass flow rate. The user inputted primary bedrock composition parameter informs values such as rock density and specific heat. If primary bedrock composition is not known, then it is best to input quartzite, which has a density and specific heat capacity close to the median of all rock types.

The selected distribution type of each input parameter governs which cells need to be filled in. If selecting triangular or uniform distributions, enter the “minimum,” “mean,” and “maximum” values. If selecting normal or lognormal distributions, enter the “mean” and “standard deviation” values. If only one value is known for a certain parameter, select the constant distribution type and enter that number

under the “most likely/mean.” For guidance on determine values to input for each property, see section “V: Input Values.” Instructions and guidance for entering these parameters are summarized below.

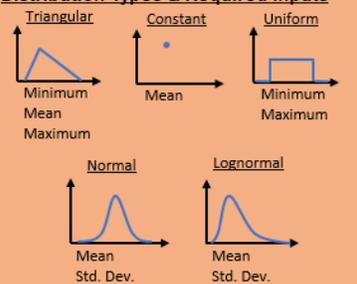
<p><b>Instructions</b></p> <p>Enter all known information to the best of your ability.</p> <p>Use the given information (right) to ensure that all required cells are populated for the selected distribution types and desired calculation methods.</p> <p>If bedrock composition is not known, input Quartzite.</p> <p>Default values are generalized estimations. Values tailored to the specifications of a system will more accurately represent a project.</p> <p>Refer to the RSAT Protocol document for more information.</p>	<p><b>Distribution Types &amp; Required Inputs</b></p>  <p>Triangular: Minimum, Mean, Maximum</p> <p>Constant: Mean</p> <p>Uniform: Minimum, Maximum</p> <p>Normal: Mean, Std. Dev.</p> <p>Lognormal: Mean, Std. Dev.</p>	<p><b>Required Variables for Calculation Methods</b></p> <table border="0"> <tr> <td><u>Volumetric Method</u></td> <td><u>Power Density Method</u></td> </tr> <tr> <td>Temperature</td> <td>Temperature</td> </tr> <tr> <td>Area &amp; Thickness</td> <td>Area</td> </tr> <tr> <td>OR</td> <td>Tectonic Setting</td> </tr> <tr> <td>Volume</td> <td></td> </tr> <tr> <td><u>Flow Rate Method</u></td> <td></td> </tr> <tr> <td>Temperature</td> <td></td> </tr> <tr> <td>Mass Flow Rate</td> <td></td> </tr> </table>	<u>Volumetric Method</u>	<u>Power Density Method</u>	Temperature	Temperature	Area & Thickness	Area	OR	Tectonic Setting	Volume		<u>Flow Rate Method</u>		Temperature		Mass Flow Rate	
<u>Volumetric Method</u>	<u>Power Density Method</u>																	
Temperature	Temperature																	
Area & Thickness	Area																	
OR	Tectonic Setting																	
Volume																		
<u>Flow Rate Method</u>																		
Temperature																		
Mass Flow Rate																		

Figure 3. Guidance for entering input parameters

Utilization Properties			
	Default (years)	User input (years)	
Project lifetime	30		
Power Generation			
		Conversion Efficiency	
Plant type		Default	User Input
Binary	Min	-	
	Mean/Most likely	0.08	
	Max	-	
	Standard Deviation	-	
	Distribution type	Constant	
	Default	User Input	
Abandonment Temperature (C)	105.36		
Direct Use			
		Heat Exchange Efficiency Factor	
Use Type		Default	User Input
Space Heating	Min	0.6	
	Mean/Most likely	0.7	
	Max	0.8	
	Standard Deviation		
	Distribution type	Uniform	
	Default	User Input	
Reference/ambient air temperature (C)	15		

Figure 4. “Utilization Properties” section of Input Sheet

Demand Properties			
Direct Use			
		Utilization/Load Factor	
Use Type		Default	User Input
Space Heating	Min	0.3	
	Mean/Most likely	0.37	
	Max	0.4	
	Standard Deviation	-	
	Distribution type	Triangular	

Figure 5. “Demand Properties” section of Input Sheet

All parameters in the Utilization Properties and Demand Properties sections of the Input Sheet are given default values. For some parameters, these defaults change based on user-inputted power plant or use type. For the beneficial heat or power to be calculated properly, the user must input the anticipated power plant or use types in this section.

If the user wishes to change the default values, they can override the defaults by entering their preference in the User Input column. Be sure to select the proper distribution shape and inputs for that shape as described above. When entering the direct use Heat Exchange Efficiency Factor, the user should consider each of the efficiency and heat loss elements specific to their system to represent their project more accurately. The default Heat Exchange Efficiency Factor values are generalized estimations of efficiency and may not account for some aspects of a project. For definitions of each input parameter, reasoning behind the choice of default values, and guidance on user input, see Section V: Input Values.

To run the Resource Size estimations, simply click the “Run Monte Carlo” button at the bottom of the Input Sheet.



Figure 6. “Run Monte Carlo” button on the Input Sheet

The Monte Carlo simulation may take several minutes to run, during which time the progress of the simulation can be tracked in the lower left corner of the Excel sheet. The spreadsheet will first “seed” the equation with values, and then will compute the result of each iteration of the equations with the seeded values.

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## RESULTS

Results of the Monte Carlo simulation can be found in the three tabs following the Input Sheet.

In the “Power Results” tab, a histogram, or probability distribution, of all calculated values from the volumetric, power density, and flow rate methods are shown, with the predicted P10, P50, and P90 values from each method shown in a table above the histogram. In the “Direct Use Results” tab, the results from the volumetric and flow rate methods are shown. The shape of the histogram may vary depending on the shapes of the probability distributions given for the input parameters.

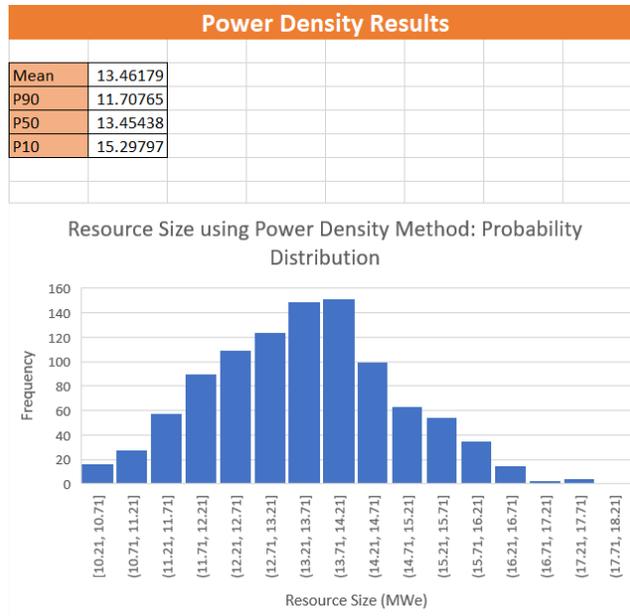
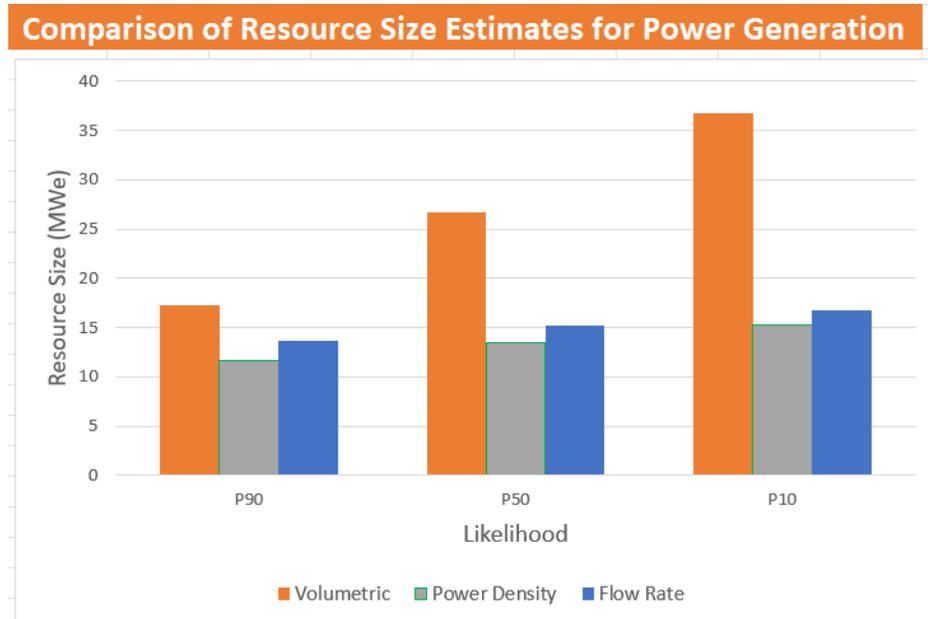


Figure 7. Example results of Monte Carlo simulation with power density method

The results of the methods are compared against one another at the bottom of the results tabs. The P10s, P50s, and P90s of each method are clustered in bar graphs next to one another so as to visually compare the magnitudes of the resource size estimations as well as the ranges of probable sizes predicted.



**Figure 8. Example juxtaposition of results of Monte Carlo simulation with three resource size estimation methods**

Finally, the tab titled “Cascaded Use Potential” aims to give the user an idea of the ways in which their resource may be utilized. The MW<sub>e</sub> resource size estimations are superimposed on the MW<sub>th</sub> estimations (both from the volumetric and flow rate methods) in order to demonstrate the total MW that could be extracted from the reservoir, and the different ways in which those MW might be used. The blue bar shows the amount of power potential the resource holds, and the remainder in orange represents the leftover thermal energy that cannot be converted to electricity but could still be directly used for heating or cooling after power has been generated (cascaded use). The sum of the orange and blue bars equals the total MW<sub>th</sub> available, all of which may alternatively be utilized in direct-use process(es).



Figure 9. Example figure from “Cascaded Use Potential” tab

## V. INPUT VALUES

### TEMPERATURE

Even with the same measurement technique, temperature variations are commonly observed at different sampling locations and measurement depths at the same sampling location. Therefore, determining a single representative temperature value for the entire geothermal resource is challenging. This section clarifies how these values should be incorporated into realistic bounds for the resource: the most likely temperature and the upper and lower limits. For more guidance on measuring the temperature of geothermal resources, see the Geological Assessment Tool's temperature attribute.

#### Most Likely Temperature

Ideally, the representative temperature is measured in a well that penetrates the actual geothermal reservoir at depth.

If these measurements are not available, then a combination of chemical geothermometers or multicomponent geothermometry could be used to derive the best estimate.<sup>1</sup> These estimates are made from the best quality and most representative spring or well samples available, based on their chemistry and completeness of analysis for calculating equilibrated chemical geothermometry temperatures.

If no appropriate water samples exist, gas geothermometers from fumarole and spring gas samples can provide reasonable estimates of reservoir temperatures. For more guidance, see the best practices recommended in the Geological Assessment Tool.

#### Upper Temperature Limit

The highest recorded well temperature in the field or the upper range of geothermometry estimates are the best choices for the upper limit of the geothermal resource, as these can indicate a higher temperature associated with a deeper reservoir zone.

#### Lower Temperature Limit

The following measurement outcomes, if available, can be used together to constrain the lowest likely temperature:

- The measured temperature of a shallow outflow zone
- The lower range of chemical geothermometry estimates
- The highest measured value from shallow temperature gradient wells.

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<sup>1</sup> An option would be to average a combination of geothermometer results to derive this estimate; for example, Bloomquist et al. (1985) averaged the results of silica, Na-K-Ca, and sulfate-water oxygen isotope geothermometers.

## RESERVOIR VOLUME

Reservoir volume is an estimation based on estimates of the areal extent of the geothermal resource and the thickness of the available geothermal system that can be tapped for heat. The thickness and areal extent of the resource varies throughout the reservoir. Therefore, determining a single representative value for area and thickness for the entire geothermal resource is challenging.

This section clarifies what measurements are the best choices to define the most likely values and the upper and lower limits for area and thickness to calculate reservoir volume.

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## AREA

Ideally, the margins of the geothermal system are determined by an inferred boundary between productive geothermal wells encountering elevated temperature and permeability and failed wells. However, this level of information from drilling does not exist during exploration phases.

### Most Likely Area

Delineating the most likely extent is best determined by combining surveys of temperature with estimates for reservoir permeability. One example, if working in a high enthalpy system, is to overlap the distribution of high temperature fumaroles with resistivity surveys that correspond to an anticline of intense alteration forming a clay cap.

### Upper Area Limit

The upper estimate of the reservoir area can be constrained by measurements indicating the perimeter of a zone of intensely altered clay that is consistent with a cap over upward thermal flow. If these estimates are not available for the subsurface, the surface extent of all related thermal features and associated hydrothermal alteration can be used instead.

### Lower Area Limit

The lower bounds to the likely area of the geothermal system are best constrained by the extent of successful production wells. Without access to drilled wells, lower bounds can be constrained by resistivity measures around high geothermometry fumaroles, which indicate the perimeter of shallow alteration above the upflow zone of the system.

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## RESERVOIR THICKNESS

Ideally, the thickness of the geothermal system is determined by a combination of the highest and lowest fluid entry points within the reservoir—and that demonstrate deep wells have penetrated the full extent of the reservoir. However, this level of information from drilling does not exist during exploration phases.

Estimating the base of the reservoir from any other methods prior to deep drilling has significant uncertainty, which has in the past led to arbitrary depth values assigned.<sup>2</sup>

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<sup>2</sup> Arbitrary depth values ranging from 3–6 km have been chosen based on the deepest wells drilled or the depth to the brittle-ductile transition zone.

### Most Likely Thickness

For systems that do not yet have deep exploration wells, the top of the reservoir could be detected using magnetotelluric or other electrical methods to estimate the elevation of the base of the clay cap.

If these geophysical methods are not available, the boiling-point-to-depth curve could be used to project the thickness down from the top of the reservoir, if integrated with measured or estimated temperatures at depth. The elevation of distal chloride springs, which can represent lateral outflow from a high temperature reservoir, can be used to represent the top of liquid pressure gradient in the reservoir. Stratigraphic columns from nearby wells may also provide bounds on reservoir thickness for target formations.

If none of the above information is available, thicknesses from analogous, well-characterized geothermal systems could be used as a proxy.

### Upper Limit of Reservoir Thickness

The uppermost limit to the top of the reservoir can be determined by a conductive temperature gradient, the base depth of the clay cap, or the depth of the first fluid entry point in a well.

The maximum limit to the base of the reservoir can be estimated by any of the following:

- The maximum drilling depth
- The estimated limit of “commercial” permeability (e.g., technical limits or financial costs to drill)
- The bottom of reservoir as defined by well data or geophysics (e.g., depth of microseismicity in the geothermal reservoir).

### Lower Limit of Reservoir Thickness

The lowest estimate can be determined by the average distance encountered between upper and lower fluid entry points in geothermal wells. Alternatively, the lower limit can be estimated by a well depth that does not fully penetrate the thickness of the reservoir.

If none of the above information is available, thicknesses from analogous, well-characterized geothermal systems can be used as a proxy.

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## FLOW RATE

The flow rate, in combination with the fluid temperature, reflects the ability of the designed flow rate of all wells total to meet the heat demand of the use. In the course of project development, a flow rate at which water will be pumped from the reservoir will be determined based on factors such as potential thermal breakthrough or pressure drawdown, artisan well flow rate, and financial considerations. Determining the sustainability of reservoir utilization and pressure support requirements such as re-injection requires rigorous geological characterization of the reservoir, determination of reservoir capacity and heat storage, and numerical modeling (Axelsson 2010; Franco and Vacarro 2012). Thus, determination of a flow rate that is sustainable for the reservoir and aligns with other project characteristics is not within the scope of GeoRePORT.

Input the total flow rate, combined from all wells, into the Input Sheet if calculating resource size using flow rate.

## TECTONIC SETTING

Four options for tectonic setting are given in a drop-down menu on the Input Sheet. These are based on the four settings that Wilmarth and Stimac (2015) classify on their power density plot (see Figure 1). These four environments are very broad, and it should be fairly straightforward to place a site into one setting. A brief description of each type is given below:

1. **Rift:** Extensional and/or transtensional tectonics (e.g., the Basin and Range province in California and Nevada, the San Andreas fault in Hawaii).
2. **Arcs:** Large-scale arc compressional setting with smaller-scale fault-based structures (e.g., Indonesia, Costa Rica, Kamchatka Peninsula).
3. **Hot Arcs:** Compressional and/or transpressional arc setting with minimal fault structures. These tend to have lower, constant power density regardless of temperature due to the lack of permeability from faults, which tend to act as conduits for hydrothermal fluid (e.g., Japan, the Philippines, Italy).
4. **Fault-Based:** Purely fault-driven temperature anomaly. These tend to be lower-temperature resources (e.g., Steamboat Springs, Chena Alaska).

It is important to distinguish between an arc and constant power hot arc, if applicable, as this choice makes a large difference in the power density prediction.

Passive tectonic settings, such as sedimentary basins, are not included in this list because the power density method has not yet determined their relationship between areal extent and power density.

## RECOVERY FACTOR

Quantitatively, the thermal recovery factor,  $R_g$ , is a ratio that calculates the amount of heat in the geothermal reservoir in comparison to the heat actually recovered at the wellhead:  $q_{WH}/q_R$ .

The heat within the reservoir,  $q_R$ , is calculated as:

$$q_R = V\overline{\rho c}(T_R - T_r),$$

where  $T_R$  = reservoir in-situ temperature;  $T_r$  = reference (or ambient) temperature;

$V$  = reservoir volume (= reservoir area (**A**) x reservoir thickness (**H**)); and  $\overline{\rho c}$  = volumetric heat capacity of fluid saturated rock =  $\phi S_l \rho_l c_l + \phi S_g \rho_g c_g + (1 - \phi) \rho_r c_r$ , where  $\rho_l, \rho_g, \rho_r$  are the density and  $c_l, c_g, c_r$  are the specific heat capacities of liquid, steam, and rock;  $S_l, S_g$  is liquid and steam saturation in pores, respectively; and  $\phi$  is the porosity.

The heat recovered at the wellhead,  $q_{WH}$ , is calculated as:  $q_{WH} = m_{WH}(h_{WH} - h_0)$ , where  $m_{WH}$  is the mass of the fluid extracted,  $h_{WH}$  is the enthalpy of the produced fluid, and  $h_0$  is the enthalpy of a fluid at a reference or plant rejection temperature.

Using the values calculated above, the available work (exergy) of the geothermal reservoir in terms of MW is calculated as:  $E = m_{WH}[h_{WH} - h_0 - T_0(s_{WH} - s_0)]$ , where  $s_{WH}$  is the entropy of the fluid at the wellhead,  $s_0$  is the enthalpy of a reference fluid, and  $T_0$  is a reference temperature (in Kelvin) (DiPippo 2004; Williams et al. 2008; Williams 2014; Garg and Combs 2015).

Recovery factor is not directly measurable but is instead derived from knowledge of other resource characteristics, such as permeability and porosity. Recovery factor is highly variable within a geothermal reservoir and between similar reservoirs because of natural variability in fracture flow and spacing that have the possibility of creating compartments of different permeability. In order for a volume of rock to contribute, the permeability must be sufficient to allow fluid flow over the lifetime of production. Therefore, it is not reasonable to assign either a narrow range or a single value for the recovery factor prior to flow tests (Grant 2014; Williams et al. 2008).

In early exploration phases, the most representative range of recovery factors is derived from data of an analogous, well-characterized geothermal system. However, no published data sets currently exist that catalog measured values from current or past reservoirs. This tool automatically uses a range of 0.08 to 0.2, with a uniform distribution over that range, as recommended by Garg and Combs (2015). This is based on a recommended adjustment of the USGS's original choice of value for the recovery factor. Original USGS studies generally assumed a value of 0.25. However, this factor was found to be too high in most cases (Grant 2014).

The highest and lowest limits of reasonable recovery factors are largely determined by whether the reservoir's porosity is consistently distributed and the size of the fractures themselves. To account for the high uncertainty of well productivity prior to flow tests, Garg and Combs (2015) suggest that a minimum recovery factor of zero should be considered as a reasonable lower bound. 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 RSAT. 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.

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## **POROSITY**

Porosity is assumed to be 0.05 and uniform across the reservoir in the tool. It is simulated in the Monte Carlo analysis with a log-normal distribution and a standard deviation of 0.02. This choice is based on recommendations and use of the equation throughout the literature (Pocasangre and Fujimitsu 2018). Porosity is a difficult characteristic to measure. There is a hypothetical direct relationship between the porosity of a reservoir and its recovery factor, but because recovery factor cannot be determined until production is ongoing and must be assumed, porosity must also be assumed in the initial phases of development (during which GeoRePORT would be used). Further updates to the tool should focus on refining this variable. If porosity for a reservoir is better known by the user, they can change its value (input as a fraction) in the "Equation Inputs and Defaults" tab under "Most Likely."

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## REJECTION TEMPERATURE

The rejection temperature is not a measured value but an assumption that determines the temperature difference driving the estimation of “recoverable heat.” Options for this value include:

- Ambient temperature (e.g., 15°C)
- Condenser temperature (e.g., 40°C)
- Abandonment temperature, depending on the power cycle used for the power plant (e.g., the saturation temperature for a flash plant or the pinch point temperature for a binary cycle plant).

The choice of the abandonment temperature is the most reliable value to calculate the recoverable heat when the heat is used for power production. Accordingly, it is recommended that the saturation temperature corresponding to saturator pressure be used for flash plants, 151.8°C as calculated by Garg and Combs (2015). The abandonment temperature of a binary plant is determined by its pinch-point, or the minimum temperature difference between geothermal brine and working fluid in the heat exchanger, which depends on the working fluid used. Garg and Combs (2015) define the pinch point temperature as that of the bubble point of the secondary fluid plus the temperature difference at the pinch point.

The RSAT spreadsheet automatically uses 151.831°C as the abandonment temperature if the reservoir temperature is above 180°C (and thus a flash plant would be used in most cases). If the reservoir temperature is below 180°C and above 125°C, then an abandonment temperature of 105.36°C is used, or the pinch point temperature if isobutane is used as the working fluid in a binary plant (a commonly used working fluid). If the reservoir temperature is below 125°C, then the abandonment temperature is taken to be 70°C, to represent a pinch-point temperature for a working fluid in a lower-temperature binary plant.

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## REFERENCE TEMPERATURE (DIRECT USE)

The reference temperature is defined as the point below which heat can no longer be extracted from geothermal fluid (Garg and Combs 2015). The reference temperature is a consequential figure as it dictates the amount of heat that can be extracted from reservoir fluid for power or heat applications (i.e.,  $T_{res}-T_{ref}$ ). As described above, the reference temperature for power plants is considered to be the abandonment temperature.

In direct-use applications, the reference temperature is often assumed to be the ambient air temperature or 15°C (Reed 1982); as in heating applications, the aim is to increase the temperature of the site to above the ambient temperature. This ambient air temperature represents the lower limit of the fluid rejection temperature for a direct use system; however, some applications may have a rejection temperature above ambient air temperature. The default reference temperature in the RSAT is therefore 15°C; however, the user may override this default to the ambient air temperature of their specific site or to some other reference temperature specific to the project.

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## HEAT CAPACITY

Heat capacity is a feature of the rock types in the geothermal reservoir as well as reservoir temperature. In the volumetric equation, heat capacity is calculated as the specific heat capacity of the geothermal fluid multiplied by its density, added to the heat capacity of the bedrock multiplied by its density.

The user is asked to input the primary reservoir bedrock type into the Input Sheet in the RSAT spreadsheet. Based on this input, the density of the rock and its specific heat capacity is found in standard tables taken from USGS reports and rock density tables (Robertson 1988, Jemmal et al. 2016, Hartlieb et al. 2015, Gilliam et al. 1987, Alden 2019).

Specific heats and densities of fluid were taken from standard tables of water thermal properties by temperature (Engineering ToolBox), based on the mean reservoir temperature input by the user. The properties of pure water are here used as a proxy for typically dilute hydrothermal fluids.

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## CONVERSION EFFICIENCY

Conversion efficiency is a factor that represents the fraction of the energy that the geothermal power plant can extract. It is dependent on factors including the geofluid temperature, the working fluid type (Augustine 2009), and the plant engineering, and it can vary. The RSAT spreadsheet assumes a value of 0.11 for the  $C_e$  of flash plants based on a survey of geothermal power plants worldwide conducted by Zarrouk and Moon (2011). The default assumption for binary plants is .08, as discussed in Toselli et al. (2019). Which of these values is used in the volumetric and flow rate equation is determined based on the plant type selected by the user in the Input Sheet. The user can override the default spreadsheet conversion efficiency to reflect the value of their site.

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## HEAT EXCHANGE/THERMAL EFFICIENCY

The heat exchange efficiency factor is the direct-use analogue of the conversion efficiency factor considered for power plants. Due to potentially detrimental fluid chemistry of the geothermal brine, most direct-use projects involve closed systems, and do not circulate the geothermal brine directly through the site. Instead, a heat exchanger is used, which transfers the heat of the geothermal fluid to another fluid, which then delivers heat to the application. The heat exchange efficiency factor, also known as the thermal efficiency, describes the percentage of heat that is not lost in the process of heat exchange and delivery to the end-use application.

For industrial applications, the thermal efficiency is set as a default range between 0.25 and 0.5 with a uniform distribution (personal correspondence, Bart van Campen 2021). All other use types are given an efficiency factor ranging between 0.6 and 0.8 with a uniform distribution (personal correspondences, Annamaria Nador 2021; Bart van Campen 2021). If the user wishes to override these values to more accurately represent their project, they may. "Open"-type distribution systems, in which no working fluid or heat exchanger is necessary, may list a thermal efficiency closer to 1 (in these cases, heat is lost in the transport of the fluid to the site but not in any heat exchange).

To more accurately represent their direct-use project, the user should consider each of the efficiency and heat loss elements specific to their system. The default Heat Exchange Efficiency Factor values are generalized estimations of efficiency and may not account for some aspects of a project.

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## POWER FACTOR

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 (Pocasangre and Fujimitsu 2018). The power factor is often called the capacity factor.

## LOAD FACTOR/UTILIZATION EFFICIENCY (DIRECT USE)

The load factor, or utilization efficiency, is defined as the percentage of time that the direct-use site is utilized. The load factor can vary widely depending on the type of use application, the purpose of the site, and variables such as the local climate and economy. Default minimum, mean, and maximum values in the RSAT are determined based on a survey of worldwide capacity/load factors for different use types conducted by Lund (2010). These defaults are presented in Table 2 but can be overridden by the user if desired. The default load factor distribution shape is set to triangular.

**Table 2. Load Factors for Various Direct-Use Types (%)**

Direct-Use Type	Min	Median/Mean	Max
Space heating	0.3	0.37	0.4
Greenhouse heating	0.4	0.48	0.5
Pool heating (aquaculture/balneology)	0.5	0.54	0.6
Agricultural drying	0.4	0.41	0.5
Industrial	0.65	0.7	0.75
Snow melting or cooling	0.1	0.18	0.3

## PLANT LIFESPAN

Plant lifespan is automatically assumed to be 30 years, a value that is generally used in heat-in-place estimations (Klein et al. 2004).

## VI. INTERPRETATION OF RESULTS

The USGS volumetric method and the power density method each has its strengths and weaknesses. As such, each method's prediction can be considered individually or the combination of the volumetric and power density MW ranges can be taken as a total prediction for the possible resource size of the reservoir.

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. This can be remediated by ranging the recovery factor from 0 to 0.2, as opposed to the automated setting for the RSAT, 0.08 to 0.2. 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

RSAT. 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 RSAT 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 estimation, to more realistically give probability outcomes in the exploration phase of a reservoir (Rubin et al. 2021).

The volumetric method tends to overestimate when compared to values for current production. This discrepancy may be due to the method's tendency to represent total potential power available in that reservoir, as opposed to how much power is generally actually extracted by an operation. So, the volumetric's overestimation could be due to insufficient utilization, as opposed to inaccurate estimations of reservoir size (Rubin et al. 2021).

As such, the USGS volumetric method, while consistently estimating higher values than the actual production numbers for our case sites, may 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 that they could obtain from a resource.

For more detailed analysis and comparison of the two resource size estimation methods, as well as case study examples using the RSAT, see Rubin et al. (2021).

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