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Derisking Superhot Geothermal Plays with Value of Information: Utilizing Play Fairway Analysis, Geophysics & Technoeconomics

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ABSTRACT

This paper describes a methodology for evaluating how the play fairways analysis (e.g., favorability) can improve our chances of making geothermal development decisions. We make statistical resource assessments and couple them with technoeconomic analysis utilizing previous favorability work performed for the Newberry Volcano. We demonstrate how the favorability can be used in a decision analysis framework because the Newberry favorability also estimated an associated uncertainty. The specific decision considered is how large of a power plant to build, which is difficult given the uncertainty about the resource size. Our results focus on two resource types, hydrothermal and enhanced geothermal systems, and they demonstrate how estimates of the minimum, most likely, and maximum estimates of the geothermal resource (denoted as the P10, P50, and P90, respectively) can be used in a decision analysis framework. Lastly, the value of information results explore using favorability with and without the magnetotelluric and gravity data from the Newberry Volcano. As expected, the favorability is more reliable, according to our methodology, at indicating the resource size when it includes the two geophysical models.

1. INTRODUCTION

The results presented within this paper represent the final efforts of the DEEPEN USA project: DErisking Exploration for multiple geothermal Plays in magmatic ENvironments (DEEPEN) (Kolker et al., 2022; Taverna et al., 2024). DEEPEN's objective was to identify methodologies that could de-risk exploration of geothermal plays in magmatic systems, with a focus on superhot geothermal systems. Both Kolker et al. and Taverna et al. discuss how play fairway analysis (PFA) (Faulds et al., 2015; Pauling, Taverna, et al., 2023) was adapted for the Newberry Volcano. Through the PFA, favorability was determined by looking at 10 different data attributes: electrical resistivity (from magnetotellurics), density (from gravity), earthquake density and magnitude, primary wave velocity (V_P), shear wave velocity (V_s), alteration, geology, temperature, and distance to faults. These geological and geophysical data ultimately were combined to identify the favorability of three different resources: conventional hydrothermal, superhot enhanced geothermal systems (EGS), and supercritical.

Here we describe the technoeconomic calculations that estimate the costs and revenues for developing these resources. Specifically, we look at the percentiles of the favorability (P10, P50, and P90) in conjunction with the P10 for uncertainty to determine a maximum, most likely, and minimum volumes; and areas, respectively. Reservoir capacity estimates were determined for each of the three resource types, and a technoeconomic analysis was conducted using the GETEM model (Mines, 2016). However, it should be noted that the GETEM tool is limited only to EGS and hydrothermal resource types, as its maximum operating temperature is 370°C.

We connect these resource estimates to their use in geothermal decisions—namely, to determine how large of a power plant to build. This decision is difficult because the size of the resource is uncertain, which is captured with our maximum, most likely, and minimum estimates. The consequences of building a power plant that exceeds the actual geothermal resource can result in suboptimal economics or even losses. Optimal decision outcomes are when the plant built matches the actual capacity of the subsurface resource. We use all the possible combinations of the different capital expenses and revenues associated with the three resource sizes (P10, P50, and P90) to model all potential decision outcomes.

Lastly, we describe how these decision outcomes are used in a value of information (VOI) methodology that utilizes the size estimations and the uncertainty calculations associated with the favorability (Trainor-Guitton, 2014). Specifically, the uncertainty scores are used to devise a reliability: how frequently does the favorability accurately identify the size of the reservoir? The results and the economics from the GETEM model are used in conjunction with the favorability reliability to estimate the value of favorability.

2. RESERVOIR AND RESOURCE CAPACITY CALCULATIONS

Resource capacity estimates were determined through the utilization of the National Renewable Energy Laboratory's (NREL's) Resource Size Assessment Tool (RSAT), which was developed in 2022 as part of the GeoRePORT package of reporting tools (Rubin et al., 2020). The input parameters for this analysis were established based on favorability volumes for superhot EGS and conventional hydrothermal resources at Newberry Volcano derived from prior DEEPEN Newberry research (Kolker et al., 2022; Taverna et al., 2024). These favorability volumes incorporated P10, P50, and P90 classifications.

Geothermal resource assessment techniques have been thoroughly reviewed (Ciriaco, Zarrouk, and Zakeri 2020). RSTAT includes the volumetric heat in place and power density method (an areal calculation). Volumetric heat is described by

$$Q_{thermal} = \rho C_p V \Delta T R_g \tag{1}$$

where the recoverable heat $Q_{thermal}$ [MJ_{th}/km^3] includes the volume of rock (V) at a temperature differential with the surface (ΔT). The other variables are assumed constant (the rock density ρ and heat capacity C_p) (Augustine, 2016).

The power density method assumes that power capacity per unit area MWe/km^2 of the productive resource is a function of reservoir temperature T.

$$\frac{MW_e}{km^2} = \left(\frac{T}{86.9}\right)^2 \tag{2}$$

As denoted in (Ciriaco et al., 2020), this relationship was updated with further observations of operating geothermal power plants; however, there are no prescribed guidelines about the process of estimating the resource area.

The EGS favorability volume at Newberry was characterized by a P50 area measuring around 110 km^2, accompanied by P50 temperatures of 350°C. The EGS reservoir thickness was determined using the 220°C isotherm as the upper boundary of the reservoir. The hydrothermal favorability volume was characterized by a P50 area of 100 km^2 with P50 temperatures of 300°C. For hydrothermal resources, the epidote-chloride isograde served as the top of the reservoir since it indicates a high temperature hydrothermal reservoir zone (those hydrothermal minerals form at temperatures at or above ~250 °C). The dimensions calculated from these volume and areal constraints for the two resource types are shown in Table 1. The mineralogy and temperature information were obtained from the composite 3D Newberry data and model compilation in Leapfrog (Pauling, Schultz, et al., 2023). It is important to mention that these favorability values do not consider the national monument boundaries. However, the National Monument is later considered in the TEA section where the accessible resource area was calculated.

Table 1: The P10, P50, and P90 estimates for the inputs that go into the volumetric and power density methods. (a) EGS reservoir capacity estimates from PFA. (b) Hydrothermal reservoir capacity estimates from PFA.

	Area [km^2]	Volume [km^3]	Thickness [km]	Temperature [C]
a. EGS				
P90 (minimum)	60		2	220
P50	110	253	2.3	350
P10 (maximum)	140		2.5	400
b. Hydrothermal				
P90	44		1.1	250
P50	100	160	1.6	300
P10	123		1.8	350
Probability Distribution	Triangular	Normal	Triangular	Triangular

When the quantities of Table 1 are input into the two resource assessment methods (Equations 1 and 2), the power capacities shown in Table 2 were achieved. The volumetric method is on the order of four times larger than the power density method. Reservoir estimates obtained through the volumetric method span several orders of magnitude. Despite this limitation, the method proves adequate for estimating potential output in the early stages of exploring non-producing geothermal prospects. The substantial error margin is attributed to the lack of reservoir production data and limited surface information (Wilmarth et al., 2021). The power density calculations on the other hand have been refined by incorporating actual field reservoir production data across various geological settings. This refinement has helped reduce uncertainty, leading to lower but more reasonable reservoir values.

Table 2: Volumetric and power density results for (a) EGS reservoir capacity estimates and (b) hydrothermal reservoir capacity estimates in Megawatt electric (MWe)

	Volumetric Method	Power Density Method
a. EGS	Reservoir capacity in MWe	Reservoir Capacity in MWe
Mean	2190	590
P90	1245	218
P50	2120	540
P10	3210	1050
b. Hydrothermal	Reservoir capacity in MWe	Reservoir Capacity in MWe
Mean	1150	340
P90	730	200
P50	1130	310
P10	1600	510

It is essential to highlight that not all calculated resource values are accessible, primarily due to the protected boundaries of the Newberry National Volcanic Monument within the Deschutes National Forest. Consequently, we conducted an additional assessment specifically focused on accessible resource reservoir estimates, which were subsequently utilized in the technoeconomic analysis. To determine the accessible area, we considered the previously calculated P50 resource area. The national monument area was then subtracted from this P50 area to derive the accessible area (Figure 1) as a percentage of the total area.

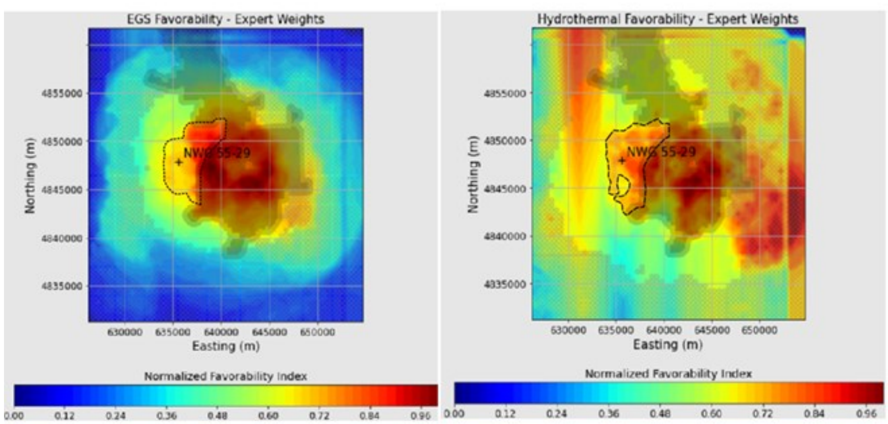

Figure 1: Map views of favorability. Left: panel is the accessible P50 EGS resource area (~33 km²). Right: panel black dotted boundary is the accessible P50 hydrothermal resource area (~36 km²).

This percentage was applied to constrain the P50 reservoir capacity estimates. The analysis reveals that around 30% of the designated area suitable for EGS is accessible, with 36% of the hydrothermal area being available. The summarized results can be found in Table 3 below.

Table 3: Accessible resources considering the national monument boundary.

	Total Resource Area (km^2)	Available Area (km^2)	Available Area (%)	Total Reservoir P50 Power Density (MWe)	Available Reservoir (MWe)
EGS	110	33	30	540	162
Hydrothermal	100	36	36	310	110

Utilizing the percentage of accessible area, the reservoir capacity estimates were computed using the previously acquired data from RSAT and are outlined in Table 4 below. The P50 power density values are emphasized in the subsequent technoeconomic analysis section. However, all were used in the subsequent VOI analysis (Section 4).

Table 4: Accessible reservoir capacity estimates in megawatts, considering the national monument boundaries. Highlighted values are estimates utilized for the technoeconomic calculations.

	Volumetric Method (MWe)	Power Density (MWe)
a. EGS		
Mean	657	177
P90	373.5	65
P50	636	162
P10	963	315
b. Hydrothermal		
Mean	414	120
P90	260	72
P50	410	110
P10	576	183.6

3. TECHNOECONOMIC ANALYSIS

The initial plan was to simulate the technoeconomics of the three geothermal play types (superhot EGS, supercritical, and hydrothermal) at Newberry Volcano using NREL's technoeconomic analysis tools GEOPHIRES and GETEM. However, GEOPHIRES only allows inputs of temperatures 300°C, and only computes a single fluid phase (Beckers & McCabe, 2019), thus cannot capture the conditions expected in the superhot EGS and supercritical play types at Newberry. GETEM is also limited but allows inputs of temperatures up to 370°C. Therefore, the GETEM model was used to estimate superhot EGS and conventional hydrothermal resource technoeconomics at Newberry.

Considering all relevant factors, including accessible reservoir areas, we conducted a technoeconomic analysis using GETEM for a proposed 162-MW superhot EGS resource and a 110-MW hydrothermal resource. GETEM calculates levelized cost of energy (LCOE) using two different methodologies. We considered the methodology utilized by the U.S. Department of Energy Geothermal Technologies Office, which replicates discounted flow sheet for the superhot EGS technoeconomic analysis. Input parameters included reservoir temperatures of 350°C, power sales of 162 MW, production flow rate of 40 kg/s, and drilled depths of 3.5 km. The results indicate that feasible **electricity prices of 7.43 cents/kWh** can be achieved, with a requirement for 20 production wells and 11 reinjection wells. The total capital expenditure for the superhot EGS development was calculated to be **657.19 M USD** without contingency (Table 5).

In the technoeconomic analysis of the hydrothermal resource, a GETEM methodology similar to that used for EGS was adopted with input parameters including reservoir temperatures of 300°C, power sales of 110 MW, production flow rate of 80 kg/s, and drill depths of 2.8 km. The results suggest that feasible **electricity prices of 4.99 cents/kWh** can be achieved, with a requirement for 9 production wells and 4 reinjection wells. The total capital expenditure for the hydrothermal development was estimated to be **273.56 M USD** without contingency (Table 5).

Table 5: Summary of technoeconomic analysis for P50 EGS and hydrothermal resources using GETEM.

Description	EGS	Hydrothermal
Average net electricity production	162 MWe	110 MWe
Electricity breakeven price	7.43 cents/kWh	4.99 cents/kWh
Number of production wells	20	9
Number of injection wells	11	4
Flow rate per production well	40kg/s	80 kg/s
Exploration	125.67 M USD	43.40 M USD

Description	EGS	Hydrothermal
Drilling and completion	305.46 M USD	66.52 M USD
Field gathering system	22.00 M USD	13.40 M USD
Power plant and transmission	204.06 M USD	150.25 M USD
Project life	30 years	30 years
Discount rate	0.07	0.07
Net capacity	0.95	0.95
Annual generation	1348.16 GWh	915.42 GWh
Total Annual OPEX	**18.21 M USD**	**9.96 M USD**
Total CAPEX	**657.19 M USD**	**273.56 M USD**
Net Present Value	**1330.00 M USD**	**606.51 M USD**

The NPV is calculated assuming a 7% discount rate with project life, LCOE and annual generation as highlighted in table 5. The capital expenditure is higher for EGS compared to hydrothermal resource types. A significant portion of the CAPEX costs, accounting for 46% in the case of EGS, is allocated to drilling, whereas in hydrothermal projects, most CAPEX costs are directed towards surface power plant expenses (Figure 2). This difference can be attributed to the need for additional wells in EGS for production and reinjection, water, simulation costs, and the deeper drill depths required, resulting in higher drilling expenditures.

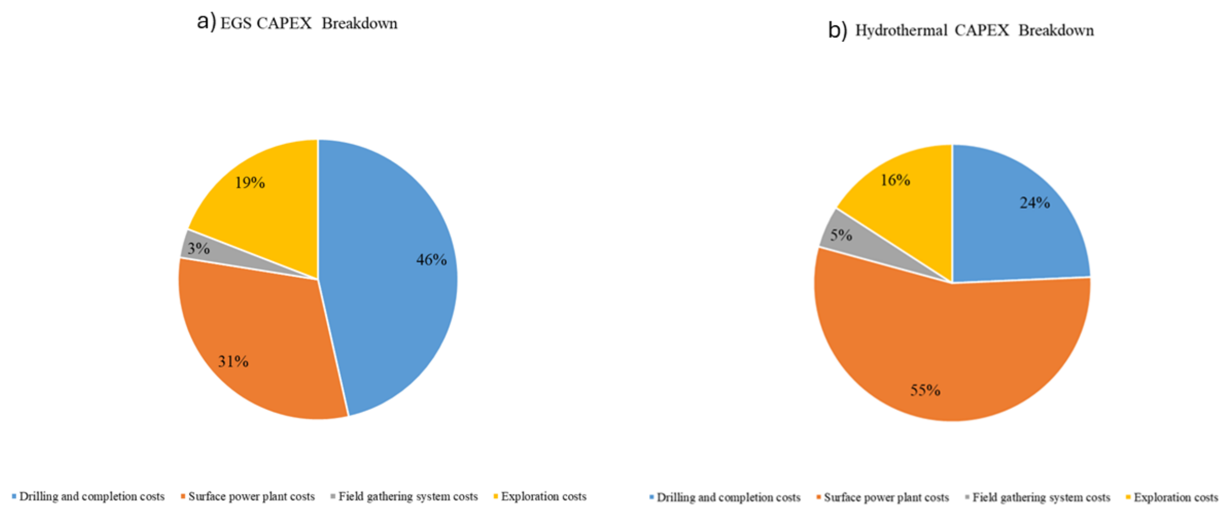

Figure 2: Summary of CAPEX costs from the technoeconomic analysis. (a) Costs breakdown for 162-MW EGS. (b) Costs breakdown for 110-MW hydrothermal resource type using GETEM.

4. VALUE OF INFORMATION

The DEEPEN team at NREL has devised a VOI methodology utilizing the previous favorability and uncertainty calculations and the technoeconomic calculations described in Section 3. VOI consists of two parts. The first, V_{prior}, quantifies the uncertainty in the main parameter that controls a decision outcome. For the Newberry DEEPEN VOI example, we continue with estimated sizes of the resource for two different resource types: hydrothermal and EGS. The second part is to the quantify the reliability of favorability to inform about the size of the resource. This was done utilizing the uncertainty scores. Taverna et al. (2024) provides detail on how the uncertainty was calculated.

The resource sizes described in the previous sections considered not only the percentiles of the favorability (P10, P50, and P90) but also uses the P10 for estimating the uncertainty of the favorability to determine the "true" maximum, most likely, and minimum volumes; and areas. The logic is that the intersection of a low uncertainty with the favorability thresholds give the most confident areas and volumes for the three reservoir sizes. Figure 3 demonstrates the minimum volume of the EGS resource, which is the intersection of the favorability above the P90 threshold and uncertainty below the P10 threshold. The surface shown is that of the 220°C isotherm (described in Section 2). Figure 4 contains the same thresholding but for the hydrothermal resource.

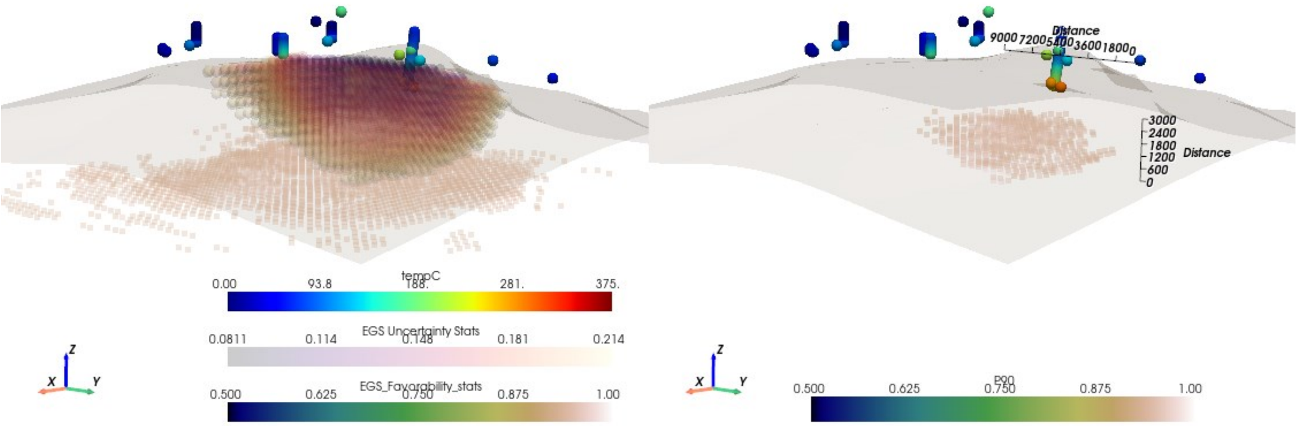

Figure 3: EGS resource with well temperatures shown above the 220°C isotherm surface. Left: the >P90 of favorability (earth color map) and ≤ P10 uncertainty (magma color). Right: intersection of the two. Note horizontal scale bar (9km) and vertical scale bar (3km).

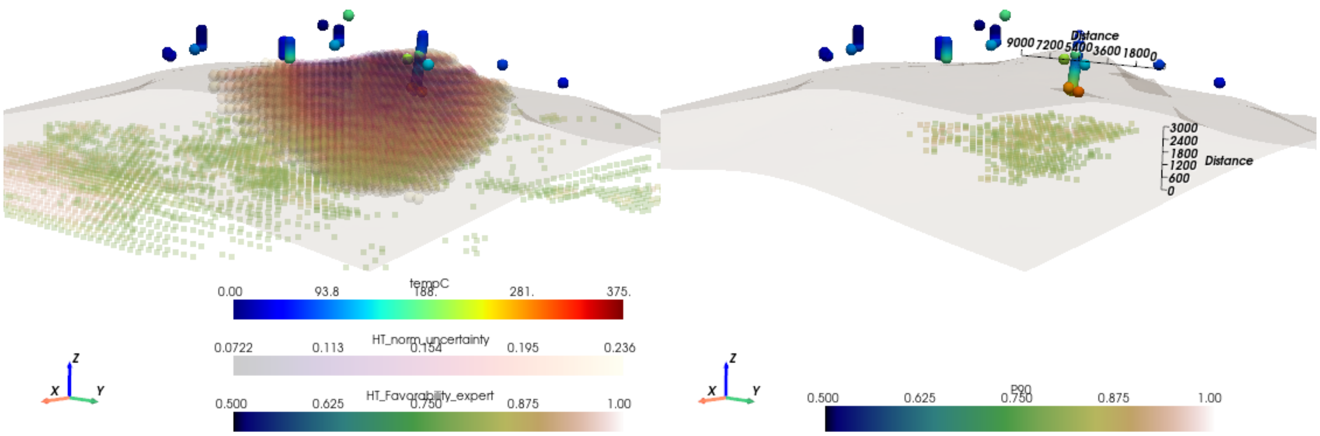

Figure 4: Hydrothermal resource with well temperatures shown above the 220°C isotherm surface. Left: the >P90 of favorability and ≤P10 of uncertainty. Right: intersection of the two. Note horizontal scale bar (9km) and vertical scale bar (3km).

4.1 V_{prior}: Average economic outcome given uncertainty about reservoir size

V_{prior} estimates the average economic outcomes of building a geothermal power plant while accounting for our uncertainty about the resource size. The uncertainty on resource size is represented by $\Pr(\Theta = \theta_i)$, also called the prior distributions. We test two prior distributions: a basecase and high probability of a small resource case. The basecase follows the probability of the P10 and P90 (each with a 10% chance) and 80% for medium. The second case we tested gives a 91% chance of a small resource size, 8% for medium, and 1% for a big resource. These are denoted in Table 6. The physical size of these are given in Table 1 (e.g. hydrothermal P10 is 140km^2 versus 60km^2 for P90, etc.).

Table 6: Two prior uncertainties for the three possible resource sizes

	P10 (Big)	P50 (Medium)	P90 (Small)
Basecase	10%	80%	10%
High % Smaller	1%	8%	91%

The dimensions from Table 2 are used in GETEM to estimate the capital expenditures and revenues of electricity generation for resources of these sizes. As described in the Introduction, determining the size of a geothermal power plant is a difficult decision, as the power plant built may not be optimal for the actual or realized resource. We assume the decision actions are finite and contained by three choices: build for a P10 (big) resource, build for a P50 (medium) resource, or build for a P90 (small) resource. We also make the simplifying assumption that only these three resource sizes are possible (P10, P50, P90). All combinations of these build choices (actions represented by a) and resource size possibilities (represented by θ_i) are shown in the tables of Figure 5 (EGS left and hydrothermal right). The tables represent the individual value outcomes $v_a(\Theta = \theta_i)$, where the rows are the actual reservoir sizes (θ_i) and the columns represent the decision action taken a.

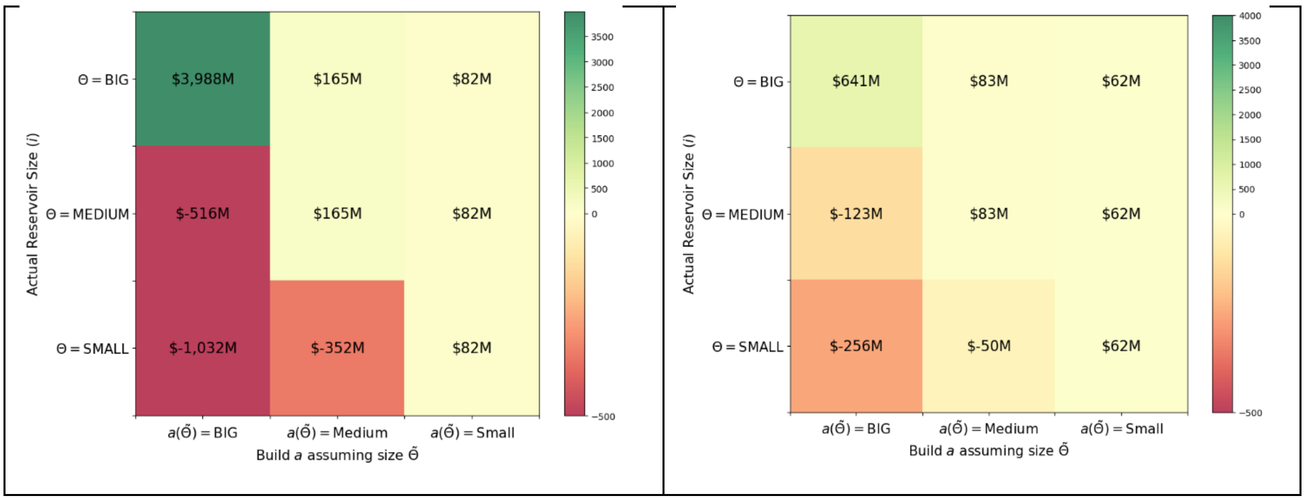

Figure 5: Value outcomes as function of resource size (rows) and build capacity decision (columns). Left: EGS. Right: Hydrothermal.

The diagonal values in the arrays shown in Figure 5 represent "optimal" economic outcomes: the actual reservoir sizes (rows) align with the decision to build for that size (columns). The off-diagonal values reflect how economic value is lost when the power plant is either over- or underbuilt compared the size of the resource. The cost of the built size (columns) is subtracted from the revenue from the actual size (row). Specifically, we use the time horizon of 10 years, calculating the revenue using the annual generation for the actual resource, the capital costs for the build decision (action) and a scaled operating cost (build/actual):

$$v_a(\theta_i, a_k) = Revenue(i,k) - \text{CapEx}_{\text{a}_\text{k}} - \text{OpEx}_{\text{a}_\text{k}} * time \tag{3}$$

$$where\ Revnue(i,k) = \begin{cases} Breakeven\ LCOE(\theta_i) * Annual\ Generation(\theta_i) * time & if\ i == k \\ Breakeven\ LCOE(\theta_k) * Annual\ Generation(\theta_k) * time & otherwise \end{cases}$$

$$\theta_i = \text{Actual large resource (P10), Actual medium resource (P50), Actual small resource (P90)}$$

$$a_k = \text{Build big, Build medium, Build small}$$

This results in an economic loss (negative \$) in the case where one builds for a big reservoir (first column) yet the actual reservoir size is small (bottom row).

We want to know the average economic outcome expected, accounting for the uncertainties identified in Table 6. V_{prior} provides this weighted average by combining the prior probabilities and the value outcomes of Figure 5.

$$V_{prior} = \max_a \left[\sum_{i=1}^{NreservoirSizes} \Pr(\Theta = \theta_i)\, v_a(\Theta = \theta_i) \right] \tag{4}$$

$$a = \text{Build big, Build medium, Build small}$$

V_{prior} gives a quantitative estimate of how we successful our "build" decision will be given the current information.

4.2 Value With Imperfect Information Using the Reliability

Now we want to consider how the play fairways (i.e., favorability) work will improve our chances of making better "build" decisions. This requires an estimate of how reliable the information is at revealing the actual resource size (our decision parameter in this example), referred to as the information reliability, and computed via the Bayes posterior. Typically to compute the reliability of an information type, we use calibrated data or synthetic data. Neither is available at Newberry, so to determine the reliability of the favorability, the intersection of high certainty (low uncertainty) and the magnitude of favorability are evaluated. As defined previously, we consider the "true volume" for the three sizes as the intersection of the P10 uncertainty and the three percentiles of favorability. This is depicted in the Figure 3 and Figure 4.

Next, we look at the intersection of the true volumes and the other favorability values and to quantify how often one may interpret a different reservoir size within that volume. Table 7 depicts how these frequencies are calculated by integrating the favorability values within each of the three reservoir "true" volumes. Figure 6 attempts to show which values are used on the numerator in the reliability according to the favorability distribution curve. Ultimately, the likelihood is calculated to say "given we know the θ_i true volume, what is the likelihood of interpreting $\tilde{\theta}_j$ reservoir size $\Pr(\tilde{\Theta} = \tilde{\theta}_j | \Theta = \theta_i)$?"

Table 7: Likelihood (reliability) of favorability (Fav) to detect resource size. Rows are actual reservoir size. Columns are interpreted size.

	Interpret P10 (Big Reservoir)	Interpret P50 (Medium Reservoir)	Interpret P90 (Small Reservoir)
Actual Big	$\frac{\text{Fav} < \text{P50}}{True\ Volume\ Big}$	$\frac{\text{P50} \leq \text{Fav} < \text{P90}}{True\ Volume\ Big}$	$\frac{\text{Fav} > \text{P90}}{True\ Volume\ Big}$
Actual Medium	$\frac{\text{Fav} < \text{P50}}{True\ Volume\ Medium}$	$\frac{\text{P50} \leq \text{Fav} < \text{P90}}{True\ Volume\ Medium}$	$\frac{\text{Fav} > \text{P90}}{True\ Volume\ Medium}$
Actual Small	$\frac{\text{Fav} < \text{P50}}{True\ Volume\ Small}$	$\frac{\text{P50} \leq \text{Fav} < \text{P90}}{True\ Volume\ Small}$	$\frac{\text{Fav} > \text{P90}}{True\ Volume\ Small}$

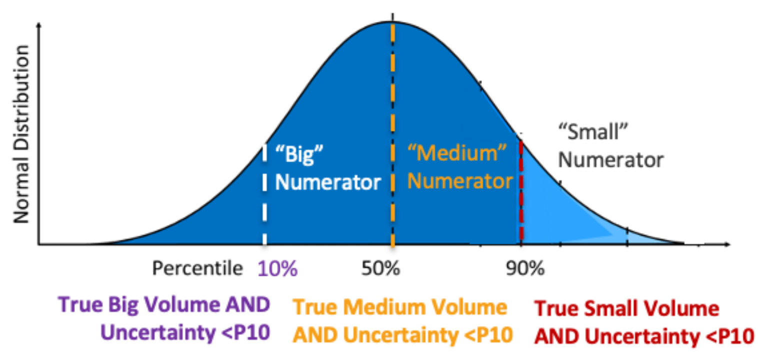

Figure 6: Intervals of the distributions that are used for the numerators within reliability of favorability.

The resulting fractions within each of the true volumes for the resource are shown in Figure 7, with the EGS resource on the top row and the hydrothermal on the bottom row. On the left are the reliabilities for when all data types are used to calculate both favorability and uncertainty. On the right, both magnetotelluric and gravity data are removed from the favorability, thus the diagonal values for "big" and "medium" have declined. In all cases, the small reservoir is "perfectly" defined: 100% of small reservoir will be interpreted as small (columns). This is a consequence of how we have defined the true reservoir volumes and the reliability; it is not possible that any favorability will fall into the true big nor true medium volume. In general, the EGS cases have higher reliability (higher proportional along the diagonal).

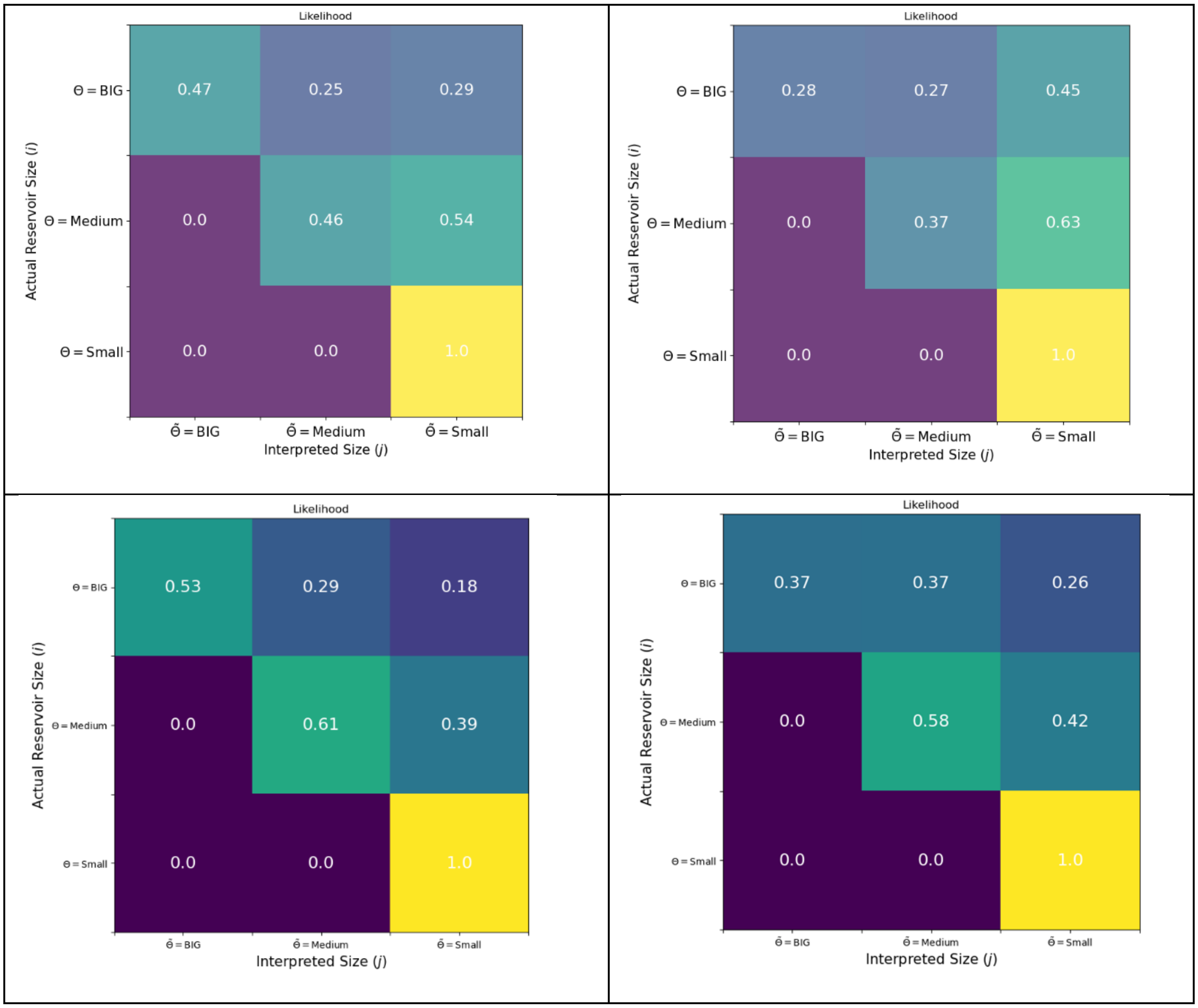

Figure 7: Reliability to interpret actual reservoir size utilizing all data (left); no magnetotelluric nor gravity data (right). Top row: EGS resource. Bottom row: hydrothermal resource.

These reliabilities are then "updated" with the two priors proposed in Table 6 to become the posteriors $\Pr(\Theta = \theta_i | \tilde{\Theta} = \tilde{\theta}_j)$, which are used in the value with imperfect information.

$$V_{imperfect}(\boldsymbol{u}) = \sum_{j=1}^{3} \Pr(X = x_j) \left[\max_a \left[\sum_{i=1}^{3} \Pr(\Theta = \theta_i | \Theta = \theta_j) \, v_a(\Theta = \theta_i) \right] \right] \tag{5}$$

$$a = \text{Build big, Build medium, Build small}$$

Finally, we have eight preliminary results of the value of favorability (Table 8). The results compare two favorabilities (using all data versus without magnetotellurics and gravity) for two resource types (EGS and hydrothermal) and considering two different prior probabilities. $VOI_{perfect}$ assumes a hypothetical data type that perfectly identifies big, medium, or small reservoir sizes.

Table 8: V_{prior}, $VOI_{perfect}$, and $VOI_{imperfect}$ results.

Prior	Resource/data	V_{prior}	$VOI_{perfect}$ (V_{PI})	$VOI_{imperfect}$ ($V_{imperfect}$)
Basecase	EGS/all	113	425 (539)	184 (296)
Higher small %	EGS/all	82	47 (128)	22 (104)

Basecase	EGS/no magnetotellurics nor gravity	113	425 (539)	107 (221)
Higher small %	EGS/no magnetotellurics nor gravity	82	47 (128)	14 (96)
Basecase	Hydrothermal/all	69	67.08 (136.41)	33.91 (103.24)
Higher small %	Hydrothermal/all	62	7.55 (69.55)	4.18 (66.18)
Basecase	Hydrothermal/no magnetotellurics nor gravity	69	67.08 (136.41)	24.23 (93.55)
Higher small %	Hydrothermal/no magnetotellurics nor gravity	62	7.55 (69.55)	3.18 (65.18)

As we may expect, the $VOI_{imperfect}$ is higher when favorability includes MT and gravity. Also, it is higher for the EGS case. This is partly because of the possibility of losing money if the action to build big is taken and the EGS reservoir is actually small (this is the outcome in the lower left of Figure 5 for EGS). This gives the information more value as you could avoid this very suboptimal outcome with more information. The basecase prior probability downweighs this as occurring; thus the VOI is smaller.

5. CONCLUSIONS

We have presented a methodology that utilizes the previous Newberry PFA and uncertainty results to calculate the three estimated resource sizes: P10, P50, and P90. The technoeconomic values capture the capital costs and revenue that can be expected for building different sized power plants. Using these different combinations, we can model all the optimal and suboptimal combinations of geothermal plant decisions and possible geothermal resource size. Lastly, these decision analysis outcomes feed directly into a VOI methodology to assess statistical reliability of PFA to identify the actual resource size. This was done for favorability using all data layers available at Newberry and repeated for a calculated favorability that did not include the electrical resistivity model from magnetotellurics nor the density model from gravity (Pauling, Schultz, et al., 2023). This approach was only possible because uncertainty measures were also produced in the PFA workflow. Our analysis found that the joint inversion brought value to both the EGS and hydrothermal exploration decisions, but was less valuable in both cases when the prior probability was larger for a small resource.

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