GEOREPORT

PROTOCOL VOLUME III

TECHNICAL ASSESSMENT TOOL

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GeoRePORT Protocol Volume III: Technical Assessment Tool

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The Geothermal Resource Portfolio Optimization and Reporting Technique (GeoRePORT) is a product of the considerable effort of many parties. Analysts at the National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory, and New West Technologies have spent several years deeply involved in research, meetings, outreach, reviews, and workshops, and analyzing and negotiating content to find solutions to divergent views.

The six documents of the GeoRePORT Protocol reflect the intellectual contributions of these many players. These end products have been enabled because of a shared vision that this work can make a significant contribution to advancing geothermal deployment.

LIST OF ACRONYMS

BOP	blow-out preventer
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
EGS	enhanced geothermal systems
FG	frac gradient
GAT	Geological Assessment Tool
GeoRePORT	Geothermal Resource Portfolio Optimization and Reporting Technique
MT	magnetotelluric
NCG	noncondensable gas
PP	pore pressure
SA	sub-attribute
SEAT	Socioeconomic Assessment Tool
TEM	transient electromagnetic
TGH	thermal gradient hole
USFS	U.S. Forest Service
USGS	U.S. Geological Survey

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I. PRINCIPLES OF THE METHODOLOGY

The GeoRePORT System 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 readiness level).

By assessing the major characteristics of a geothermal resource and categorizing the techniques used and how well the research technique was implemented, users can report a **resource grade.** The resource grade covers multiple geological, technological, and socioeconomic attributes that can be compared across play types and geothermal areas. The "grade" of each resource is intended to be refined, if needed, as new and better information is collected and interpreted.

By assessing the exploration and development activities of the project, users can report on past and planned incremental **project readiness levels**. Like the resource grade, the project readiness level will continually be updated throughout the project lifetime.

Resource grade and project readiness level are reported for three assessment categories: geological, technical, and socioeconomic. Each category has specific criteria and guidelines for assessing both resource grade and project readiness level, 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)

These Assessment Tools are written for geothermal community professionals assigned to report the resource grade and project readiness level to DOE. Therefore, it is assumed that:

- The exploration activities described in this report will be planned, executed, and interpreted by skilled geoscientists.
- Preparers of reports using the GeoRePORT Protocol are knowledgeable of geothermal systems and the different exploration activities. The guidance in these documents does not replace intelligent expertise in preparing, selecting, and interpreting data.

For additional background on the GeoRePORT Protocol, see the Background Document.

II. PROJECT READINESS LEVEL

The GeoRePORT Protocol breaks the concept of project readiness level into ordered categories. As projects progress from one development phase to the next, they pass through "activity thresholds"—minimum activities required to qualify for the next category.

DEFINING TECHNICAL PROJECT READINESS LEVEL

Technical Project Readiness Level is an assessment of the development of a geothermal area as a power generation facility. Five separate progression levels ranging from "unknown/unrecoverable" to "demonstrated" are designated, with criteria specific to technical development that must be completed to move up the scale, as outlined in Table 1.

Table 1. Criteria to move between levels of technical project readiness level

Technical Project Readiness Level		Qualifying Criteria
T1	**Unknown/ Unrecoverable**	Resource undeveloped. No drill holes, fluid chemistry, or flow tests have been conducted to confirm existence/viability of the area. Geological assessment has been performed, but no technical evaluation of the resource as an energy production site has taken place. For a resource to be considered "Unknown/Unrecoverable," one of the following criterion must be met: 1. Site analysis completed, including a geotechnical site analysis. 2. Site evaluated and determined not to have economic potential.
	Promising geophysical surveys and conceptual model	
T2	**Potential**	Surveyance of the site confirms potential as an energy production site through geophysical analysis. For a resource to be considered "Potential," the following criterion must be met: 1. Promising geophysical analyses and conceptual model completed.
	Successful well drilled into reservoir	
T3	**Discovered**	For a resource to be considered "Discovered," the resource must meet initial temperature and permeability estimates. The following criterion must be met: 1. Well drilled into reservoir proves reservoir temperature and fluid flow.
	Well field drilled and successfully tested	
T4	**Confirmed**	For a resource to be considered "Confirmed," all of the following criteria must be met: 1. Two or more successfully drilled and tested wells. 2. Production wells produce geofluids at necessary temperatures and flow rates for a minimum of 30 days.
	Plant Development	

Technical Project Readiness Level		Qualifying Criteria
T5	**Demonstrated**	For a resource to be considered "Demonstrated," power plant must be able to demonstrate integrated system operation. All of the following criteria must be met: 1. Well field and supporting infrastructure must be operational for a minimum of 30 days. 2. Plant must produce power at or above initial power production estimates.

The Technical Project Readiness Level is meant to indicate whether the activities conducted in an area resulted in the identification of a viable geothermal reservoir. Choose the level that best describes the successful technical progress that has occurred to date. For example, a project that has a well drilled into the reservoir (a quality described under "T3 - Discovered") that did not have economic temperatures or flow rates would be classified as having a Technical Project Readiness Level of "T2 - Potential." In the GeoRePORT, the project would be classified as "T3 - Discovered" if temperatures and flows were initially encountered but may move down to "T2 - Potential" if the temperature and/or flows decline in the future.

The GeoRePORT recognizes that a single axis cannot describe a viable geothermal resource. In this protocol, the project readiness level is determined by the combination of the geological, technical, and socioeconomic project readiness levels. Figure 1 graphically shows the relationship between these combined project readiness levels. For more information on the Technical and Socioeconomic Progress Readiness Levels, please refer to the Background Document and the associated Assessment Tools.

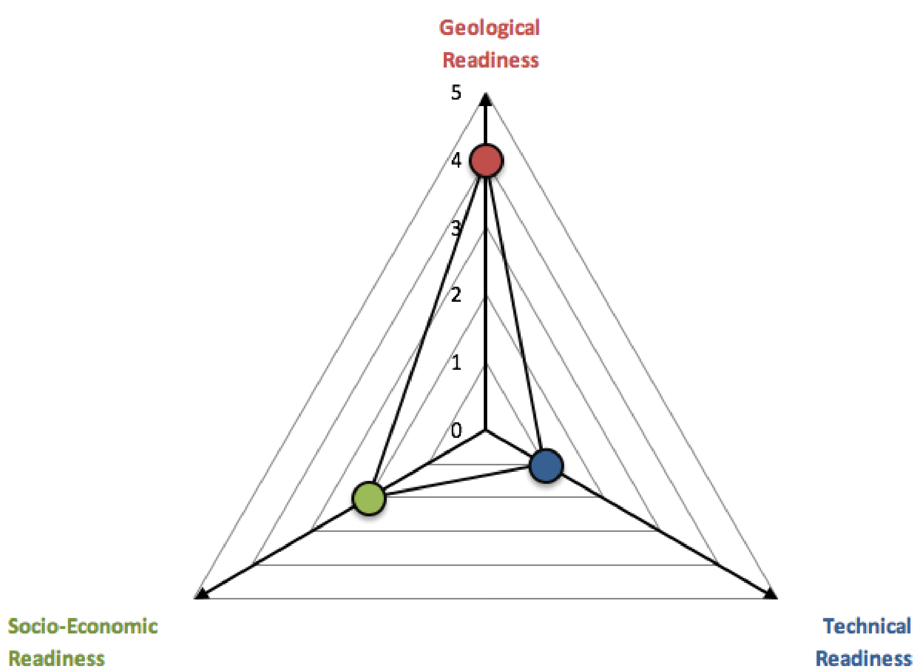

Figure 1. Depiction of technical progress in relation to other forms of project readiness level

III. RESOURCE GRADE

The attributes used by this protocol to describe a geothermal resource include the constraints on the quality of the geothermal resource as well as the geological and socioeconomic characteristics that determine whether the heat can be produced.

Each attribute is ranked on a scale of A through E, with A indicating the highest of the range of values for that attribute. ***An attribute grade of A is not necessarily the "best" value for a specific project goal.*** Some business models or plant designs may target grades lower than A for some or all of the attributes. In some areas, a low temperature binary plant may be the known, targeted plan for development. Each developer must evaluate which grades are appropriate for his or her target business model. Resources with all attribute grades equaling A rarely exist.

TECHNICAL GRADE ATTRIBUTES

Attributes relevant to the feasibility of extracting the geothermal resource, such as power conversion technology, could be altered or overcome by technology advancements, and are thus used to describe the **technical grade**. Technical feasibility can be described by the challenges involved in producing the resource. The influence of these items in developing geothermal resources may vary as technology improves. By nature of technical advancement, the same conditions can become feasible through incremental and/or radical innovations. The technical grade is a combination of these attributes that describes the fundamental areas of technical challenges to resource development.

- **Reservoir Management**: The inherent conditions that affect the ability of operators to efficiently manage a geothermal reservoir during or prior to power production.
- **Logistics**: Physical barriers to reaching a resource (e.g., weather, elevation, slope, and volcanic hazards) requiring advanced or specific tools or materials that potentially increase project costs.
- **Power Conversion**: The inherent conditions that affect the ability to convert recovered heat energy to electric power in geothermal power plants. Conversion efficiency of the power plant is evaluated.
- **Drilling:** The inherent conditions that affect the ability to drill a resource. Difficulties and delays caused by drilling can strongly determine the economics of project development. Factors contributing to delays and equipment malfunctions are considered.

COMPONENTS OF TECHNICAL GRADE

In addition to the attributes listed above, the GeoRePORT also considers the activities conducted to understand each attribute, and what is known about the quality of the data collected. The methodology breaks each attribute into three separate indices describing distinct features of each attribute, outlined in Table 2. Note that the third column contains simple examples from the Geological Assessment Tool (GAT).

Table 2. Indices used to describe resource grades: character grade, activity index, and execution index

Index	Description	Example
Character Grade	Used to describe the character itself—i.e., what is the intrinsic measurement that best describes the geothermal reservoir?	Is this a high-temperature (Grade A) or low-temperature (Grade E) resource?
Activity Index	Qualitative ranking of activities used to assign the character grade appropriate for each attribute—i.e., how well is the character grade known?	Do you have a downhole measurement of reservoir fluid temperatures (Activity A), or did you estimate the value from a heat flow map (Activity E)?
Execution Index	Compares the diligence with which the activity was executed—i.e., how much do we know about the quality of execution of that activity?	If activity is geochemistry, was the appropriate geothermometer used? Were proper assumptions made? Were fluids sampled appropriately? Were cations and anions in balance?

For each attribute, the **character grade** uses quantitative and qualitative measurements that describe the current project within the range of possible outcomes found in geothermal resources and projects.

When evaluating a resource's attribute character grade, there are sometimes multiple aspects of the attribute that contribute to its grade. To assess multiple aspects, **sub-attribute (SA)** indices have been developed for applicable components of the technical grade. For example, when considering the power conversion attribute, several sub-attributes are considered, such as the temperature difference between the inlet and condenser, water for cooling, and noncondensable gas content of the geothermal fluid.

To determine an attribute's character grade, first evaluate each sub-attribute. Each sub-attribute is given a weight (wt_n) that was derived based on discussions with industry experts who determined the relative significance of the specific sub-attribute. The total attribute-weighted sum would be calculated as:

$$\text{Sub-attribute-weighted sum} = SA_1*wt_1 + SA_2*wt_2 + SA_3*wt_3 + \ldots + SA_n*wt_n \qquad \textit{(eq 1)}$$

The range of sub-attribute-weighted sums is then broken down into grades A–E for each attribute. For example, for power conversion, the minimum weighted sum (if all grades are A) is 7, while the maximum weighted sum (if all grades are E) is 38.

In some cases, data is not available to assign grades for all sub-attributes. Since the character grade is assigned using a weighted sum that accounts for the scores of all sub-attributes, the grade would be weighted inaccurately due to gaps in data available for the geothermal system. The GeoRePORT spreadsheet tool addresses these shortcomings by defining character grade breakpoints based only on those sub-attributes that have been completed in the spreadsheet. In other words, the breakpoints for assignment of character grades in the technical assessment tool are based only on sub-attributes that are populated. The character grade is not negatively impacted if a number of sub-attributes are not populated (i.e., data does not exist to assign a sub-attribute grade). This is unique to the technical assessment tool as the data needed for this tool is often available only for geothermal systems high in technical readiness level. Please reference the GeoRePORT Spreadsheet tool for further information.

The **activity index** describes the common activities used to understand the character attributes—both directly (measured values) and indirectly (by proxy). Activity sub-indices are used to evaluate sub-attribute grades. The **execution index** describes how well the activity was implemented. During the exploration process, activities are performed (activity index), the quality of the data is determined (execution index), and the outcome is reported (character grade).
These four attribute grades, and their associated activity and execution indices, can be displayed graphically in a polar area chart (Figure 2). The dark wedges indicate resource grade (what is your resource like?); the light wedges indicate certainty (how much do you trust the data?). For more information, please see the Background Document.

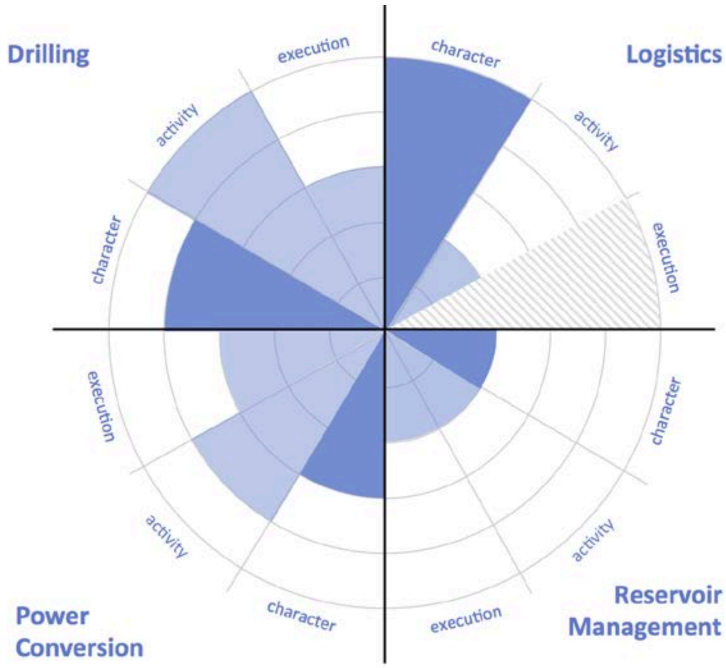

Figure 2. Combined technical grade diagram of a hypothetical project

As a reminder, this Protocol 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.

Refer to the Geological Assessment Tool (GAT) and Socioeconomic Assessment Tool (SEAT) for details on the factors relevant to geological and socioeconomic grades.

EXAMPLES: REPORTING TECHNICAL GRADE

To aid users in understanding how to evaluate resources with this protocol, two examples are provided in this section, evaluating the logistics (Example 1) and the power conversion (Example 2) sub-attributes. These tables and their associated sub-attributes are described in more detail later in the report. This initial look at the methodology is included here to provide a sense of how the GeoRePORT works.

Example 1

Suppose the following logistical data are available for a geothermal area:

Table 3a. Example logistical data for a given project location. User-provided information is shown in highlighted column.

Sub-Attribute	Reported Value
Degree of Isolation	Land-locked system; no major continental boundaries or barriers present in accessing resource, and area is within reach of existing infrastructure
Volcanic Hazards	Site located within a U.S. Geological Survey (USGS)-identified "Area Subject to Specific Volcanic Hazard"
Landslide Hazards	Area located within an area classified by USGS as "Moderate Susceptibility/Low Incidence" for landslide hazards
Earthquake Hazards	Site located in an area with a value of peak acceleration less than 0.04
Wildfire Hazards	Site located in U.S. Forest Service (USFS) "Very High" wildfire potential
Site Road Access	Site located 7–10 miles from roads considered a "Rural Local Road" at minimum by Federal Highway Administration
Topography	Terrain with slopes up to 10°
Severe Weather Events	No annual days of prevented access (as a result of severe weather events)

To characterize the logistical aspects of this particular field, the first step is to determine the grade associated with each sub-attribute, and then multiply by the sub-attribute weight to obtain the calculated weight. The logistics section of this report gives details regarding the reported values and their corresponding grades, which allows the user to properly assign a grade for each sub-attribute. Table 3b shows the process of grading each sub-attribute and applying the corresponding weight to calculate the final weighted sum.

Table 3b. Example application of GeoRePORT, showing assigned grades. User-provided information is shown in highlighted column.

Sub-Attribute	Reported Value	Assigned Grade	Sub-Attribute Weight	Calculated Weight
Degree of Isolation	Land-locked system; no major continental boundaries or barriers present in accessing resource, and area is within reach of existing infrastructure	A	2	2
Volcanic Hazards	Site located within a USGS-identified "Area Subject to Specific Volcanic Hazard"	C	2	6
Landslide Hazards	Area located within an area classified by USGS as "Moderate Susceptibility/Low Incidence" for landslide hazards	C	2	6
Earthquake Hazards	Site located in an area with a value of peak acceleration less than 0.04	A	2	2
Wildfire Hazards	Site located in USFS "Very High" wildfire potential	E	2	10
Site Road Access	Site located 7–10 miles from roads considered a "Rural Local Road" at minimum by Federal Highway Administration	D	2	8
Topography	Terrain with slopes up to 10°	B	1	2
Severe Weather Events	No annual days of prevented access (as a result of severe weather events)	A	1	1
			Sub-Attribute-Weighted Sum:	**37**
			Reported Grade:	**C**

To report the logistics character grade, use the sub-attribute-weighted sum (37 in this case) and use the assigned character grade criteria (shown in Table 4) to determine the overall character grade, C.

Table 4. Logistics character grade criteria

Grade	Sub-Attribute-Weighted Sum	Description
A	>20	No logistical barriers present
B	20–35	Manageable logistical barriers
C	>35–50	Logistical barriers present
D	>50–65	Difficult logistical barriers
E	>65	Extreme logistical barriers

Similar methodology is used to determine the area's activity grade. The logistics attribute is unique in that no sub-attributes are needed to assess the activity grade for the area. Instead, a single index criterion is used to assign a grade, which is detailed in Table 5. In the case of this example, the site conditions were inferred from nearby geothermal developments with the help of supplemental publications and maps. According to Table 5, the use of this type of activity corresponds to an activity grade of C. Furthermore, the use of a single, self-sufficient activity index means that the logistics attribute does not require an execution index; the attribute is assumed to not have any uncertainty associated with the reported values. Thus, the execution index is not applicable for this attribute.

Table 5. Logistics activity grade criteria

Index	Description
A	Surveyed: Logistics graded through detailed physical site analysis (e.g., probabilistic volcanic hazard assessment, state/local geological survey)
C	Extrapolated: Site conditions inferred from nearby developments and from published geographical characteristics of the area, including road maps, geological hazard maps, topographical maps, and climate maps
E	Extrapolated: Site characteristics inferred ONLY from published geographical characteristics of the area, including road maps, geological hazard maps, topographical maps, and climate maps

Activity Grade: C
Execution Index: Not Applicable

Example 2

As a second example, we present data used to report power conversion grade for a given location, as presented in Table 6a.

Table 6a. Example power conversion data for a given project location.
User-provided information is shown in highlighted columns.

Sub-Attribute	Value	Activity Used	Execution
Noncondensable Gas Content	0.03 weight %	Downhole in-line precision logging tool	Assumed from a nearby analogous geothermal system
Water for Cooling	Hybrid cooling, 60% of water needed for cooling is available for purchase economically	Regional water availability report	N/A
Temperature Difference: Inlet to Condenser	ΔT=125˚C	Measured downhole temperature	Results taken from third-party survey/report

We again start by assigning character grades to each of the sub-attributes, then calculating the weights.

Table 6b. Example application of GeoRePORT, showing assigned grades.
User-provided information is shown in highlighted column.

Sub-Attribute	Value	Assigned Grade	Sub-Attribute Weight	Calculated Weight
Noncondensable Gas Content	0.03 weight %	C	2	6
Water for Cooling	Hybrid cooling, 60% of water needed for cooling is available for purchase and economical	C	2	6
Temperature Difference: Inlet to Condenser	ΔT=125˚C	D	3	10
	Sub-Attribute-Weighted Sum:			**22**
	Reported Power Conversion Grade:			**C**

To report power conversion character grade, use the sub-attribute-weighted sum (22 in this case) and use the assigned character grade criteria (Table 7) to determine the character grade, C.

Table 7. Power conversion character grade

Grade	Sub-Attribute-Weighted Sum	Favorability for Power Conversion
A	7–14	Reservoir very favorable for power conversion
B	>14–21	Reservoir favorable for power conversion
C	>21–28	Reservoir moderately favorable for power conversion
D	>28–35	Below average favorability for power conversion
E	>35	Very low favorability for power conversion

The next step is to determine the activity and execution indices. Based on the activity used to determine the sub-attribute grade and the manner of execution of said activity, two additional weights are assessed.

For the “noncondensable gas content” sub-attribute in this example, a downhole gas pressure monitoring tool was used to measure the noncondensable gas content weight percentage, resulting in a grade of A being assessed for the activity index (weighted score of 1). However, this activity was completed in a nearby, analogous geothermal system, not in the geothermal system being assessed for this example. Therefore, the execution index score is a grade of E, corresponding to a weighted score of 5.

For the “water for cooling” sub-attribute, a regional water availability report was used to determine the grade and weighted score. This represents an activity index grade of E, corresponding to a weighted score of 5. Note that there is no associated execution index for this sub-attribute, representing no uncertainty in the activities used to determine the sub-attribute grade.

Finally, for the “temperature difference: inlet to condenser” sub-attribute, this example notes that the temperature difference of 125˚C was determined by using a measured downhole temperature in the sub-attribute grade assessment. This represents an activity index grade of A and a weighted score of 1. Since the downhole temperature probe measurement result was taken from a third-party survey/report, with little or limited information known about the survey methods, the execution index score is a C (corresponding to a weighted score of 3).

Table 8. Power conversion sub-attribute overview table showing character grade, activity index, execution index, and their corresponding scores.

Sub-Attribute	Reported Value	Character Weight	Activity Used	Activity Weight	Execution	Execution Weight
Noncondensable Gas Content	0.03 weight %	6	Downhole in-line precision logging tool	1	Assumed from a nearby analogous geothermal system	5
Water for Cooling	Hybrid cooling, 60% of water needed for cooling is available for purchase and economical	6	Regional water availability report	5	N/A	N/A
Temperature Difference: Inlet to Condenser	ΔT=125˚C	10	Measured downhole temperature	1	Results taken from third-party survey/report	3
Sum	**N/A**	**22**	**N/A**	**7**	**N/A**	**8**
Reported Grade (Tables 9, 10)		**C**	**N/A**	**B**	**N/A**	**D**

To report the character grade, the weight for each sub-attribute is summed, and a grade is assigned via Table 8.

Character Grade: C

Table 9. Power conversion activity grade criteria

Index	Activity Weighted Sum Ranges
A	<6
B	6–8
C	>8–10
D	>10–12
E	>12

Similar methodology is used to determine the area's activity grade. The sum of each activity sub-index determines the activity grade. According to Table 9, an activity index score of 7 (Table 8) corresponds to a grade of B.

Activity Grade: B

Table 10. Power conversion execution index criteria

Grade	Execution Weighted Sum Ranges
A	0–2
B	>2–4
C	>4–6
D	>6–8
E	>8

Execution grade also functions similar to character and activity grades. The sum of each weighted execution grade determines the execution grade. According to Table 10, an execution index score of 8 (Table 8) corresponds to a grade of D.

Execution Index: D

ATTRIBUTE: RESERVOIR MANAGEMENT

Effective management of a producing geothermal reservoir is essential to maintaining economical and sustainable power production over a geothermal plant's lifetime. Geothermal reservoirs are dynamic systems that may change in response to fluid chemistry, principle stress orientations, fracture interactions, and other factors. The reservoir management attribute is designed to consider each aspect of a geothermal reservoir that may impact how effectively and sustainably power is produced from a reservoir. Each sub-attribute listed is known to contribute to a geothermal system's reservoir management potential. As every sub-attribute may not affect the management of the reservoir equally, each is assigned a weight relative to its contribution to reservoir management. For a description of characteristics that were considered but are not included in this reporting protocol, see Appendix A.

Attribute Character Grade

The reservoir management character grade is composed of five sub-attributes. These sub-attributes take into consideration multiple aspects of reservoir management and allow users to assign a character grade based on those individual sub-attributes.

The sub-attributes and their associated weights are shown in Table 11 and are described in more detail below.

Table 11. Reservoir management sub-attribute weights

Sub-Attribute	Weight
System Permeability	3
Storativity	3
Cost of Supplemental Injectant for Pressure Maintenance	2
Coldwater Breakthrough	2
Calcite Saturation	1

The five sub-attribute grades are combined into a single resource grade using the sub-attributed weighted sum ranges outlined in Table 12.

Table 12. Reservoir management character grade: sub-attribute weighted-sum ranges

Grade	Sub-Attribute-Weighted Sum	Description
A	<20	Ideal reservoir management conditions
B	>20–28	Favorable reservoir management conditions
C	>28–36	Manageable reservoir management conditions
D	>26–44	Challenging reservoir management conditions
E	>44	Difficult reservoir management conditions

Activity Index

Grades for the presented sub-attributes can be estimated through a variety of different measurements. Techniques of measurement range from operational plant data to idealized reservoir models with field measurement values. Each technique presents a different set of errors, which are assessed in the activity index of this grade.

Research and exploration methods used to evaluate recovery factors fall into three general areas: theoretical reservoir modeling, exploratory well test data, and operating plant data. The activity used to a sub-attribute is very dependent on which phase of development the project is in. Areas with developed wells and power plants have higher confidence in measured values when contrasted with reservoir models generated with surveying data.

Table 13. Reservoir management activity index: sub-attribute-weighted sum ranges

Index	Activity Weighted Sum Ranges
A	<20
B	>20–28
C	>28–36
C	>26–44
E	>44

When selecting the activity index, choose the most representative measurements after considering how all of the different measurement activities fit within the framework of a conceptual model. If measurement results are inconsistent with the conceptual model, select the index that corresponds to the activity/activities that was/were performed with the highest quality, i.e., the data quality corresponds to an execution index of A or B (and consider re-evaluating the conceptual model).

Execution Indices

Due to the number of execution indices and the use of these indices for multiple sub-attributes, the full execution indices tables are provided in Tables 65–97.

Sub-Attribute Character Grades and Activity Indices Tables

The following tables provide descriptions of each sub-attribute grade and associated weight, the sum of which is used to assign resource grade in Table 13. For each sub-attribute, select the most appropriate grade to describe the resource, and choose the associated activity and execution indices that describe how you arrived at the reported grade.

Sub-Attribute 1: System Permeability

Permeability is a crucial component of any geothermal reservoir. Heat exists throughout the Earth's crust. However, if there is no pathway for a working fluid to be injected and recover said heat energy, the resource is inaccessible.

Steps have been taken over the years to artificially enhance reservoir permeability through a technique known as enhanced geothermal systems (EGS), which aims to increase fluid transmission through the reservoir using hydraulic, thermal, and chemical stimulation (DOE 2012).

System permeability is quantified in terms of reservoir permeability, in units of millidarcy-feet (mD-ft). In the oil and gas industry, permeability is typically reported in millidarcys (Schlumberger 2016). However, this value incorporates the reservoir thickness, which is not typically an easily determined value. Therefore, permeability is expressed in millidarcy-feet, eliminating uncertainty associated with reservoir thickness values. The values in Table 14 were given by industry experts as a hierarchy for grading the system permeability sub-attribute.

Table 14. Reservoir management sub-attribute grade: system permeability

Grade	Weight	System Permeability	Description *from Geological Attribute: Permeability*
A	3	>300,000 mD-ft	Very High
B	6	>200,000–300,000 mD-ft	High
C	9	>50,000–200,000 mD-ft	Medium
D	12	>10,000–50,000 mD-ft	Low
E	15	<10,000 mD-ft	Very Low

Table 15. Reservoir management sub-attribute activity: system permeability

Index	Weight	Description	See Related Execution Index
A	3	For one well, combination of flow tests including: Step-rate injectivity or productivity tests, image log and/or core description, pressure temperature spinner logs, or distributed temperature sensor log. For multiple wells, combination of pressure build-up/draw-down flow test, tracer tests	65
B	6	Lithological cores (and laboratory measurements); formation microimaging-borehole televiewer or acoustic reflectivity	83, 82, 84
C	9	Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error	92
D	12	Structural field mapping; distribution of thermal features; fault dilation analysis	67, 93
E	15	Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas	95

Sub-Attribute 2: Storativity

Storativity is used to evaluate how a reservoir will recharge and react when fluid is extracted. It is expressed in units of meters/bar and is determined via the equation:

$$S = \emptyset C h$$

where:
Ø=reservoir porosity [%]

h=reservoir thickness [m]

C=fluid compressibility [1/bar]

This equation shows that storativity is directly dependent on fluid compressibility. This value can range depending on whether the reservoir is liquid- or steam-dominated, or mixed-phase. It is therefore most effective to consider the magnitude of storativity values, as there is a large range between different geothermal systems.

Table 16. Reservoir management sub-attribute grade: storativity

Grade	Weight	Description	Storativity Order of Magnitude (m/bar)
A	3	Steam-phase reservoir, high porosity	$>10^{-1}$
B	6	Two-phase reservoir, high porosity	$>10^{-2}$
C	9	Mixed-phase reservoir, dominantly liquid phase	$>10^{-3}$
D	12	Liquid-phase reservoir, high porosity	$>10^{-4}$
E	15	Liquid-phase reservoir, low porosity	$>10^{-5}$

Table 17. Reservoir management sub-attribute activity: storativity

Index	Weight	Description	See Related Execution Index
A	3	Well flow tests	65
B	6	Reservoir modeling	94
C	9	Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error	92
D	12	Properties assumed from field mapping/surveys of surface manifestations, distribution of hydrothermal alteration, and bounding geologic structures	67
E	15	Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas	95

Sub-Attribute 3: Cost of Supplemental Injectant for Pressure Maintenance

A typical hydrothermal system contains a natural fracture network that facilitates fluid flow through the reservoir. This fluid flow typically exists naturally and is recharged over time. However, when this fluid is recovered through a production well, the reservoir fluid content may not recharge quickly enough to maintain its undisturbed water level.
Injection wells are therefore necessary to ensure that water and pressure levels are sustained over the course of long-term power production. In addition, reinjection alleviates the problem of dealing with produced brines and helps to reduce the amount of subsidence that occurs over the reservoir. However, injection can also have less desired effects, such as induced seismicity and accelerating thermal breakthrough. Geothermal reservoirs are typically not closed systems; water injected into the reservoir is not all recovered, and notable amounts are lost in the subsurface. This sub-attribute is graded in units of dollars per megawatt (MW) of unappropriated groundwater ($/MW). This sub-attribute does not have an associated execution index, as the activities documented in Table 19 do not typically have any uncertainty associated with them.

Table 18. Reservoir management sub-attribute grade: cost of supplemental injectant for pressure maintenance

Grade	Weight	Description	Cost of Unappropriated Groundwater (USD/MW)
A	2	Supplemental injectant not needed	N/A
B	4	Water available and is economical for purchase	<$1,000/MW
C	6	Water available, may be expensive or difficult to acquire	$1,000–25,000/MW
D	8	Some water available, may not be enough and is expensive to acquire	>$25,000/MW
E	10	Water needed and unavailable	N/A

Table 19. Reservoir management sub-attribute activity: cost of supplemental injectant for pressure maintenance

Index	Weight	Description	See Related Execution Index
A	2	Water use, permits, rights secured	N/A
B	4	Water use, permits, rights applied for and in the process of being secured (process straightforward)	
C	6	Water use, permits, rights applied for and in the process of being secured (process uncertain—e.g., court process required)	
D	8	Identification of water source, owner (if applicable), and process to obtain rights	
E	10	Regional water availability reports	

Sub-Attribute 4: Coldwater Breakthrough

Injection wells are necessary in conventional geothermal systems to provide pressure maintenance as well as to recharge the fluid levels within the reservoir. Typically, fluid injected is at a lower temperature than the fluid that is produced, with the desire that the pathway the fluid takes through the reservoir is long enough to gather sufficient heat from the surrounding formation. If the pathway between the injection and production wells has a high enough transmissivity (i.e., permeability in faults or fractures is high), this heat cannot be mined effectively, and colder fluid temperatures are seen at the production well (i.e., thermal breakthrough), reducing the heat energy contained in the reservoir fluid.

This sub-attribute is measured in yearly change in fluid enthalpy (evaluated in kilojoules per kilogram (kJ/kg). As fluid temperature decreases, enthalpy decreases as well, and this measured change gives rise to the sub-attribute grade. Typically, tracer tests of different lengths can be used to determine this change in enthalpy over the yearly timeframe.

Table 20. Reservoir management sub-attribute grade: coldwater breakthrough

Grade	Weight	Injectate Breakthrough
A	2	No noticeable change in geofluid enthalpy on a yearly timeframe
B	4	0–5 kJ/kg per year of enthalpy change
C	6	>5–7.5 kJ/kg per year of enthalpy change
D	8	>7.5–10 kJ/kg per year of enthalpy change
E	10	>10 kJ/kg per year enthalpy change

Table 21. Reservoir management sub-attribute activity: coldwater breakthrough

Index	Weight	Description	See Related Execution Index
A	2	Well calibrated reservoir model—tracer data, >5 years production data, complete temperature, pressure and fluid chemistry data for all wells	66, 81, 94
B	4	Well calibrated reservoir model—tracer data, >3 years production data, complete temperature, pressure and fluid chemistry data for all wells	66, 81, 94
C	6	Well calibrated reservoir model—tracer data, >1 year production data, complete temperature, pressure and fluid chemistry data for all wells	66, 81, 94
D	8	Field mapping/surveys of surface manifestations, distribution of hydrothermal alteration, and bounding geologic structures	67
E	10	Anecdotal evidence of spring cooling (T Drawdown)	67, 68

Sub-Attribute 5: Calcite Saturation

The presence of calcite in thermal waters increases the likelihood of scaling within the reservoir and power plant infrastructure. Calcite scaling is one of the most common production issues and occurs in geothermal systems around the world. The following processes can form calcite: hydrolysis, boiling, and heating of peripheral fluids. When formed, it can significantly decrease the production potential of geothermal systems (Izgec 2005). For example, wells in the southern area of the Ahuachapán field in El Salvador exhibit extremely high calcite saturation indices when the fluids reach the boiling point. To manage precipitation of calcite at the wells, anti-scaling chemicals have been used to prolong the production levels of the reservoir. By utilizing these chemicals, the scaling potential of the waters is reduced, increasing the lifetime of the wells and subsequently ensuring the area's prolonged productivity (Jacobo 2012). Additionally, the presence of carbonate rocks in the reservoir fractures may indicate potential future calcite scaling issues. For example, many fields in Turkey have issues with carbonate scaling due to their collocation with carbonate reservoir rocks. The calcite in these rocks provides a large source of carbon dioxide (CO_2) when equilibrated with water (Haizlip and Haklidir 2011; Haizlip et al. 2016).

The concentration of calcite, as well as the temperature of the reservoir fluid, controls the likelihood of calcite precipitation. Low temperature fluids are more likely to precipitate calcite from solution than fluids with high temperatures. To account for the effect the temperature has on calcite precipitation, as well as the concentration of silica within the fluid, the calcite saturation index is used to grade the presence of calcite.

Table 22. Reservoir management sub-attribute grade: calcite saturation

Grade	Weight	Calcite Saturation Index
A	1	0
B	2	>0–0.5
C	3	>0.5–0.75
D	4	>0.75–1
E	5	>1

Table 23. Reservoir management sub-attribute activity: calcite saturation

Index	Weight	Description	See Related Execution Index
A	1	Ion chromatograph	88
B	2	Colorimeter-Molybdosilicate method	89
C	3	Colorimeter-Heteropoly Blue method	90
D	4	Pocket colorimeter/test kit	91
E	5	Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas	95

ATTRIBUTE: LOGISTICS

The logistics character grade assesses the topographical and geographical barriers to development of a geothermal resource. Any physical characteristic of the area that creates a barrier and requires special tools or techniques to overcome threatens to increase project costs and slow development. For a description of characteristics that were considered but are not included in this reporting protocol, see Appendix B.

Attribute Character Grade

The logistics character grade is composed of eight sub-attributes. These sub-attributes take into consideration multiple aspects of logistics and allow users to assign a character grade based on those individual sub-attributes.

The sub-attributes and their associated weights are shown in Table 24 and are described in further detail below.

Table 24. Logistics sub-attribute weights

Sub-Attribute	Weight
Degree of Isolation	2
Volcanic Hazards	2
Landslide Hazards	2
Earthquake Hazards	2
Site Road Access	2
Wildfire Hazards	2
Topography	1
Severe Weather Events	1

Table 25. Logistics character grade criteria

Grade	Sub-Attribute-Weighted Sum	Description
A	>24	Ideal: no logistical barriers present
B	24–36	Favorable: few logistical barriers
C	>36–48	Manageable logistical barriers
D	>48–60	Challenging logistical barriers
E	>60	Difficult logistical barriers

Activity Index

The activity index for logistics is based on the level of geological site assessment performed by developers. As exploration and development phases are completed, knowledge about the site will increase. Unlike other sections with sub-attribute indices, logistics only uses one activity index. Since most of the sub-attribute indices can be assessed using similar methods, a singular activity determines the resource's activity grade.

The logistics activity index is designed to encompass commonly used site-surveying techniques and the relevant data they may provide for evaluation of this attribute. The activities presented below are not all encompassing, however. Please contact the authors of this report for guidance in creating/grading an unlisted activity.

Table 26. Sub-attribute activities: logistics

Index	Description
A	Surveyed: Logistics graded through detailed physical site analysis (e.g., probabilistic volcanic hazard assessment for volcanic hazards)
C	Extrapolated: Site conditions inferred from nearby developments and from published geographical characteristics of the area, including road maps, geological hazard maps, topographical maps, and climate maps
E	Extrapolated: Site characteristics inferred ONLY from published geographical characteristics of the area, including road maps, geological hazard maps, topographical maps, and climate maps

Execution Indices

Unlike the majority of Geological and Technical attributes considered within the GeoRePORT, the logistics attribute does not typically have any known uncertainty associated with reported values. As most sub-attributes can be evaluated accurately with publicly available data sets, an execution index was not developed. However, any reported values that are uncertain should be noted in a submitted report.

Sub-Attribute Character Grades

Sub-Attribute 1: Degree of Isolation

A power plant located close to drilling companies and support infrastructure is more economically viable when compared to a remote work site, as it reduces drilling mobilization costs (Eustes 2015). The geographical setting of the geothermal area is a strong driver of costs and time required to transport equipment to the work site.

It is necessary to consider the availability of materials for development of a geothermal resource (Hawaii Department of Planning and Economic Development 1982). In the case of some areas, such as Hawaii, long distances separate the geothermal prospect from equipment necessary for exploration and development. Although severely isolated areas are not impossible to develop, they present unique barriers that must be assessed and overcome for exploration and utilization of the resource.

As bounding geographic settings can range from location to location, the grades developed are designed to assess a range of areas and the geography that determines their accessibility.

Table 27. Logistics sub-attribute grade: degree of isolation

Grade	Weight	Proximity to Drilling Equipment
A	2	Land-locked system; no major continental boundaries or barriers present in accessing resource, and area is within reach of existing infrastructure
B	4	Land-locked system; long distances necessary to travel to access resource, but area is without continental barriers (mountains, large lakes, arctic landscape, etc.)
C	6	Area isolated by continental barriers (mountains, large lakes, arctic landscape, etc.)
D	8	Area isolated by less than 500 miles of ocean
E	10	Area isolated by more than 500 miles of ocean

Sub-Attribute 2: Volcanic Hazards

By their nature, geothermal systems tend to occur near volcanically active landscapes. Active volcanic zones tend to exhibit higher potential for geothermal development.

In 1977 at the Námafjall Geothermal Field in Iceland, magma moving through a dike encountered a geothermal borehole, which provided a pathway to the surface for the magma (Witter 2012). The resulting eruption caused minimal damage but does serve as a reminder that volcanic events are possible in developed geothermal fields. The event at Námafjall is a relatively conservative example of the possible effects of volcanic eruptions on geothermal infrastructure.

Geothermal resource developments near volcanoes should perform an assessment of the area, completed by an expert or consultant in volcanology. Recently, developers began relying on a probabilistic approach to quantify the likelihood of various types of volcanic events, such as ashfall, lava flows, lahars, pyroclastic flows, and sector collapses (Witter 2012). This probabilistic volcanic hazard assessment approach is used to grade the volcanic hazard sub-attribute.

Table 28. Logistics sub-attribute grade: volcanic hazards

Grade	Weight	Description
A	2	No or very low probability of prohibitive volcanic activity
B	4	Low probability of prohibitive volcanic activity
C	6	Moderate probability of prohibitive volcanic activity
D	8	Site is located within a USGS-classified “vent area”
E	10	Site is located within 30 km of a USGS-classified “Large Volcano”

Sub-Attribute 3: Landslide Hazards

Geothermal systems located in near proximity to or on steep mountainous slopes may be susceptible to landslides and slope instability. These steep slopes, combined with hydrothermal alteration, can result in unstable ground. In the event of slope movement on an operating geothermal plant, the resulting alteration to the subsurface system could affect the production of wells and the geothermal plant.

In 2007, a large landslide occurred in the Valley of Geysers in Kamchatka, Russia, illustrating that landslides can and do occur near geothermal areas. The slide altered and, in some cases, totally destroyed natural geysers in the valley, changing the geothermal nature of the area (Gvozdeva 2015).

A 1991 landslide at the Zunil I geothermal field in Guatemala resulted not only in the destruction of geothermal plant infrastructure but also the loss of 23 lives (Flynn 1991).

In 1975, reactivation of an existing landslide led to the blowout of well GDC 65-28 in The Geysers geothermal field, resulting in the formation of a crater issuing steam. Two steam relief systems were installed prior to killing the well and sealing it with cement (Bacon et al. 1976). The field has many quaternary landslides, so the siting of wells, pipelines, and power plants requires special attention in terms of engineering geology issues (e.g., Hovland and Storchillo 1977).

These events illustrate the need for consideration and identification of landslide hazards during geothermal exploration. Landslide susceptibility is considered in terms of classifications developed and mapped by the USGS (Radbruch-Hall 1982).

Table 29. Logistics sub-attribute grade: landslide hazards

Grade	Weight	Description
A	2	Area not located within 3 km of any USGS-identified landslide hazard
B	4	Area located within 2 km of any USGS-identified landslide hazard
C	6	Area located within an area classified by USGS as “Moderate susceptibility/low incidence” for landslide hazards
D	8	Area located within an area classified by USGS as “High susceptibility/low incidence” for landslide hazards
E	10	Area located within an area classified by USGS as “High susceptibility/moderate incidence” for landslide hazards

Sub-Attribute 4: Earthquake Hazards

Natural seismic activity near a producing geothermal system creates hazards for plant infrastructure and personnel. As so much of geothermal power production is related to subsurface infrastructure, any shifts or movements can affect how the system produces power. Geothermal areas do require some form of faulting to create a permeable hydrothermal reservoir; however, these tectonic environments may be active. The magnitude 7.2 El Mayor-Cucapah Earthquake Sequence in Baja, California, in 2010 demonstrated that large tectonic events can occur near geothermal developments, and the resulting implications must be accounted for (Hauksson 2010).
Grades are classified in terms of units developed and used by the USGS for the probability of earthquake occurrence. Units used are peak acceleration as a fraction of standard gravity (Petersen et al. 2014).

Table 30. Logistics sub-attribute grade: earthquake hazards

Grade	Weight	Description
A	2	Site located in an area with a value of peak acceleration < 0.04
B	4	Site located in an area with a value of peak acceleration of 0.04–0.1
C	6	Site located in an area with a value of peak acceleration >0.1–0.2
D	8	Site located in an area with a value of peak acceleration >0.2–0.4
E	10	Site located in an area with a value of peak acceleration >0.4

Sub-Attribute 5: Wildfire Hazards

As geothermal systems are common in arid regions of the western United States, relative susceptibility of those areas to wildfires is an important consideration to be made. The 2015 Valley Fire in California affected the operating infrastructure of several power plants at the Geysers Geothermal area. Five of fourteen facilities at The Geysers were affected by the fire, with damage sustained to infrastructure including cooling towers and communications equipment. These damages restrict the operating capacity at The Geysers and will continue to affect the power output of the area until repairs have been completed (Calpine Corporation 2015).

Grades are classified in terms of USFS wildfire hazard map units (USDA, USFS 2014).

Table 31. Logistics sub-attribute grade: wildfire hazards

Grade	Weight	Description
A	2	Site located in USFS “Very Low” wildfire potential
B	4	Site located in USFS “Low” wildfire potential
C	6	Site located in USFS “Moderate” wildfire potential
D	8	Site located in USFS “High” wildfire potential
E	10	Site located in USFS “Very High” wildfire potential

Sub-Attribute 6: Site Road Access

Developing a geothermal area requires access to the geographical area by a range of different equipment, including drill rigs, geophysical equipment, and construction crews. This need for access is eased by the presence of any passable roads that may already be present at the site. If roads must be constructed or enlarged, additional costs, permits, and longer project timelines are likely.

As not all roads are equally passable, the proximity of roads considered “Rural Local Roads” by the Federal Highway Administration is defined in this sub-attribute (Federal Highway Administration 2013).

Table 32. Logistics sub-attribute grade: site road access

Grade	Weight	Description
A	2	Roads and supporting infrastructure already present at site; roads considered a “Rural Local Road” at minimum by Federal Highway Administration
B	4	Site located 1–3 miles from roads considered a “Rural Local Road” at minimum by Federal Highway Administration
C	6	Site located 4–6 miles from roads considered a “Rural Local Road” at minimum by Federal Highway Administration
D	8	Site located 7–10 miles from roads considered a “Rural Local Road” at minimum by Federal Highway Administration
E	10	Site located >10 miles from roads considered a “Rural Local Road” at minimum by Federal Highway Administration

Sub-Attribute 7: Topography

Topography of the landscape has an impact on power plant deployment. Steep and mountainous terrain is more difficult to access than a comparable area located on flat ground. Cost and time required to bring equipment to the work site increase proportionally with the ruggedness of the landscape.

Grades are evaluated in terms of average slope in the area, with grade A constituting a flat area and grade E being an area with rugged topography and slope angles greater than 30°.

Table 33. Logistics sub-attribute grade: topography

Grade	Weight	Description
A	1	Flat, accessible resource area
B	2	Terrain with slopes up to 10°
C	3	Terrain with slopes up to 20°
D	4	Rugged terrain with slopes up to 30°
E	5	Rugged topography with slopes >30°

Sub-Attribute 8: Severe Weather Events

Harsh weather conditions at the geothermal site restrict construction windows and inhibit access to the site during extreme weather events. Arid, arctic, tropical, and high-elevation environments are likely to result in landscapes that hinder resource development.

As the specific type of weather event experienced will vary from area to area, it is most effective to consider the annual number of days said weather event prevents access to the geothermal site. These severe weather events could include typhoons; hurricanes and other tropical storms; heavy rains and flooding; blizzards; and tornados.

Table 34. Logistics sub-attribute grade: severe weather events

Grade	Weight	Description
A	1	No annual days of prevented access (as a result of severe weather events)
B	2	1–15 annual days of prevented access (as a result of severe weather events)
C	3	>15–30 annual days of prevented access (as a result of severe weather events)
D	4	>30–45 annual days of prevented access (as a result of severe weather events)
E	5	>45 annual days of prevented access (as a result of severe weather events)

ATTRIBUTE: POWER CONVERSION

When geofluid is recovered at the wellhead, several different power conversion techniques can convert the recovered heat energy into electric power. The conversion technology used is dependent on the temperature of the geothermal reservoir, the ambient climate, and any restrictions on plant infrastructure. Commonly used power conversion technologies include flash, double flash, and binary systems, as well as combinations of these systems.

In geothermal areas with undeveloped infrastructure, it can be difficult to assess power conversion efficiency without test well flow data. Similar to other developed sub-attributes, four separate attributes that are known to affect the power conversion character grade are considered here.

Elements of the geothermal resource that allow power plants to operate efficiently are not attributes that are typically well known prior to power plant operation. Thus, character grade is evaluated for an undeveloped power plant by using sub-attributes in Table 35 and weighted criteria given in Table 36. For a description of characteristics that were considered but are not included in this reporting protocol, see Appendix C.

Attribute Character Grade

The power conversion character grade is composed of four sub-attributes. These sub-attributes take into consideration multiple aspects of power conversion and allow users to assign a character grade based on those individual sub-attributes.

The sub-attributes and their associated weights are shown in Table 35 and are described in more detail below.

Table 35. Power conversion sub-attribute weights

Sub-Attribute	Weight
Temperature Difference: Inlet to Condenser	3
Specific Exergy Index	3
Water for Cooling	2
Noncondensable Gas Content	1

Table 36. Power conversion character grade criteria

Grade	Sub-Attribute-Weighted Sum	Favorability for Power Conversion
A	<16	Ideal: Resource very favorable for power conversion
B	16–24	Favorable: Resource favorable for power conversion
C	24–32	Manageable: Resource moderately favorable for power conversion
D	32–40	Challenging: Below average favorability for power conversion
E	>40	Difficult: Very low favorability for power conversion

Activity Index

As with other attributes of this protocol, it is necessary to assess the certainty within a reported character grade value. We do this with an activity index. Each sub-attribute index is accompanied by an activity index that ranks the methods available to estimate the sub-attribute grade according to accuracy.

Similar to a geothermal resource's power conversion grade, its activity grade is a function of multiple sub-activity indices. Rather than reporting a single activity grade, activities are recorded for each sub-attribute, and the reported activity grade is determined by summing the weights of each sub-attribute activity.

Table 37. Power conversion activity index: sub-attribute-weighted sum ranges

Index	Activity Weighted Sum Ranges
A	<16
B	16–24
C	24–32
D	32–40
E	>40

Execution Indices

Due to the number of execution indices and the use of these indices for multiple sub-attributes, the full execution indices tables are provided in Tables 65–97.

Sub-Attribute Character Grades and Activity Indices Tables

The following tables provide descriptions of each sub-attribute grade and associated weight, the sum of which is used to assign the resource grade in Table 36. For each sub-attribute, select the most appropriate grade to describe the resource, along with the associated activity and execution indices that describe how you arrived at the reported grade.

Sub-Attribute 1: Temperature Difference

Geothermal power plants generate power by extracting heat from geofluid collected at the surface. A larger temperature difference between geofluid and ambient temperature leaves more heat available for conversion to electric power. The lower an area's ambient temperature is, the more efficiently a plant can operate; this is more critical for air-cooled power plants than water-cooled units. Seasonal temperature changes can leave plants less efficient in summer months when demand is higher and more efficient in cooler winter months. The temperature difference should be calculated as:

$$\Delta T = [Reservoir\ Temperature - 5°C] - [95^{th}\ percentile\ of\ ambient\ air\ temperature^{*}]$$

From cumulative distribution function of hourly temperature for a year (Turchi 2016)

Table 38. Power conversion sub-attribute grade: temperature difference (inlet to condenser)

Grade	Weight	Conversion Technology	Quantification
A	2	Double flash	ΔT>180˚C
B	4	Single flash	ΔT>150˚C
C	8	Binary cycle, working fluid: geothermal fluid	ΔT>125–150˚C
D	10	Binary cycle, working fluid: isobutane, etc.	ΔT>100–125˚C
E	14	Binary cycle, working fluid: isobutane, etc. OR direct use	ΔT< 100˚C

Table 39. Power conversion sub-attribute activity: temperature difference (inlet to condenser)

Index	Weight	Description	See Related Execution Index
A	2	Measured temperatures: Downhole temperature probe readings (well[s] drilled into reservoir)	66
B	4	Estimated temperatures: Geothermometry (geothermal brines and gasses)	73–77
C	8	Estimated temperatures: Geothermometry (immature or mixed fluids, inconsistent results between geothermometers)	73–77
D	10	Extrapolated temperature: Thermal gradient hole (TGH)/well(s); alteration mineral assemblages; mineral water stable isotopes; fluid inclusion compositions	66, 78, 86
E	14	Extrapolated temperature: Regional heat flow data	68

Sub-Attribute 2: Specific Exergy Index

The total energy of a geothermal system correlates to the potential power production of that system (i.e., higher energy systems may be able to produce more power than lower energy systems).

Lee (1996) proposes grading the ability of a geothermal fluid to do work in terms of exergy, via the following general equation:

$$e = h - h_o - T_o(s - s_o)$$

where:
h = specific enthalpy [kJ/kg]
T = reservoir temperature [˚K]
s = specific entropy [kJ/kg K]
(o subscripts are reference points)

With the above equation, the exergy is sensitive to the reference point used. In Lee (1996) exergies are normalized to three references: 1) triple point, 2) 10˚C, and 3) 20˚C. Lee (1996) proposes normalizing exergies to the triple point to reach the equation below, when SEI is the specific exergy index. When normalization is set to the triple point, the equation for SEI simplifies to:

$$SEI = (h - 273.15s)/1192$$

Activities used for estimating SEI range from direct drilling into the geothermal reservoir to estimating likely enthalpy between analogous geothermal systems. Apart from measuring fluid from producing wells or test wells, SEI can be inferred from reservoir models, inferred from surface measurements of hydrothermal features, or extrapolated from analogous geothermal systems.

Table 40. Power conversion sub-attribute grade: specific exergy index

Grade	Weight	Conversion Technology	Quantification
A	3	Very high SEI field	SEI ≥0.5
B	6	High SEI field	0.5>SEI≥0.2
C	9	Moderate SEI field	0.2>SEI≥0.1
D	12	Low SEI field	0.1>SEI≥0.05
E	15	Very low SEI field	0.05>SEI

Table 41. Power conversion sub-attribute activity: specific exergy index

Index	Weight	Description	See Related Execution Index
A	3	SEI estimated from: Fluid sampled from completed in-field test well or slimhole	96-97
B	6	SEI inferred from: Reservoir model	94
C	9	Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	92
D	12	SEI inferred from: Field mapping/surveys of surface manifestations, distribution of hydrothermal alteration, and bounding geologic structures	67
E	15	SEI inferred from: Analogous geothermal field	95

Sub-Attribute 3: Water for Cooling

The use of cooling systems increases temperature differences across the power generation system and subsequently increases plant efficiency (Kagel 2008). Most geothermal plants utilize one of two techniques for cooling systems: water- or air-based. Water-based cooling systems are more efficient than air-based systems, but they require water—either nearby or from geothermal fluid—to operate. Due to relative efficiencies, it is assumed that when water is available, water-based cooling will be used rather than air-based. This sub-attribute is therefore evaluated on the geothermal site's proximity to available water sources. Also considered is hybrid cooling technologies, which use a combination of water and air to cool the working fluid. This sub-attribute does not have an associated execution index, as the activities documented in Table 43 do not typically have any uncertainty associated with them.

Table 42. Power conversion sub-attribute grade: water for cooling

Grade	Weight	Percent of Water Required for Cooling Available	Cooling Technology
A	2	100%	Water
B	4	75%	Hybrid
C	6	50%	Hybrid
D	8	10%	Hybrid
E	14	0%	Air

Table 43. Power conversion sub-attribute activity: water for cooling

Index	Weight	Description	See Related Execution Index
A	2	Water use, permits, rights secured	N/A
B	4	Water use, permits, rights applied for and in the process of being secured (process straightforward)	
C	6	Water use, permits, rights applied for and in the process of being secured (process uncertain, e.g., court process required)	
D	8	Identification of water source, owner (if applicable), and process to obtain rights	
E	10	Regional water availability reports	

Sub-Attribute 4: Noncondensable Gas Content

One impact on power plant efficiency is noncondensable gas (NCG) content. When the geofluid is flashed to steam, it goes through a turbine and back into a condenser to return it to liquid form. Any NCGs present in the condenser will build up and decrease the pressure gradient across the turbine, thereby decreasing efficiency. Techniques used for removal of these gasses also result in additional parasitic loads being placed on the plant. Power plants using binary conversion technology do not experience issues with NCGs because the plant is in a closed cycle, meaning the geofluid is never flashed to steam. Low temperature reservoirs normally utilize binary conversion technology, so to account for the advantages available with binary conversion, any reservoir with a resource temperature grade of D or lower (<150°C) (Young et al. 2016) is assigned an NCG ranking of A.
NCGs are an important consideration for many geothermal areas around the world. Common NCG compositions consist of greater than 90% CO_2, but the exact makeup can range slightly from system to system (Haizlip et al. 2013). At the Germencik plant in Turkey, the high NCG content is managed through a series of ejectors and vacuum pumps. This method provides an economical solution for NCG removal while maintaining adequate levels of steam production (Wallace 2009). Other NCGs (such as Hydrogen Sulfide [H_2S]) may need to be scrubbed from the gas stream for environmental reasons, resulting in additional expense. Proper management of any NCGs in a geothermal area is important for ensuring a productive reservoir and power plant.

Table 44. Power conversion sub-attribute grade: noncondensable gas content

Grade	Weight	NCG Content [wt %]
A	2	0–0.1 wt%
B	4	>0.1–0.25. wt%
C	6	>0.25–0.5 wt%
D	8	>0.5–0.75 wt%
E	10	> 0.75 wt%

Table 45. Power conversion sub-attribute activity: noncondensable gas content

Index	Weight	Description	Related Execution Index
A	2	NCG content of steam fraction determined from operational power plant data	N/A
B	4	Pressure gauge—reservoir gas directly sampled in field	86
C	6	Pressure gauge—mixed reservoir gas sampled in field	86
D	8	Pressure gauge—bottled reservoir fluid in lab	87
E	10	Pressure gauge—bottled mixed gas in lab	87

ATTRIBUTE: DRILLING

Exploration, injection, and production well drilling costs can account for 30%–60% of total capital investment of a geothermal project (Tester et al. 2006). To economically develop geothermal resources, any project delays or problems resulting from drilling must be minimized. Technologies developed by the oil and gas industry have been applied to geothermal drilling, enabling numerous advancements in practices and well design in recent years (Taylor 2007; Eustes et al. 2015). To determine the factors that most impact drilling, publications and industry research were reviewed (e.g., Fairbank and Niggeman 2004; Augustine et al. 2006; Entingh 2006; International Finance Corporation 2013; Finger and Blankenship 2010; Thorhallsson and Sveinbjornsson 2012; Denninger 2015; Eustes et al. 2015; Knudsen et al. 2014).

To reflect physical, geological, and logistical aspects that contribute to drilling difficulty, eight sub-attributes were developed, outlined in the tables below. Each sub-attribute is known to be a significant driver of drilling difficulty, either by requiring advanced (and expensive) drilling techniques or by creating mechanical difficulties resulting in drill rig downtime. Grades were developed for each of the eight sub-attributes. For a detailed description of these sub-attributes, and those that were considered but are not included in this reporting protocol, see Appendix D.

Attribute Character Grade

The drilling character grade is composed of eight sub-attributes. These sub-attributes take into consideration multiple aspects of drilling and allow users to assign a character grade based on those individual sub-attributes.

The sub-attributes and their associated weights are shown in Table 46 and are described in more detail below.

Table 46. Drilling sub-attribute weights

Sub-Attribute	Weight
Well Depth	4
Drilling Experience in Area	3
Bottom-Hole Diameter	2
Temperature	2
Wellbore Control	2
Anticipated Rig Downtime	1
Well Direction	2
Drilling Restrictions	2

Table 47. Drilling character grade criteria

Grade	Sub-Attribute-Weighted Sum	Description
A	<28	Ideal Drilling Conditions
B	>28-42	Favorable Drilling Conditions
C	>42-56	Manageable Drilling Conditions
D	>56-70	Challenging Drilling Conditions
E	>70	Difficult Drilling Conditions

Activity Index

As with other aspects of this protocol, it is necessary to assess the certainty within a reported character grade value. Each sub-attribute index is accompanied by an activity index that ranks the methods available to estimate the sub-attribute grade according to accuracy.

Similar to a reservoir's drilling grade, its activity grade is a function of multiple sub-activity indices. Rather than reporting a single activity grade, activities are recorded for each sub-attribute, and the reported activity grade is determined by summing the weights of each sub-attribute activity.

Table 48. Drilling activity index: sub-attribute-weighted sum ranges

Index	Activity Weighted Sum Ranges
A	<28
B	>28-42
C	>42-56
D	>56-70
E	>70

Execution Indices

Due to the number of execution indices and the use of these indices for multiple sub-attributes, the full execution indices tables are provided in Tables 65–97.

Sub-Attribute Character Grades and Activity Indices Tables

Since geothermal well drilling faces economic and technical obstacles, users must consider numerous aspects of the reservoir to assess the drilling grade.

Each sub-attribute index is ranked from 1 to 5, with 5 being most likely to negatively affect drilling and 1 being least likely. Since not all factors affect drilling cost equally, a multiplier has been assigned to each sub-attribute. This number increases each index ranking as it applies to drilling difficulty. The sum of all sub-attribute indices weights determines the resource's drilling character grade via Table 47.

Sub-Attribute 1: Well Depth

To access hotter resources, geothermal wells continue to be drilled deeper and deeper into the Earth's crust. When considering drilling difficulty, crews consider the total measured well depth to be a reliable indicator of how expensive drilling will be (Eustes et al. 2015). The deeper a well is drilled, the longer drilling operations take, increasing the cost of the well while also increasing the likelihood of equipment failures. Deeper wells also intersect more rock formations, increasing the likelihood of geologically caused drilling problems. The total depth of a well is evaluated at the base of the well's production zone or may be averaged between a series of wells within a well field.

Table 49. Drilling sub-attribute grade: well depth

Grade	Weight	Description	Quantification (Meters)
A	4	Shallow well	<1,000 m
B	8	Moderately deep well	1,000–2,000 m
C	12	Average depth well	>2,000–3,000 m
D	16	Deep well	>3,000–4,000 m
E	20	Extremely deep well	>4,000 m

Table 50. Drilling sub-attribute activity: well depth

Index	Weight	Description	See Related Execution Index
A	4	Well depth known from: Test well or slimhole, well(s) drilled into reservoir	96,97
B	8	Well depth interpreted from: Geophysics: magnetotelluric (MT), transient electromagnetic (TEM), gravity, seismic in conjunction with conceptual modeling	69–72, 94
C	12	Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error	92
D	16	Extrapolated Well Depth: TGH/well(s) with associated data from alteration mineral assemblages and/or fluid inclusion compositions used to identify target temperature and depth of reservoir	66, 78, 79
E	20	Well depth extrapolated from: Temperature at depth maps	68

Sub-Attribute 2: Drilling Experience in Area

When performing initial site evaluations, crews use data available from previously drilled wells in the area to estimate subsurface conditions that will be encountered during drilling (Augustine 2015). These existing wells are not necessarily geothermal-specific; they can range from thermal boreholes to water wells to oil and gas exploration wells. Although helpful, data from these wells are not always applicable to geothermal drilling. To garner useful information from these wells, the wells must be of similar geological setting and depth to the well to be drilled. The proximity of the geothermal site to these existing wells is assessed in the drilling experience sub-attribute index, and the comparable depth, geology, and density of nearby wells is considered in the activity index.

Table 51. Drilling sub-attribute grade: drilling experience in area

Grade	Weight	Description
A	3	High density (>4) of wells within 1 km of potential drill site into the same formation to similar depths
B	6	Moderate density (3–4) of wells within 1.5 km of potential drill site into the same formation to similar depths
C	9	Low density (1–2) of wells within 1.5 km of potential drill site into the same formation to similar depths
D	12	Low density (1–2) of wells within 2 km of potential drill site into the same formation but not to similar depths
E	15	No nearby wells (e.g., greenfield)

Table 52. Drilling sub-attribute activity: drilling experience

Index	Weight	Description	See Related Execution Index
A	3	Complete well log and drilling data reports available	N/A
B	6	Large well log database published (flow rate, temperature, well design, rate of penetration, lithologies)	
C	9	Well design and measured values available (temperature at depth)	
D	12	Minimal well information available (bottom-hole temperature, stratigraphy, etc.)	
E	15	Minimal or no well log data given, only available information may be the success/failure of drilling operation	

Sub-Attribute 3: Bottom-Hole Diameter

Designing a geothermal well requires a “bottom-up” approach, wherein the location of the production zone and flow rate requirements dictate the diameter at the bottom of the hole (Finger and Blankenship 2010). Once this has been determined, the remainder of the well to the surface can be designed based on nominal pipe sizes and necessity for cased zones. Larger bottom-hole diameters require larger casing strings in the sections above. Due to the increased costs of drilling geothermal wells, especially with regard to casing and cementing considerations, the bottom-hole diameter directly influences the cost and complexity of drilling the well, as larger holes lead to more expensive drilling equipment and higher well completion costs needed in the upper sections.

Table 53. Drilling sub-attribute grade: bottom-hole diameter

Grade	Weight	Downhole Well Diameter (in.)	Downhole Well Diameter (cm)
A	2	<=6-1/8 in.	<=15.56 cm
B	4	> 6-1/8–8-1/2 in.	>15.56–21.59 cm
C	6	>8-1/2–9-7/8 in.	>21.59–25.08 cm
D	8	>9-7/8–12-1/4 in.	>25.08–31.12 cm
E	10	>12-1/4 in.	>31.12 cm

Table 54. Drilling sub-attribute activity: bottom-hole diameter

Index	Weight	Description	See Related Execution Index
A	2	Test well or slimhole drilled into reservoir, production diameter can be extrapolated from the analogous well situated in the same well field	96, 97
B	4	Reservoir/geologic model with identified permeability targets (fault and/or fracture zones)	94
C	6	Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error	92
D	8	Flow rates from surface manifestations and thermal features used to estimate potential well flow rates	67
E	10	Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas	95

Sub-Attribute 4: Temperature

The high-temperature environment of geothermal reservoirs impacts the drilling procedure and materials specifications for each well. These high subsurface temperatures cause risks of blowout/boil-out, and managing corrosive fluids and scaling is a common issue related to the high-temperature fluids. In addition, materials specifications must be carefully researched due to the presence of H_2S gas and/or different fluid compositions in conjunction with elevated temperatures, typically requiring heaver pipe and drill strings to avoid cracking (Eustes et al. 2015).

Table 55. Drilling sub-attribute grade: temperature

Grade	Weight	Value Range	Description
A	2	<=90°C	Very low temperature systems
B	4	>90°C–150°C	Low temperature systems
C	6	>150°C–230°C	Moderate to low temperature, moderate to low enthalpy liquid-only systems
D	8	>230°C–300°C	Two-phase, liquid-dominated systems; high temperature, high enthalpy; moderate temperature, moderate enthalpy
E	10	>300°C or steam	High temperature, two-phase liquid-dominated OR high enthalpy vapor-dominated

Table 56. Drilling sub-attribute activity: temperature

Index	Weight	Description	See Related Execution Index
A	2	Measured reservoir temperatures: Downhole temperature probe readings (well[s] drilled into reservoir)	66
B	4	Estimated reservoir temperatures: Geothermometry (geothermal brines and gasses), analogous well in field	73–77, 80
C	6	Estimated reservoir temperatures: Geothermometry (immature or mixed fluids, inconsistent results between geothermometers)	73–77
D	8	Extrapolated reservoir temperature: TGH/well(s); alteration mineral assemblages; fluid inclusion homogenization temperature estimates	66, 78, 79
E	10	Extrapolated temperature: Regional heat flow data	68

Sub-Attribute 5: Wellbore Control

There are many controls on a geothermal well design. The subsurface pore pressure varies with depth and with changes in lithology and must be accounted for by the well casing program. When a casing string is inserted within the wellbore, it increases the pressure within the wellbore. This is a crucial component of well design, because if the pressure within the formation exceeds the pressure of drilling fluids, the structural integrity of the well can be compromised. Subsequently, the pressure of drilling fluids must also be below that of the pressure within the existing fracture network. If the fluid pressure were to exceed the fracture network pressure, loss of circulation would occur, hindering drilling operations. It is therefore essential for the driller to maintain a casing program that keeps fluid pressure within the pore pressure/fracture gradient envelope. The margin of error, measured as a ratio of pore pressure to fracture gradient, allowed by the envelope for a particular drill site is considered in this sub-attribute.

Table 57. Drilling sub-attribute grade: wellbore control

Grade	Weight	Ratio of Pore Pressure (PP) to Frac Gradient (FG)	Description
A	2	<0.6	Ratio not an issue, drilling can proceed normally
B	4	0.6–0.7	Slight difficulty in staying within PP-FG envelope; drilling can proceed normally
C	6	0.7–0.8	Moderately difficult to stay within PP-FG envelope; stress state monitored more carefully, but drilling can proceed normally
D	8	0.8–0.9	Challenging to stay within PP-FG envelope; stress state monitored carefully, danger of blowout or fracturing present
E	10	0.9–1.0	Extremely difficult to stay within PP-FG envelope; stress state monitored carefully, danger of blowout or fracturing high

Table 58. Drilling sub-attribute activity: wellbore control

Index	Weight	Description	See Related Execution Index
A	2	PP-FG estimated through analogous well in field	80
B	4	Geophysics (MT, TEM, seismic, etc.) used to predict PP-FG ratio at drill site	69–72
C	6	Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error	92
D	8	Reservoir/geologic model with rock strength data and estimated hydraulic gradient	94
E	10	Assumed from studies of analogous geothermal settings, extrapolated from studies of nearby areas or based off of global stress distribution	95

Sub-Attribute 6: Anticipated Rig Downtime

Drillers anticipate a certain amount of downtime, or "flat time," when drilling a well. This includes breaks from drilling for events such as running and cementing casing, rigging up and testing blow-out preventers (BOPs), changing drill bits, running well logs, and anticipating zones of lost circulation (Capuano 2016). It is important to note that this is distinct from "nonproductive" time, a term usually reserved for actions in which the well is not being progressed further, such as for repairs, fishing for twisted off drill pipe, or weather-related events. Although the time for each action during rig downtime varies from well to well, some "standard" times for each event were estimated as such (Capuano 2016):

- **Running casing**: Approximately 24 hours (on average—shorter strings can be done more quickly);
- **Cementing casing**: Usually a 24-hour period to rig up, pump cement, rig down, and wait for cement to set;
- **Rigging up and testing BOPs**: Completed after new casing is set, BOPs must be nippled up and tested; takes between 24 and 60 hours based on the size of the BOP stack;
- **Bit changes**: Much more dependent on individual wells, due to time required for tripping out of well. Changing bit takes only a few hours, but the trip could take half a day or more to complete;
- **Lost circulation**: Can be anticipated with adequate knowledge of subsurface lithology; typically, each zone adds 24 hours to set a cement plug.

Table 59. Drilling sub-attribute grade: anticipated rig downtime

Grade	Weight	Value Range	Description
A	1	< 5 days	Simple/standard well; anticipated downtime not significant
B	2	5–10 days	Simple/standard well; minimal downtime anticipated
C	3	10–20 days	Moderately complex well; fair amount of downtime anticipated
D	4	20–30 days	Moderately complex well; moderate amount of downtime anticipated
E	5	> 30 days	Complex well; several trips and lost circulation zones anticipated; significant amount of downtime

Table 60. Drilling sub-attribute activity: anticipated rig downtime

Index	Weight	Description	See Related Execution Index
A	1	Rig downtime estimated using: Results from test well or slimhole drilled into reservoir	96, 97
B	2	Rig downtime estimated using: Reservoir/geologic model	94
C	3	Rig downtime estimated using: Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error	92
D	4	Rig downtime estimated using: Geophysics (MT, TEM, seismic, etc.)	70–72
E	5	Rig downtime estimated from studies of analogous geothermal settings, extrapolated from studies of nearby areas	95

Sub-Attribute 7: Well Direction

To drill into resources that are difficult to access, crews will often use directional drilling. Rather than drilling vertically into the Earth, wellbores can be positioned at a specified angle or deviated to run horizontally. This angle may be to create a perpendicular angle of intersection with a fracture network, or it can direct the well into an area that may not be accessible from straight above due to volcanic or geologic hazards or other land use restrictions. On some occasions, well designs require the drilling of a perfectly vertical well. Meeting these design criteria also creates difficulties for drilling crews.

It is generally considered easiest to let the drill bit proceed freely downward, following the path of least resistance versus adhering to strict well design criteria (Eustes et al. 2015). Any deviation from a vertical path requires more complex monitoring systems and increases costs. In addition, the high-temperature environment of a geothermal well limits the type of electronics and measurement while drilling systems that can be effectively utilized to drill directionally/horizontally.

Table 61. Drilling sub-attribute grade: well direction

Index	Weight	Well Direction	Description
A	2	Vertical	Well angle does not exceed 10˚ from vertical
C	4	Directional	Well angle reaches maximum angle of 60˚ from vertical
E	6	Horizontal	Bottom-hole well angle between 60˚ and 90˚ from vertical

Table 62. Drilling sub-attribute activity: well direction

Index	Weight	Description	See Related Execution Index
A	2	Well direction estimated using: Experience from test well or slimhole drilled into reservoir	96, 97
B	4	Well direction estimated using: Reservoir/geologic model	94
C	6	Well direction estimated using: Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error	92
D	8	Well direction estimated using: Geophysics (MT, TEM, seismic, etc.)	70–72
E	10	Well direction estimated from studies of analogous geothermal settings, extrapolated from studies of nearby areas	95

Sub-Attribute 8: Drilling Restrictions

Select state and local governments have put into place laws and ordinances that restrict the hours that geothermal drilling may take place (State of Hawaii 1983). These restrictions severely inhibit the ability to economically drill wells by increasing the time required to initiate and stop drilling each day. It has also been alleged that pausing drilling creates hazards for crews, including gas buildup and wellbore stability issues with the well itself (Callis 2015).

Table 63. Drilling sub-attribute grade: drilling restrictions

Grade	Weight	Description
A	2	No drilling restrictions in place
B	4	Seasonal weather and/or environmental restrictions limit drilling to 6–8 months per year
C	6	Noise restrictions limit drilling to 14 hours/day or less OR seasonal weather and/or environmental restrictions limit drilling to 3–6 months per year
D	8	Noise restrictions limit drilling to 12 hours/day or less OR seasonal weather and/or environmental restrictions limit drilling to <=3 months per year
E	10	Both of the following restrictions in place at site: noise restrictions limit drilling to 12 hours/day or less AND seasonal weather and/or environmental restrictions limit drilling to <=3 months per year

Table 64. Drilling sub-attribute activity: drilling restrictions

Grade	Weight	Description
A	2	Environmental review completed for well field
B	4	Environmental review for well field is in progress with preliminary information available
C	6	Environmental review is completed for leasing; land is posted for lease sale
D	8	Environmental review is completed for a resource management plan; land is included in a resource management plan, other type of land use plan, or zoned for geothermal development
E	10	Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas

EXECUTION INDICES

Table 65. Execution index: flow and/or injection tests

Index	Flow and/or Injection Tests	Weight
A	• Flow or injection tests are completed in full-size large diameter well. • Tests performed in multiple wells (more than 2). • Tests include but are not limited to pressure build-up and fall-off tests, interference tests, step-rate tests, and tracer tests. • Test duration of > 4 weeks. • Results correlated with temperature and pressure logs at all wells.	1
B	• Flow tests are completed in small-diameter production wells. • Tests performed in multiple wells (2 or more). • Multiple test types are performed (e.g., pressure build-up and fall-off tests, interference tests, step-rate tests, and tracer tests), but not at all wells. • Test duration of 1–4 weeks. • Results correlated with temperature and pressure logs at some, but not all, test wells.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Flow tests are completed in slimholes. • Tests performed in only 1 well. • Only one type of test is performed (e.g., pressure build-up and fall-off tests, step-rate tests, interference tests, etc.). • Test duration of 1 week or less. • Results not correlated with temperature and pressure logs.	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 66. Execution index: downhole temperature probe and thermal gradient hole (TGH)

Index	Downhole Temperature Probe and Thermal Gradient Hole (TGH)	Weight
A	• Probe allowed to equilibrate with the wellbore fluids. • Borehole has equilibrated with the surrounding formation. • Temperature log run under static conditions. • Cuttings and/or geophysics confirm measurement within the reservoir (i.e., downhole alteration mineralogy consistent with reading). • Repeated surveys at the same well/location. • Frequent calibrations completed that follow a prescribed set of procedures. • Analytical quality of results can be shown to be high (based on sampling replication and instrument calibration logs). • Knowledge of local geology/fault structure exists for the entire log depth. • Borehole is drilled as deep as possible to reduce distance of extrapolation. • Temperature-depth logs are continuous. • Knowledge of local geology/fault structure exists for the entire log depth.	1
B	• Probe allowed to equilibrate with the wellbore fluids or is from a series of temperature measurements with the use of Horner plots. • Borehole has not equilibrated with the surrounding formation (i.e., drilled recently). • Temperature log run under flowing conditions. • Cuttings and/or geophysics have *not* confirmed measurement within the reservoir (i.e., downhole alteration mineralogy not consistent with readings), but geophysical data and/or other geological knowledge have identified reservoir formations. • Single survey at the well/location. • Frequent calibrations completed, but prescribed set of procedures are not consistently followed. • Borehole is drilled as a moderately deep hole (e.g., 500 m deep). • Temperature-depth logs are continuous. • Knowledge of local geology/fault structure exists for some of the log depth.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Probe *not* allowed to equilibrate with the wellbore fluids. • Borehole has not equilibrated with the surrounding formation (i.e., drilled recently). • Unknown whether temperature log run was under static or flowing conditions. • Cuttings and/or geophysics have *not* confirmed measurement within the reservoir. • Calibrations are not completed regularly, and no prescribed set of procedures exists. • Linear extrapolation suggests anomalous high temperatures in comparison to nearby locations (i.e., conflicting gradients). • Minimal probes/TGHs placed given complexity of underlying geology—and none outside thermal features. • Boreholes show indications of temperature reversals with depth, suggesting outflow. • Temperature-depth logs are not continuous. • Knowledge of local geology/fault structure does not exist.	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 67. Execution index: field mapping/surveys of surface manifestations, distribution of hydrothermal alteration, and bounding geologic structures

Index	Field Mapping	Weight
A	• Field studies include comprehensive mapping of fine- to large-scale structures, stratigraphy, and location of surface manifestations. • Mapping is completed at a fine level of detail within the exploration area (e.g., major and minor faults). • Mapped characteristics and zones of identified hydrothermal alteration are supported by the use of remote sensing data (such as satellite imagery, air photos, LiDAR, etc.).	1
B	• Field studies include mapping of stratigraphy, fault geometry, and location of surface manifestations. • Mapping is completed at a moderate level of detail within the exploration area (e.g., major faults). • Mapped characteristics and zones of identified hydrothermal alteration are partially supported by the use of remote sensing data (such as satellite imagery, air photos, LiDAR, etc.).	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Field studies include cursory stratigraphic and fault geometry review, adequate location of surface manifestations. • Mapping is completed at a high level of detail within the exploration area (e.g., regional features only). • Mapped characteristics and zones of identified hydrothermal alteration are not supported/verified by the use of remote sensing data (such as satellite imagery, air photos, LiDAR, etc.).	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 68. Execution index: regional geologic, heat flow, topographic, and related maps

Index	Regional Geologic, Heat Flow, Topographic, and Related Maps	Weight
A	• Proximity of mapping resolution to actual calibration points is high enough to constrain the area of interest. • Map(s) encompass entire geothermal area. • Field studies include comprehensive mapping of structures, stratigraphy, and location of surface manifestations. • Mapped characteristics and zones of identified hydrothermal alteration are supported by the use of remote sensing data (such as satellite imagery, air photos, LiDAR, etc.). • Mapping is completed at a fine level of detail within the exploration area.	1
B	• Field studies include mapping of stratigraphy, fault geometry, and location of surface manifestations. • Mapping is completed at a moderate level of detail within the exploration area (e.g., major faults). • Mapped characteristics and zones of identified hydrothermal alteration are partially supported by the use of remote sensing data (such as satellite imagery, air photos, LiDAR, etc.).	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Proximity of mapping resolution to actual calibration points is too low to constrain boundaries in the area of interest. • Mapped characteristics and zones of identified hydrothermal alteration are not supported/verified by the use of remote sensing data (such as satellite imagery, air photos, LiDAR, etc.). • Mapping is completed at a high level of detail within the exploration area (e.g., regional features only). • Field studies include cursory stratigraphic and fault geometry review, adequate location of surface manifestations.	4
E	• Map presents data at a very high level (state or regional).	5

Table 69. Execution index: magnetotelluric (MT)

Index	Magnetotelluric (MT)	Weight
A	• Local resistivity anomalies are known and have been used to manually correct the telluric shift (e.g., through inversion of TEM results). • Minimal incidents of signal noise (such as cultural interference) or survey includes a quiet remote station to remove noise. • Measurements are taken over several hours at each site. • Frequency of the signal is appropriate to the depth being probed (e.g., 0.00001–10 Hz for deep crustal investigations and 10–1000 Hz for upper crust features). • Spacing between stations is adequately close to capture variability in features. • Areal extent of survey shows all field boundaries. • 2-D and 3-D inversions are performed.	1
B	• Local resistivity anomalies are fairly well known and have been used to manually correct the telluric shift. • Some incidents of signal noise (such as cultural interference) or survey includes a quiet remote station that does not fully remove noise signal. • Measurements are taken over several hours at each site. • Frequency of the signal is appropriate to the depth being probed. • Spacing between stations is adequately close to capture variability in features. • Areal extent of survey shows all field boundaries. • 2-D and/or 3-D inversions are performed.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Local resistivity anomalies are not well-known, and corrections to the telluric shift are assumed. • Some significant incidents of signal noise (and/or survey does not include a quiet remote station). • Measurements are taken for the minimum time possible at each site. • Frequency of the signal not fully appropriate to the depth being probed. • Spacing between stations does not adequately capture variability in features in any given area. • Areal extent of survey does not indicate field boundaries. • 2-D inversions are performed.	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 70. Execution index: transient electromagnetic (TEM)

Index	Transient Electromagnetic (TEM)	Weight
A	• Depth of survey is specifically adjusted to the resistivity of the area (e.g., few hundred meters in low resistivity). • Current is applied to the transmitter loop for a sufficient time. • Current is shut off abruptly. • Measurement windows/sampling "gates" are high-resolution to capture detailed changes in signal amplitude. • Conducted in area of minor external noise and interference (or survey includes a quiet remote station to remove noise signal). • Loop size is more than adequate. • Spacing between stations is adequately close to capture variability in features. • Areal extent of survey shows all field boundaries. • 2-D and 3-D inversions are performed.	1
B	• Depth of survey is appropriate to resistivity of area (few hundred meters in low resistivity, up to 1 km in high resistivity). • Current is applied to the transmitter loop for a sufficient time. • Current is shut off abruptly. • Measurement windows/sampling "gates" are adequate to capture relevant changes in signal amplitude. • Conducted in area of minor external noise and interference (or survey includes a quiet remote station that does not fully remove noise signal). • Loop size is appropriate for area. • Spacing between stations is adequately close to capture variability in features in some areas but not all. • Areal extent of survey shows some field boundaries but not all. • 2-D and/or 3-D inversions are performed.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Effective exploration depth is not appropriately adjusted to resistivity of area (e.g., 1 km in low resistivity). • Current is not applied to the transmitter loop for a sufficient time. • Current is not shut off abruptly. • Measurement windows/sampling "gates" are too wide to capture relevant changes in signal amplitude. • Conducted in area of significant external noise and interference (and/or survey does not include a quiet remote station). • Loop size is too small for area. • Spacing between stations does not adequately capture variability in features in any given area. • Areal extent of survey does not indicate field boundaries. • 2-D inversions are performed.	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 71. Execution index: gravity surveys

Index	Gravity Surveys	Weight
A	• The line direction is positioned perpendicularly to the dominant geologic strike. • Intervals are spaced finely enough to individually characterize all anticipated anomalies. • Precise measurements of altitude, rock mass, and local topography used to inform corrections. • Deep wells exist that can be used to constrain gravity model.	1
B	• The line direction is positioned perpendicularly to the dominant geologic strike. • Intervals are spaced finely enough to individually characterize all anticipated anomalies. • Precise measurements of altitude and rock mass are used to inform corrections. Local topographic maps or digital elevation models are used but are of unknown quality/not recently updated.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Use of precise values for altitude, rock mass, and/or topography, thereby estimating free-air, Bouguer, and/or terrain corrections. • Intervals spaced to capture some (but not all) anomalies. • Sampling includes only one measurement per anomaly. • Line direction is not fully perpendicular to dominant geologic strike (or strike is not known, and/or stratigraphy of the region is not well-constrained).	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 72. Execution index: active seismic reflection

Index	Active Seismic Reflection	Weight
A	• Used in areas primarily dominated or overlain by sedimentary formations. • Choice of seismic source allows for signal penetration at or below the estimated reservoir depth. • Geophones are appropriately grounded and secured. • Survey array provides high-resolution coverage (for both depth and areal extent) in areas of desired feature discovery.	1
B	• Choice of seismic source allows for signal penetration to a depth that appears to show the top of the reservoir/clay cap. Geophones are appropriately grounded and secured, although in loose soil in some areas. • Survey array adequately corresponds to desired feature discovery.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Used in areas primarily dominated by highly fractured crystalline rock types (i.e., high uncertainty in interpretation). • Choice of seismic source does not allow for signal penetration to the estimated reservoir top depth. Geophones have not been checked for security or grounding or are within very loose soil. • Survey array is sparse, with little correspondence to desired feature discovery.	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 73. Execution index: geothermometry: cation

Index	Geothermometry: Cation	Weight
A	• Water composition is appropriate for the geothermometer. • Chemistry has been evaluated for mixing and boiling relationships to determine whether the fluid is consistent with that of a deep geothermal fluid. • Interpreted in combination with high-quality data on other physical parameters (pH, dissolved gases). • Multiple cation geothermometer systems (e.g., Na-K, Na-K-Ca-Mg, K-Mg, and/or Li-Mg) used to corroborate results. • Cation and anion balance shows minimal gap in vast majority of samples. • Fluid mixing from multiple well feed points does not exist, or is known and addressed.	1
B	• Appropriate corrections are made to determine end members when fluid is known to have mixed with other water sources (e.g., seawater or nonthermal saline brine). • Appropriate selection of reaction systems (e.g., Na-K-Ca: separate equations for <100°C and >100°C). • Multiple cation geothermometer systems (e.g., Na-K-Ca-Mg, K-Mg, and/or Li-Mg) used to corroborate results. • Fluid mixing from multiple well feed points not known.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3

D	• No (or limited) corrections made, even if:
	  ○ Fluid is known to have mixed with other water sources, or
	  ○ Partial pressures of CO_2 and calcite precipitation are significant
	• Inappropriate application to bicarbonate or acid sulfate waters that are derived from steam heating of near-surface waters and interaction with geothermal gases, and where the fluid cation chemistry does not reflect equilibrium with minerals at reservoir conditions.
	• Cation and anion balance shows significant gap in majority of samples, without a functional explanation.
	• Fluid mixing from multiple well feed points known and not addressed.
		4

E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 74. Execution index: geothermometry: SiO_2 phases

Index	Geothermometry: SiO_2 Phases	Weight

A	• Corrections for the following effects:
	  ○ pH effects on silica solubility when pH > 9.
	  ○ Salinity effects corrected for waters with higher total dissolved solids than seawater.
	  ○ Mixing/dilution effects with other sources (groundwater or surface).
	  ○ Use of maximum steam loss equation if steam loss is expected from sampled feature.
	• Concentrations plotted against enthalpy to confirm appropriate phase selection: amorphous, <180°C, chalcedony or quartz; 200°C–300°C, quartz.
	• Analytical quality of results can be shown to be high (based on standards measured, sample replication, and calibration logs).
	• Samples collected appropriately (either diluted or acidified) to prevent silica precipitation.
		1

B	• All of the data correction best practices listed above. • Not plotted against enthalpy. • Appropriate phase selection: • <180°C, chalcedony or quartz; 200°C–300°C, quartz.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Not enough information available to implement data correction best practices (e.g., erroneous pH, not enough information to identify dissolved silica or proportion of steam separated). • Significant, unexplained differences in sample results. • Not plotted against enthalpy. • Possibly inappropriate phase selection: chalcedony at near or >180°C, or quartz at near or >300°C. • Sample not collected using appropriate methods—may have had silica precipitation, resulting in lower than expected values.	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 75. Execution index: geothermometry: stable isotope

Index	Geothermometry: Stable Isotope	Weight
A	• Multiple isotope systems (hydrogen, carbon, oxygen, and/or sulfur) provide narrowly constrained temperature based on calculated equilibrium values. • Analytical quality of results can be shown to be high (based on standards measured, sample replication, and calibration logs). • Steam and water discharge samples are both collected without air contamination.	1
B	• Some, but not all, of multiple isotope systems (hydrogen, carbon, oxygen, and/or sulfur) provide similar temperatures. • Corrections can be made for mixing/dilution effects with other water sources (groundwater or surface)—particularly relevant for oxidation of H_2S and sulfur-oxidizing bacteria.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Multiple isotope systems (hydrogen, carbon, oxygen, and/or sulfur) do not yield consistent temperature estimates. • Mixing/dilution effects with other water sources are not well-understood or corrected for. • Steam and water discharge are not separated completely or have evidence of air contamination.	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 76. Execution index: geothermometry: multicomponent

Index	Geothermometry: Multicomponent	Weight
A	• Complete liquid and gas analyses, particularly for Al and Fe. • Selection of suite of minerals that have equilibrated with the geothermal fluids based on complimentary analyses on geologic setting and/or reservoir petrology. • Optimization captures key processes that may have affected fluid compositions (e.g., boiling, degassing, mixing). • Uses appropriate thermodynamic database. • Interpreted in combination with high-quality data on other physical parameters (pH, dissolved gases). • Multiple geothermometer systems used to corroborate results. • Cation and anion balance shows minimal gap in vast majority of samples.	1
B	• Complete liquid analyses, but no gas measurements. • Assignment of appropriate mineral phases to control Al and Fe solubility. • Assumption of suite of minerals that have equilibrated with the geothermal fluids based on similar geologic settings and/or reservoir petrology. • Appropriate corrections are made to determine end members when fluid is known to have mixed with other water sources. • Optimization captures some but not all processes that may have affected fluid compositions (e.g., boiling, degassing, mixing). • Any CO_2 loss can be constrained accurately. • Uses appropriate thermodynamic database. • Cation and anion balance shows minimal gap in vast majority of samples.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3

D	• Cation and anion balance shows significant gap in majority of samples, without a functional explanation.
	• Application of a standard suite of minerals without any recognition of the appropriate geologic setting (e.g., use of alteration suite for volcanic-hosted system when reservoir rocks consist of altered sedimentary rocks).
	• No (or limited) optimization made, even if:
	  ○ Fluid is known to have mixed with other water sources, or
	  ○ Partial pressures of CO_2 and calcite precipitation are significant
	  ○ Uses a default thermodynamic database.
		4

E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 77. Execution index: geothermometry: gas

<table>
<tr><th>Index</th><th>Geothermometry: Gas</th><th>Weight</th></tr>
<tr><td>A</td><td>High-quality samples (well gas separates, fumaroles).
Appropriate sampling methods to minimize air contamination.
Sampling minimizes interaction with shallow fluids.
Samples from high flow, high T (superheated) vents.
Complete analysis of the following gasses:
H_2S and SO_2
CO
CO_2
CH_4
N_2
Ar
O_2
NH_3
H_2
Gas grid geothermometer.
R_h values affect results—presumed value of -2.8 based on FeO—Fe_2O_3 may not be appropriate.</td><td>1</td></tr>
<tr><td>B</td><td>Sampling completed only from fumaroles and springs (not wells).
Appropriate sampling to minimize air contamination.
Sampling minimizes interaction with shallow fluids.
Samples from high T (superheated) vents with low flow.
Complete analyses of some, but not all, of the following:
H_2S
SO_2
CO
CO_2
CH_4
N_2
Ar
O_2
NH_3
H_2.
Assumption of R_h value of -2.8 without confirmation that this is appropriate.</td><td>2</td></tr>
<tr><td>C</td><td>Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.</td><td>3</td></tr>
<tr><td>D</td><td>Sampling completed from bubbling springs.
Air contamination in some samples.
Samples indicate some interaction with shallow fluids (depletion of gas sulfur species due to formation of dissolved sulfate).
Samples' features have diffuse flow and have temperatures at or below boiling.</td><td>4</td></tr>
<tr><td>E</td><td>Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.</td><td>5</td></tr>
</table>

Table 78. Execution index: mineral assemblages

Index	Mineral Assemblages	Weight
A	• Mineralogy of multiple core samples/cuttings displays similar hydrothermal mineral suite, and alteration appears to be latest stage.	1
B	• Mineralogy of core samples/cuttings shows similar mineral suites with at least one episode of significant hydrothermal alteration.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Mineralogy of core samples/cuttings shows dissimilar mineral suites (i.e., significantly different temperature ranges) with multiple episodes of hydrothermal alteration. • Alteration mineralogy not consistent with fluid chemistry from well (may reflect relict hydrothermal activity).	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 79. Execution index: fluid inclusions

Index	Fluid Inclusions	Weight
A	• Mineralogy of multiple core samples/thin sections displays similar hydrothermal mineral suite, and alteration appears to be latest stage. • Heating/freezing table is appropriately and regularly calibrated for geothermal fluid ranges (daily or weekly, depending on frequency of use). • Temperature increases/decreases are performed gradually (i.e., 0.1°C–0.2°C/min) for high resolution. • Multiple large inclusions allow analysis. • Results create reproducible conclusion, not multiple populations.	1
B	• Mineralogy of core samples/thin sections shows similar mineral suites with at least one episode of significant hydrothermal alteration. • Heating/freezing table is appropriately calibrated for geothermal fluid ranges, but not recently (e.g., not within the past 6 months). • Temperature increases/decreases are performed gradually (i.e., 0.1°C–0.2°C/min) only when nearing target temperature ranges and are otherwise 0.5°C/min. • Most inclusions (>50%) are too small for measurement, but some (>25%) can be analyzed. • Results create reproducible conclusion—with few outliers.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Mineralogy of core samples/thin sections shows dissimilar mineral suites (i.e., significantly different temperature ranges) with multiple episodes of hydrothermal alteration (and multiple fluid inclusion populations). • Alteration mineralogy not consistent with fluid chemistry from well (may reflect relict hydrothermal activity). • Heating/freezing table is not calibrated for geothermal fluid ranges. • Most inclusions (>75%) are too small for measurement or have leaked their gas phase. • Results suggest multiple populations or are inconclusive.	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 80. Execution index: analogous well in field

Index	Analogous Well in Field	Weight

A	• The following parameters must be within 10% deviation between wells:
	  ○ Bottom-hole depth
	  ○ Bottom-hole temperature.
	• The following must be identical between wells:
	  ○ Structural geological setting
	  ○ Geological formation/lithology.
		1

B	• The following parameters must be within 20% deviation between wells:
	  ○ Bottom-hole depth
	  ○ Bottom-hole temperature.
	• The following must be identical between wells:
	  ○ Geological formation/lithology.
		2

C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3

D	• The following parameters must be within 30% deviation between wells:
	  ○ Bottom-hole depth
	  ○ Bottom-hole temperature.
		4

E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 81. Execution index: tracer test

Index	Tracer Test	Weight
A	• Tracer is appropriate for the reservoir temperature and type (liquid- or steam-dominated). • Measured at regular, frequent intervals, including measurement of initial arrival of tracer and time of peak concentration. • Liquid- and vapor-phase tracers are injected with precisely metered rates. • Tracer is conservative and not thermally sensitive. • Tracer is injected as aliquots over time. • Small, known quantity of fluid is injected after the tracer.	1
B	• Tracer is appropriate for the reservoir temperature or type (liquid- or steam-dominated). • Measured at regular intervals, including measurement of initial arrival of tracer and time of peak concentration. • Liquid- and vapor-phase tracers are injected with precisely metered rates. • Tracer is conservative but exhibits some thermal sensitivity. • Tracer is injected as either aliquots over time or as a single slug. • Moderately large, but known, quantity of fluid is injected after the tracer.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Tracer is not appropriate for either the reservoir temperature or type (liquid- or steam-dominated). • Measured at irregular and infrequent intervals. Initial arrival of tracer or measurement of peak concentration time is not recorded. • Liquid- and vapor-phase tracers are injected with some error (metered rates are not consistent). • Tracer is neither conservative nor thermally sensitive. • Tracer is injected as a single slug. • Moderately large unmeasured quantity of fluid is injected after the tracer.	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 82. Execution index: formation microimaging logs

Index	Formation Microimaging Logs	Weight
A	• Combined with other geophysical wireline measurements (e.g., azimuthal resistivity imager or induction imager). • Available for significant thickness/depth of reservoir (i.e., able to identify heterogeneity). • Evaluated for fractures, faults, stress direction, and lithology. • Corresponds to other lithology cores and subsurface geology. • Imaging run with sufficient injection flow to regulate instrument temperature.	1
B	• Combined with minimal geophysical wireline measurements (e.g., temperature, pressure). • Available for significant proportion of reservoir. • Evaluated for fractures, faults, stress direction, and lithology. • Minimally corresponds to other lithology cores and subsurface geology (e.g., cannot fully trace faults). • Imaging run with intermittent injection flow to regulate instrument temperature.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Combined with no other geophysical wireline measurements (e.g., temperature, pressure). • Available for small, limited interval of reservoir. • Evaluated for some, but not all, of the following: stress direction, fractures, faults, and lithology. • Does not correspond to other lithology cores and subsurface geology (e.g., cannot fully trace faults). • Imaging run without injection flow to cool the tool.	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 83. Execution index: lithologic cores

Index	Lithologic Cores	Weight
A	• Core oriented with an image log. • Follows consistent labeling, record keeping, and description methods. • Hydrothermal alteration minerals examined in thin section. • Frequency of faulting and fracture orientation measured. • Stratigraphic sequences well captured when core is recovered.	1
B	• Core oriented by visual inspection. • Follows consistent labeling, record keeping, and description methods. • Hydrothermal alteration minerals examined in thin section. • Frequency of faulting and fracture orientation measured. • Stratigraphic sequences mostly captured in the recovered core.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Core received from previous studies and/or core is not oriented. • Evidence of inconsistent labeling, record keeping, and description methods. • Spot examinations of hydrothermal alteration minerals in thin section. • Frequency of faulting and fracture direction noted. • No cohesive map correlating stratigraphic sequences from regional cores. • Poor core recovery (i.e., core not cohesive or in pieces).	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 84. Execution index: acoustic reflectivity

Index	Acoustic Reflectivity	Weight
A	• Acoustic caliper, transit times, and amplitude of televiewer logs are collected at high quality to identify fine fracture permeability. • Location, strike and dip of fractures, and lithologic contacts can be identified in all logs. • Entire signal is digitized as waveform. • Cycle skipping can be constrained to identify fractures (i.e., not due to improper signal, detection level, or gas in the fluid). • Spacing (1-ft receiver) allows identification of lithologic contacts as sharp deflections.	1
B	• Acoustic caliper, transit times, and amplitude of televiewer logs are collected at sufficiently high quality to identify fracture-driven permeability. • Location, strike and dip of fractures, and lithologic contacts can be identified in vast majority of logs. • Entire signal is digitized as waveform. • Cycle skipping can mostly be constrained to identify fractures (i.e., minor issues due to improper signal, detection level, or gas). • Spacing (1-ft receiver) allows identification of lithologic contacts as sharp deflections.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Acoustic caliper, transit times, and amplitude of televiewer logs are collected at moderate quality, enough to identify fracture-driven permeability. • Location, strike and dip of fractures, and lithologic contacts can be identified in most logs. • Entire signal is digitized as waveform. • Cycle skipping prevents fracture identification (i.e., identifiable issues due to improper signal, detection level, or gas in the fluid). • Spacing does not allow identification of lithologic contacts as sharp deflections.	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 85. Execution index: downhole gas pressure monitor

Index	Downhole Gas Pressure Monitor	Weight
A	• Probe allowed to equilibrate. • Cuttings and/or geophysics confirm measurement within the reservoir (i.e., downhole alteration mineralogy consistent with reading). • Repeated surveys at the same well/location. • Frequent calibrations completed that follow a prescribed set of procedures.	1
B	• Probe allowed to equilibrate. • Cuttings and/or geophysics have not confirmed measurement within the reservoir (i.e., downhole alteration mineralogy not consistent with readings). • Single survey at the well/location. • Frequent calibrations completed, but prescribed set of procedures are not consistently followed.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Probe not allowed to equilibrate. • Cuttings and/or geophysics have not confirmed measurement within the reservoir. • Calibrations are not completed regularly, and no prescribed set of procedures exists.	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 86. Execution index: field sampling (NCGs)

Index	Field Sampling (NCGs)	Weight
A	• Gas and water phases measured; different phases were sampled with a miniseparator. • Temperature, conductivity, and pH probes used within recommended operating temperatures. • All probes calibrated in lab daily prior to field work. • All probes operating well within detection limits.	1
B	• Miniseparator has some leakage in capturing gas/liquid phase fractions; gas/steam ratios are not well-constrained. • All probes calibrated at least once per week during field work. • All probes operating within detection limits for majority of sample locations.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Only brine sample collected, or gas/steam ratio unknown. • Temperature, conductivity, and pH probes used at top end of recommended operating temperatures. • No known or regularly scheduled calibration schedule. • Probe detection limits are not sensitive to majority of sample chemistries.	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 87. Execution index: laboratory analysis (NCGs)

Index	Laboratory Analysis (NCGs)	Weight
A	• Strict sampling protocols for cleaning, preparing, and evacuating bottles. • All instruments calibrated daily. • Calibration standards span the variation of the measured samples.	1
B	• Sampling protocols for rinsing and sealing bottles, implemented with some variation between researchers. • All instruments calibrated at least once per week. • All instruments operating within the analytical limits for majority of samples.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• No set sampling protocols for rinsing and sealing bottles specific to methods. • No known or regularly scheduled calibration schedule. • Analytical measurement limits are not appropriate for the majority of sample chemistries. • Calibration standards do not span the variation of the measured samples.	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 88. Execution index: ion chromatograph

Index	Ion Chromatograph	Weight
A	• Reagent stored in polyurethane bottles. • Dilution within calibration range for all runs. • Calibration done on regular schedule. • Standards measured at or near face value.	1
B	• Reagent stored in polyurethane bottles. • Dilution within calibration range for most runs. • Calibration done on regular, but not frequent, schedule. • Standards measured at or near face value.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Reagent stored in glass bottles. • Calibration done on regular, but not frequent, schedule. • Not diluted to within calibration range. • Standards significantly deviate from face value.	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 89. Execution index: colorimeter—molybdosilicate method

Index	Colorimeter—Molybdosilicate Method	Weight
A	• Reagent stored in polyurethane bottles. • Dilution within calibration range for all runs. • Calibration done on regular schedule. • Standards measured at or near face value.	1
B	• Reagent stored in polyurethane bottles. • Dilution within calibration range for most runs. • Calibration done on regular, but not frequent, schedule. • Standards measured at or near face value.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Reagent stored in glass bottles. • Calibration done on regular, but not frequent, schedule. • Not diluted to within calibration range. • Standards significantly deviate from face value.	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 90. Execution index: colorimeter-heteropoly blue method

Index	Colorimeter—Heteropoly Blue Method	Weight
A	• Reagent nearly new. • Dilution within calibration range for all runs. • Calibration done on regular schedule. • Standards measured at or near face value.	1
B	• Reagent near two-month shelf life. • Dilution within calibration range for most runs. • Calibration done on regular, but not frequent, schedule. • Standards measured at or near face value.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Reagent older than the two-month shelf life. • Calibration done on regular, but not frequent, schedule. • Not diluted to within calibration range. • Standards significantly deviate from face value.	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 91. Execution index: pocket colorimeter

Index	Pocket Colorimeter	Weight
A	• Reagent nearly new. • Matching of sample to color key occurred consistently after wait time prescribed by manufacturer.	1
B	• Reagent near two-month shelf life. • Matching of sample to color key did not occur consistently after wait time prescribed by manufacturer.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Reagent older than the two-month shelf life. • Matching of sample to color key occurred immediately.	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 92. Execution index: third-party data

Index	Third-Party Data	Weight
A	• Third party presents methodology, errors, and repeatability of presented results. • Third-party methodology is consistent with that described in the applicable execution index for the measurement performed.	1
C	• Methodology described by third party is inconsistent with that presented in the applicable execution index for the measurement performed.	3
E	• No information provided for test methodology, error, or repeatability.	5

Table 93. Execution index: fault dilation analysis

Index	Fault Dilation Analysis	Weight
A	• Fault dilation model accounts for major and minor stress directions. • Principal stress magnitude and orientations taken from on-site measurements via geological, geophysical, and deformation analysis. • Results between methods of stress analysis consistent.	1
B	• Fault dilation model accounts for major and minor stress directions. • Principal stress magnitude and orientations taken from on-site measurements via geological, geophysical, and deformation analysis. • Results between methods of stress analysis exhibit statistically significant variance.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Principal stress magnitude and orientation taken from high level (regional or national) stress map.	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 94. Execution index: reservoir modeling

Index	Reservoir Modeling	Weight
A	• Site-specific model parameters are based on field measurements. • Model accounts for phase changes, reservoir heterogeneity, chemical species present, and noncondensable gasses within the geothermal system. • Model calibrated with geological and geophysical measurements taken from on-site measurements.	1
B	• Site-specific model parameters are based on field measurements. • Model accounts for phase changes, reservoir heterogeneity, chemical species present, and noncondensable gasses within the geothermal system. • Model calibrated with geological and geophysical measurements taken from analogous geothermal systems.	2
C	• Results taken from previous third-party studies of the area (either literature or contractors) with little or limited information on survey methods, replication, or error.	3
D	• Model parameters based on literature averages or estimated values. • Model does not account for phase changes, reservoir heterogeneity, chemical species present, or noncondensable gasses within the geothermal system. • Model calibrated with geological and geophysical measurements taken from analogous geothermal systems.	4
E	• Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.	5

Table 95. Execution index: assumed from analogous system

<table>
<tr><th>Index</th><th>Assumed from Analogous System</th><th>Weight</th></tr>
<tr><td>A</td><td>The following attributes must be within 10% difference between analogous and considered system (unless an attribute is the one being estimated):
Reservoir volume
Reservoir temperature.
The following attributes must be identical between analogous and considered system (unless an attribute is the one being estimated):
Tectonic setting (fault-based, arc, rift, etc.)
Dominant lithological units (sediment-dominated, igneous-dominated, etc.)
Same geothermal play type.</td><td>1</td></tr>
<tr><td>B</td><td>The following attributes must be within 15% difference between analogous and considered system (unless an attribute is the one being estimated):
Reservoir volume
Reservoir temperature.
The following attributes must be identical between analogous and considered system (unless an attribute is the one being estimated):
Tectonic setting (fault-based, arc, rift, etc.)
Dominant lithological units (sediment-dominated, igneous-dominated, etc.)
Same geothermal play type.</td><td>2</td></tr>
<tr><td>C</td><td>The following attributes must be within 20% difference between analogous and considered system (unless an attribute is the one being estimated):
Reservoir volume
Reservoir temperature.
The following attributes must be identical between analogous and considered system (unless an attribute is the one being estimated):
Tectonic setting (fault-based, arc, rift, etc.)
Dominant lithological units (sediment-dominated, igneous-dominated, etc.)
Same geothermal play type.</td><td>3</td></tr>
<tr><td>D</td><td>The following attributes must be identical between analogous and considered system (unless an attribute is the one being estimated):
Tectonic setting (fault-based, arc, rift, etc.)
Dominant lithological units (sediment-dominated, igneous-dominated, etc.)
Same geothermal play type.</td><td>4</td></tr>
<tr><td>E</td><td>Attributes not known sufficiently enough to compare to those of an analogous system.</td><td>5</td></tr>
</table>

Table 96. Execution index: test well drilled into reservoir

Index	Test Well Drilled into Reservoir	Weight
A	Test well depth and diameter identical to that of proposed production well.	1
B	Test well depth and diameter within 90% of proposed production well depth. Remainder of well depth and diameter extrapolated from other site survey data or published research.	2
C	Test well depth and diameter greater than 75% of proposed production well depth. Remainder of well depth and diameter extrapolated from other site survey techniques.	3
D	Test well depth and diameter less than 75% of proposed production well depth.	4
E	Test well depth and diameter less than 50% of proposed production well depth.	5

Table 97. Execution index: slimhole drilled into reservoir

Index	Slimhole Drilled into Reservoir	Weight
A	Slimhole depth and diameter identical to that of proposed production well.	1
B	Slimhole depth and diameter within 90% of proposed production well depth. Remainder of well depth and diameter extrapolated from other site survey data or published research.	2
C	Slimhole depth and diameter greater than 75% of proposed production well depth. Remainder of well depth and diameter extrapolated from other site survey techniques.	3
D	Slimhole depth and diameter less than 75% of proposed production well depth.	4
E	Slimhole depth and diameter less than 50% of proposed production well depth.	5

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CONSIDERED, BUT EXCLUDED, SUB-ATTRIBUTES

System Permeability: Several technical experts expressed the inherent difficulty in measuring the absolute permeability of a system, typically quantified by millidarcys. They stated that more often, especially in the oil and gas industry, a permeability-thickness product (*kh*) value is measured and reported.

Size of Heat Source and Power Density: Many of the experts expressed concerns with the “size of heat source and power density” sub-attribute, stating that the calculation has various uncertainties involved in it. These uncertainties ranged from the calculation of the area/extent of the reservoir (area of the reservoir is often very uncertain for geothermal projects) to the interpretation of results by different people.

Silica Content: Some experts stated that the silica content, which can pose difficulties with chemical scaling, belongs in a category relevant to temperature effects. One expert identified that the Geological Assessment Tool’s temperature sub-attribute specifically mentions silica content as a concern when measuring with geothermometers. Thus, this sub-attribute does not fit within the reservoir management attribute.

APPENDIX B: LOGISTICS

CONSIDERED, BUT EXCLUDED, SUB-ATTRIBUTES

Proximity to Equipment and Site Road Access: These sub-attributes were essentially repurposed and relabeled as the current degree of isolation sub-attribute. Both iterations of the logistics attribute attempted to address the distance and ease of access of any necessary equipment for the project site. If equipment is further from the site and more difficult to access due to road conditions or availability, then project development as a whole suffers.

Geological Hazards: This sub-attribute was initially too broad to cover the various hazards associated with the local geology and geography of the project site. To address this, four new hazard-related sub-attributes were added to the logistics category: volcanic hazards, landslide hazards, earthquake hazards, and wildfire hazards. These new sub-attributes also allow the user to better quantify the logistical difficulty by providing specific sources from various government and scientific agencies to grade the project logistics.

Climate: This sub-attribute was simply renamed to better define the intended logistical concern: severe weather events.

APPENDIX C: POWER CONVERSION

CONSIDERED, BUT EXCLUDED, SUB-ATTRIBUTES

Climate: In very early iterations of the power conversion attribute, the climate sub-attribute was used instead of the current "temperature difference: inlet to condenser" sub-attribute. However, both were included in the power conversion category due to their importance in the overall efficiency rating of a power plant. The greater the temperature difference between the subsurface geofluid and the ambient air, the greater the plant efficiency becomes. Thus, the climate sub-attribute attempted to characterize the project site region on a greater scale but has since been replaced with a more quantifiable temperature difference measurement.

APPENDIX D: DRILLING

CONSIDERED, BUT EXCLUDED, SUB-ATTRIBUTES

Drilling Angle: This sub-attribute was repurposed as the currently included well direction sub-attribute. The previous iteration focused on the difficulty in keeping the drill bit on track with the predetermined drilling plan. However, various subject matter experts expressed that the overall direction of the well (e.g., vertical, direction/deviated, or horizontal) was a better indicator of the difficulty of drilling conditions. Relatively speaking, the effort to keep the drill bit on track was small compared to the effort and cost required in maintaining a directionally drilled well.

Rock Properties, Number of Casing Strings, and Heterogeneity of Rock Types Encountered: These three previously considered sub-attributes were replaced by the "anticipated rig downtime" sub-attribute. In an attempt to reduce the number of drilling sub-attributes, these three were effectively combined, and the metric for including their effects on drilling conditions was changed to the sum of rig downtime caused by their individual effects. For example, "rock properties and heterogeneity of rock types encountered" can be quantified by rig downtime for bit changes and time to trip in and out of the hole. Furthermore, more downtime to prepare and cement new strings must be accounted for if additional casing strings are necessary.

Water for Drilling: This sub-attribute was determined to be site- and project-specific, and therefore too complex and nuanced to quantify appropriately. Some project sites may have access to plenty of water for drilling, others may not. Nonetheless, some experts stressed that it is typically not a problem and not cost-prohibitive to find alternative modes of transporting water to the site (e.g., trucking it in). Therefore, the availability of water may fall more into the logistics category than the technical category.

H_2S Discharge at Wellhead: While the discharge of H_2S gas can prove to be dangerous and potentially fatal, the drilling experts contacted for this report stated that mitigating such an issue would not cause undue difficulty in the overall drilling conditions.