

Technical Feasibility Aspects of the Geothermal Resource Reporting Methodology (GRRM)

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Keywords: Resource reporting, drilling, logistics, power conversion, reservoir management, GRRM

ABSTRACT

This paper reviews the technical assessment of the Geothermal Research Reporting Methodology (GRRM, <http://en.openei.org/wiki/GRRM>) being developed for reporting geothermal resources and project progress. The goal of the methodology is to provide the U.S. Department of Energy's Geothermal Technologies Office (GTO) with a consistent and comprehensible means of evaluating the impacts of its funding programs. The GRRM is designed to provide uniform assessment criteria for geothermal resource grades and developmental phases of geothermal resource exploration and development. This resource grade system provides information on twelve attributes of geothermal resource locations (e.g., temperature, permeability, land access) to indicate potential for geothermal development. The GTO plans to use these Protocols to help quantitatively **identify** the greatest barriers to geothermal development, **develop** measurable program goals that will have the greatest impact to geothermal deployment, objectively **evaluate** proposals based (in part) on a project's ability to contribute to program goals, **monitor** project progress, and **report** on GTO portfolio performance. The GRRM assesses three areas of geothermal potential: geological, socio-economic, and technical. Previous work and publications have discussed the work done on the geological aspects of this methodology (Young et al. 2015c); this paper details the development of the technical assessment of the GRRM. Technical development attributes considered include: reservoir management, drilling, logistics, and power conversion.

1. INTRODUCTION

The U.S. Department of Energy's (DOE) Geothermal Technologies Office (GTO) uses various metrics to track and measure impacts of its funding meant to catalyze innovation and private investment. As an example, one GTO goal is to "accelerate development of 30 GWe of undiscovered hydrothermal resources" (based on the U.S. Geological Survey [USGS] geothermal assessment of Williams et al. 2008b). For goals to be useful, however, it is important to be able to develop and measure baseline values, as well as incremental improvements, both at the individual project and aggregated portfolio levels. This need is the driving force behind the development of the Geothermal Resource Reporting Methodology (GRRM).

Although the Geothermal Energy Association (GEA) has developed Geothermal Reporting Terms and Definitions (GEA 2010) for reporting on **project** development, the U.S. geothermal industry has not adopted a systematic protocol for **resource** reporting. Several countries, including Australia and Canada, have adopted geothermal resource reporting standards, and other natural resource industries (such as mining, oil, and gas) have worldwide standards and terminologies that are used to guide resource assessments. The United Nations Economic Council for Europe has recently partnered with the International Geothermal Association (UNECE and IGA 2014) to develop a Geothermal Specifications document for the United Nations Framework Classification system (UNECE 2013). All of these guides have provided valuable background information, insight, and influence in the development of the GRRM.

The GRRM provides a process for objectively appraising project progress and resource grade in individual geothermal areas. This methodology aims to create:

- A method for assessing individual projects;
- A set of assessment tools (the GRRM Protocol, Young et al. 2015a, Young et al. 2015b, Young et al. 2016) applicable to all stages of geothermal development;
- A protocol for evidence-based, objective assessment of a project's progress and grade; and
- A tool for GTO to use in baseline assessments, goal setting, application evaluation, project close-out summaries, and portfolio reporting.

This GRRM is **not** intended to be:

- A standard or a pass/fail mark—it only provides the means to identify characteristics of geothermal resources and associated projects;
- A reporting requirement for anything beyond the needs of GTO;
- A process or plan for geothermal exploration or development at any location;
- A replacement for geothermal expertise in assessing project potential; or
- A set of new national or local regulatory reporting requirements.

The GRRM has been in development over the past three years with workshops held several times each year to solicit input and feedback from industry experts. Continuous refinement has occurred along the way and will continue throughout the development period. The details of using the GRRM for reporting are outlined in the GRRM Protocol, which will consist of six documents, including:

- **Background Document** (*original release: July 2015*)
- **Geological** Assessment Tool (*original release: July 2015*)
- **Technical** Assessment Tool (*planned for release: Summer 2016*)
- **Socio-Economic** Assessment Tool (*planned for release: Summer 2016*)
- **Resource Size** Assessment Tool (*planned for development: 2017*)
- **Case Studies:** Application of the GRRM Protocol (*planned for development: 2017*)

The GTO is currently testing the use of these Protocols on its previous and current portfolio of research, development, and demonstration (RD&D) projects (Garchar et al. 2016). In addition to expert workshops, this testing will provide input for refining the Protocol to overcome any issues identified during implementation. We welcome any feedback and suggestions from all stakeholders.

2. PRINCIPLES OF THE METHODOLOGY

The GRRM 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 exploration and development efforts over the lifetime of the project ("Project Progress").

By assessing the major characteristics of a geothermal resource, categorizing the techniques used, and evaluating how well the research techniques were implemented, users can report a **resource grade** covering multiple geological, technological, and socio-economic 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.

By assessing the development activities of the project, users can report on incremental **project progress**. Like the resource grade, project progress will continually be updated throughout the project lifetime.

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

- **Geological** Assessment Tool (representative colors: reds, oranges, browns)
- **Technical** Assessment Tool (representative colors: blues, purples)
- **Socio-Economic** Assessment Tool (representative colors: greens, yellows).

Additionally, users will need to estimate the project size (often reported in MW_e or MW_t). To provide consistency in calculating resource potential for comparisons, the Protocol also includes a separate **Resource Size Assessment Tool**.

These tools are written for industry professionals assigned to report resource grade and project progress to GTO. The Protocol is meant to aid and provide consistency in the reporting process and does not replace expertise in geothermal exploration, in project development, or in preparing and selecting data to report.

3. RESOURCE GRADE

Traditionally, a description of the grade of a natural resource includes a combination of multiple factors. For example, the grade of a mined ore is described as the ore's mineral concentration that can be technically recovered, and the grade of oil is described in terms of a combination of heavy to light and sweet to sour. We apply these concepts of grade to geothermal resources by identifying "attributes" specific to each of the three assessment categories (geological, technical, and socio-economic).

3.1 Resource Grade Attributes

The attributes used by the Protocol to describe a geothermal resource include the constraints on the quality of the geothermal resource, as well as the technical and socio-economic characteristics that determine whether the heat in the system can be produced.

Each attribute is ranked on a scale of "A" through "E," with "A" being the highest. 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. For example:

- Some developers may be interested in average temperature resources (Temperature Grade = C) and poor fluid chemistry (Fluid Chemistry Grade = D-E) to take advantage of secondary mineral recovery potential from the geothermal brine.
- Near-field resources (resources located near operating plants) may have high temperatures (Temperature Grade = A) but low permeability (Permeability Grade = C) and may be candidates for the application of Enhanced Geothermal System (EGS) techniques.

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- For some business models, a very high-temperature resource does not necessarily need to have a large volume to be economical; in fact, a small- or average-size, high-temperature resource could be a viable target.

As these examples indicate, each developer must evaluate which grades are appropriate for his/her target business model. Resources with all attributes of grade A rarely exist.

Previous papers and presentations have focused on the development and content of the Geological Assessment Tool (e.g., Young et al. 2015b, Young et al. 2015c, Young et al. 2015d). This paper focuses on presenting the background and draft content of the Technical Assessment Tool. Working meetings with industry are planned for the 2016 Stanford Geothermal Workshop to collect reviews and comments for improvement to this content. The details provided below present preliminary content and should not be considered final.

4. TECHNICAL ATTRIBUTE GRADES

Attributes important to the feasibility of extracting the geothermal resource, such as depth to the reservoir, could be overcome by technology advancements and are thus used to describe the **Technical Grade**. Even though these attributes are related to a system's geologic features, the influence of these items in developing geothermal resources may vary as technology improves. Technical feasibility can be described by the challenges of producing the resource. By nature of technical advancement, the same geologic conditions can become technically feasible through incremental and/or radical innovations. The technical grade is a combination of four attributes describing the fundamental areas of technical challenges to resource development:

- **Logistics:** Consideration of physical barriers to reach a resource (e.g., weather, topography, elevation/slope, volcanic hazards), requiring advanced or specific tools or materials that potentially increase project costs.
- **Reservoir Management:** Consideration of physical parameters that allow for sustainable management of reservoir production.
- **Power Conversion:** Specific generation technologies, such as for low temperature systems or EGS, as well as component technologies, such as air cooling, are all influential in determining whether the geothermal heat extracted can be efficiently and economically put to use for power generation.
- **Drilling:** The reservoir depth and rock properties strongly determine drilling and project development costs.

4.1 Attribute Indices

The GRRM Protocol expands upon the concept of grade by considering not only the attributes listed above, but also how the attribute is measured and what is known about the quality of the data collected. We break each attribute into three separate indices describing distinct features of each attribute:

- **Character Grade:** Describes the character itself—i.e., what is the intrinsic measurement that best describes the geothermal reservoir?
- **Activity Index:** Qualitatively ranks activities used to assign the character index appropriate for each attribute—i.e., how well is the level of this attribute grade known?
- **Execution Index:** Compares the diligence with which the technique was executed for a given activity—i.e., how much do we know about the quality of execution of that technique?

Just as each attribute is assessed independently from other attributes for the purpose of the Protocol, these indices are also independently evaluated for each attribute. The GRRM Protocol Background Document (Young et al. 2015a) gives an overview of the concepts of Character, Technique and Execution Indices. For more detail on these indices, please see the Technical Assessment Tool document of the GRRM Protocol (Young et al. 2016).

4.1.1 Character Grade

For each attribute, the **Character Grade** uses quantitative and qualitative measurements describing the current project within the range of possible outcomes encountered in geothermal resources and projects. For example, a resource with a high temperature measurement is given a temperature character grade of "A," while a resource with a low temperature would be assigned a temperature character grade of "E." Table 1 lists the proposed character grades for selected attributes associated with the Technical Attributes. Similar tables associated with the Geological and Socio-Economic Grades are being developed and reviewed at the time of this publication (February 2016).

Table 1: Character Grades of Technical Attributes

	Drilling	Logistics	Reservoir Management	Power Conversion
<u>A</u>	Easy drilling conditions	No logistical barriers present	Easy reservoir management conditions	Very efficient plants
<u>B</u>	Manageable drilling conditions	Manageable logistical barriers	Manageable reservoir management conditions	Above average efficient plants
<u>C</u>	Acceptable drilling conditions	Logistical barriers present	Acceptable reservoir management conditions	Average efficiency plants
<u>D</u>	Difficult drilling conditions	Difficult logistical barriers	Difficult reservoir management conditions	Below average efficiency
<u>E</u>	Very Difficult drilling conditions	Extreme logistical barriers	Very Difficult reservoir management conditions	Low efficiency plants

Each of these attributes has been broken into measurable sub-attributes for reporting the technical grade of resources. For example, in the current draft, the Drilling attribute has several sub-attributes, including: well depth, drilling angle, rock properties, drilling experience, number of casing strings, drilling water requirements, well completion diameter, range of lithologies encountered, and drilling restrictions. Each of the four attributes shown in Table 1 is described in more detail in the appendix.

4.1.2 Activity Index

The **Activity Index** describes the common activities used to understand the character attributes—both directly (measured values) and indirectly (by proxy). For example, activities (exploration methods) to evaluate temperature include remote sensing, surface hydrothermal manifestation surveys, geothermometry, and downhole temperature measurements. The GRRM Protocol lists the activities and their associated index values, ranked by the likelihood that the activities represent the actual value of the attribute being described.

We expect that exploration programs will use more than one technique for estimating an attribute's character grade and therefore the criteria developed accommodate such combinations. Table 2 provides an example of activity indices for the Drilling sub-attribute, Rock Properties. Details of the activity indices for all attributes and sub-attributes are provided within the related Assessment Tools of the GRRM Protocol (Young et al. 2015b, Young et al. 2016); for example, the Technical Assessment Tool describes the activity indices for the all of the sub-attributes of the drilling, logistics, reservoir management and power conversion attributes.

Table 2: Activity Indices of the Drilling Sub-attribute: Rock Properties

Index	Activity Description
a	Test well or slim hole: well(s) drilled into reservoir
b	Geophysics: MT, TEM, gravity, seismic
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.
d	Rock properties extrapolated from: Field mapping/surveys of surface outcrops
e	Regional geologic formation and analog studies of similar, well-studied systems

4.1.3 Execution Index

The **Execution Index** describes how well an activity was implemented. Potential errors and uncertainties in data collection may be associated with certain information sources. For each technique used to measure an attribute, the execution indices reflect an understanding of how much is known about the data and provide a baseline understanding of how the data were verified in relation to the best practices associated with a given technique.

For example, results of sulfate-water oxygen isotope geothermometry could show little variation, resulting in temperatures with few outliers and suggesting high confidence in the results. However, these could be impacted by shifts in the oxygen isotope compositions of the water and/or the sulfate caused by processes such as boiling, dilution, and bacterial activity (e.g., McKenzie and Truesdell 1977), which would render these results less reliable. In this case, a moderate value of the execution index could be assigned to represent this mixed confidence in the geothermometry conclusions. Table 3 provides an example of execution indices for one activity, magnetotelluric (MT) survey, used to estimate lithology.

Table 3: Example Draft Execution Indices for MT Surveys for the Drilling Sub-attribute: Rock Properties

Index	Execution Description
a	<ul style="list-style-type: none"> Local resistivity anomalies are known and have been used to manually correct the telluric shift (e.g., through inversion of transient electromagnetic, TEM, results) Minimal incidents of signal noise (such as cultural interference) or survey includes a quiet remote station to remove noise signal 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
b	<ul style="list-style-type: none"> 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 that 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
c	<ul style="list-style-type: none"> Results taken from previous third-party studies of the area (either from literature or contractors) with little or limited information on survey methods, replication, or error.
d	<ul style="list-style-type: none"> 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
e	<ul style="list-style-type: none"> Assumed from studies of analogous geothermal settings or extrapolated from studies of nearby areas.

4.2 Visualizing Resource Grades

Resource grades can be visualized using a polar area chart (**Error! Reference source not found.**), where each quadrant represents one of the four attribute grades for a category and is subdivided to show the values for the character, activity, and execution indices.

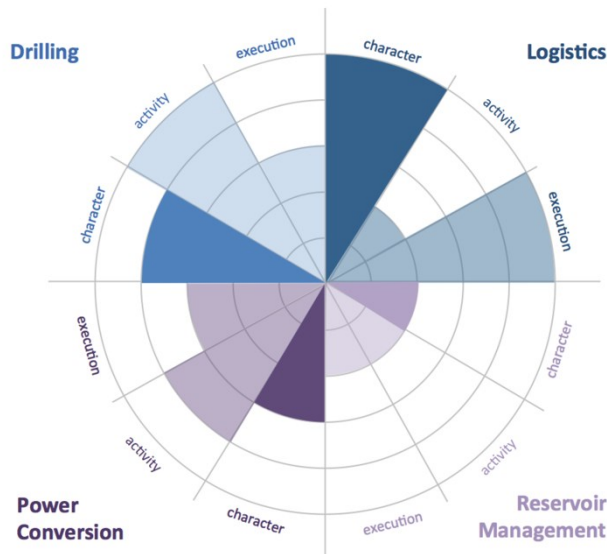


Figure 1: Example grade visualization of a hypothetical resource using a polar area chart showing the four technical attributes. Each quadrant represents a different technical attribute and is subdivided to show the character, activity, and execution index values. The darkly shaded wedges indicate the grade of the four attributes, while the lightly shaded wedges indicate certainty (activity and execution). E is located at the center of the circle, and A is located along the circumference of the circle – the larger the shaded area, the better the resource.

The diagram allows for quick assessment of the strengths and weaknesses of an area by scanning the darkly shaded wedges. In **Error! Reference source not found.**, the drilling and logistics attribute grades of the resource are high, the power conversion is about average, and the reservoir management is low.

By reviewing the lightly shaded areas, one can get a glimpse of the certainty of these values and understand where additional work may be needed to better understand the development potential. For example, the lightly shaded areas in Figure 1 show uncertainty in logistics and reservoir management.

In the context of GTO’s need for metrics, the polar area chart can be used to understand RD&D impacts at a particular location, showing how the information for a given area has changed in response to the results of funded projects. For example, the chart could enable GTO to clearly identify whether changes in the reported power conversion are due to better measurements from new techniques. The chart allows users to quickly identify increases in information from one period to the next and may illustrate differences between seemingly similar projects (e.g., two projects with the same character grades may have vastly different activity and execution indices).

Each of the three categories (geological, technical, socio-economic) will have its own, similar polar area chart showing the respective character grade and certainty wedges. The color key for each of these charts is shown in Figure 2. Detailed polar area charts for each category are provided in the Protocol documents (Young et al. 2015a, Young et al. 2015b, Young et al. 2016).

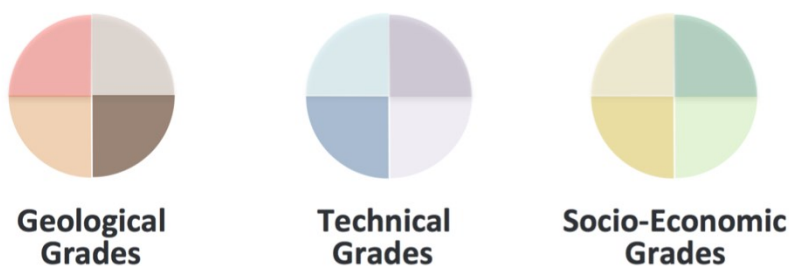


Figure 2: Color key for the polar area chart for each of the three categories: geological, technical and socio-economic. Each quadrant represents a different attribute and will be subdivided to show the character, activity, and execution index values. For detailed polar area charts for each category, see the Assessment Tools of the GRRM Protocol (Young et al. 2015b).

All of the character attributes can be shown on a single summary chart (**Error! Reference source not found.**). This chart shows only the character grades—not the activity or execution indices. Therefore, no uncertainty is illustrated in this figure.

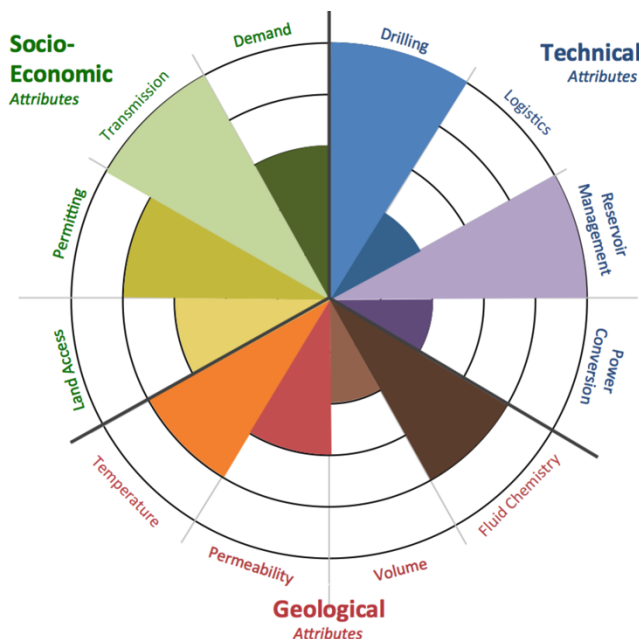


Figure 3: Summary Resource Grade Chart. The character grades for each of the twelve resource attributes are displayed in a single polar area chart. E is located at the center of the circle, and A is located along the circumference of the circle – the larger the shaded area, the better the resource. Because activity and execution indices are excluded from the diagram, no uncertainty is depicted.

5. PROJECT PROGRESS

Like geothermal grade, the GRRM breaks the concept of project progress into three assessments: geological, technical, and socio-economic. As projects progress from one phase to the next, they pass through “activity thresholds”—minimum activities required to qualify for the next project progress category. For example, the difference between an undiscovered resource and inferred resource is the completion of some form of field sampling.

5.1 Defining Project Progress

Project Progress is defined for each of the three assessment categories: geological, technical, and socio-economic. For each category, five levels of project progress are defined, with 5 representing the most advanced level of development. This section describes only the major concepts of the project progress levels. Further details on their application to projects can be found in the related geological, technical, and socio-economic Assessment Tools of the GRRM Protocol (Young et al. 2015a, Young et al. 2015b, Young et al. 2016).

5.1.1 Technical Progress

The **Technical Progress** scale describes specific technical milestones in the development of a geothermal project. These technical milestones are chosen to mark technical progress for each project’s phase; for example, testing of a well or a reservoir that produces sufficient flow for the project goals. Projects can also move backwards along this scale if, for example, the reservoir no longer produces at the anticipated rate. The Technical Assessment Tool of the GRRM Protocol, (expected release, summer 2016), will provide more detailed descriptions of the decision logic behind selecting these criteria (Young et al. 2016).

Table 4: Technical Progress Scale showing qualifying criteria for each technical phase.

	Technical Progress	Qualifying Criteria
T1	Unknown/ Unrecoverable	For a resource to be considered “Unknown,” no drill holes, fluid chemistry or heat extraction tests have been conducted to confirm existence/viability of the area. Geological assessment may have been performed, but no technical development of the resource as an energy production site has taken place. A project may also be classified as T1, “Unrecoverable,” if surveys have been conducted and do not show potential, and/or one or more wells have been drilled and have not yet been successful. For example, EGS estimates may fall into this category until permeability has been developed.
<i>Regional Reconnaissance Surveys</i>		
T2	Potential	For a resource to be considered “Potential,” surveying of the site confirms potential as an energy production site through geophysical analysis. Geologic mapping, geochemical characterization, and geophysical surveys have progressed to the point that the exploration team believes that exploration drilling is warranted. For a resource to be considered “Potential,” the following criteria must be met: <ol style="list-style-type: none"> 1. Field surveys confirm the viability of the resource and warrant exploration drilling.
<i>First Well Drilled into the Reservoir</i>		
T3	Discovered	For a resource to be considered “Discovered,” the resource must meet initial temperature and permeability estimates. Both of the following criteria must be met: <ol style="list-style-type: none"> 1. Well drilled into the reservoir prove developable reservoir temperature. 2. Well drilled into the reservoir prove developable reservoir permeability.
<i>Well Field Build-out</i>		
T4	Confirmed	For a resource to be considered “Confirmed,” extensive exploration activities must confirm the area’s potential to support a geothermal power plant. The following criterion must be met: <ol style="list-style-type: none"> 1. Well field produces geofluids at necessary temperatures and flow rates to produce power for a minimum of 30 days.
<i>Plant Development</i>		
T5	Demonstrated	For a resource to be considered “Demonstrated,” the power plant must be able to demonstrate integrated system operation. All of the following criteria must be met: <ol style="list-style-type: none"> 1. Well and supporting infrastructure must be operational for a minimum of 30 days 2. Plant must produce power at sustainable rates

5.2 Visualizing Project Progress

Project progress can be visualized on a three-dimensional project development grid, with Geological progress shown on the x-axis, Technical progress on the y-axis, and Socio-economic progress on the z-axis, as shown in Figure 4. Each project can be represented as a cube within this grid and can move independently along each of the three axes as project development progresses.

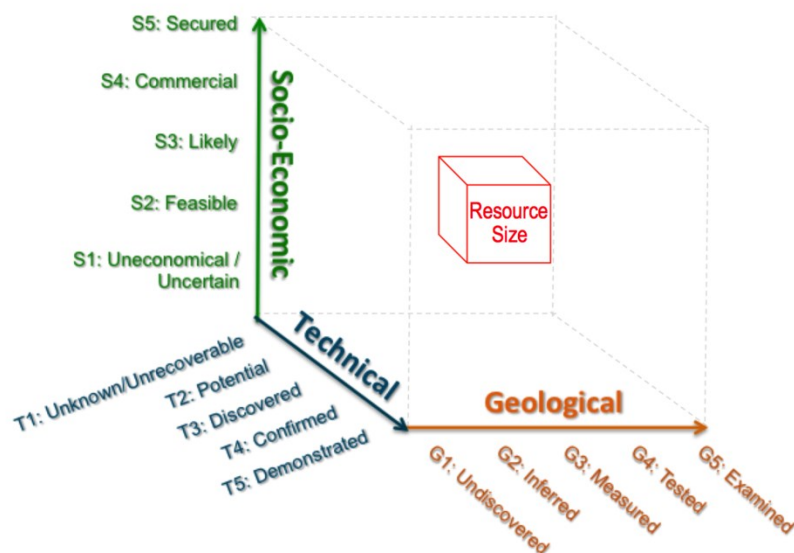


Figure 4: Project Development Grid. Each of the three categories is represented along an axis. Geological progress is shown on the x-axis, technical progress is shown on the y-axis, and socio-economic progress is shown on the z-axis. Each project can be represented as a cube within this grid, and can move independently along each of the three axes as project development progresses.

6. CONCLUSIONS AND NEXT STEPS

The GTO is required to track and report on the impacts of public funding on technology RD&D. Initial progress has been made in developing a geothermal resource reporting methodology to aid in these tasks. This paper briefly reviews the concepts of the Technical Assessment Tool in its current status, and provides the framework for how these concepts are recorded at different stages of geothermal exploration and development.

The next steps for this project (February through September 2016) include updating the Technical Assessment Tool Protocol document (Young et al. 2016) based on feedback received during the February 2016 Stanford Geothermal Workshop (Stanford, CA), to be posted for additional review and comment in July 2016. We are also in the process of developing the Socio-Economic Assessment Tool with review and input from industry experts.

In 2017, if continued funding is received, we plan to develop baseline maps of the resource attributes and project progress to help identify barriers and potential targets for research improvements. During this period, the Protocol will be tested on GTO's previous and current portfolio of RD&D projects and refined, as necessary, to overcome any issues identified in implementation of the Protocol. We welcome any feedback and suggestions from all stakeholders.

The information provided in this paper and the discussed Protocol (Young et al. 2016) is currently under review. We plan to continue to test and update these materials throughout 2016.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Geothermal Technologies Office (GTO) under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory and No. DE-AC02-05CH11231 with Lawrence Berkeley National Laboratory. It was also supported in part by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Science Undergraduate Laboratory Internship (SULI) program. The authors wish to thank Colin Williams (USGS), Paul Brophy (EGS, Inc.), Graeme Beardsmore (Hot Dry Rocks), Ann Robertson-Tait (GeothermEx), Ben Matek (GEA), Brittany Segneri (New West Technologies), Sabodh Garg (Leidos), Jeff Winick (Mighty River Power), Paul Siratovich (Mighty River Power), Gene Suemniect (EGS, Inc), Bill Eustes (CSM), Chad Augustine and Craig Turchi (NREL), Eric Hass and Laura Garchar (GTO), and numerous workshop participants for their insights and suggestions relating to this study. We also thank the NREL review team, including Kendra Palmer, Donna Heimiller, Emily Newes, and David Mooney.

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APPENDIX: DRAFT TECHNICAL ASSESSMENT GRADES

This appendix presents the draft attributes and sub-attributes of the Technical Assessment Tool. The details of these grades are still under review and refinement and are presented here to solicit comment and feedback from industry experts. Only the attribute and sub-attribute grades are presented here. For activity and execution indices, please see the Technical Assessment Tool Protocol (planned for release: Summer 2016).

If you have comments or suggestions for improvements, please feel free to contact us, and/or attend one of our workshops, to be held during the Stanford Geothermal Workshop on Monday, February 22, 2016, immediately following the afternoon sessions.

A.1 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 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 weighted ranking in terms of how it contributes to the overall attribute grade.

A.1.1 Permeability

Permeability of a geothermal reservoir considers the pathways by which fluids are circulated and heated. A lack of permeability may require the use of reservoir stimulation to maintain production rates. As system productivity is directly dependent on its permeability, this sub-attribute is crucial for consideration in any project.

Permeability is considered in the Geological Assessment of the GRRM; the permeability grades used for the Technical Assessment Tool are identical to that found in the Geological Assessment Tool.

Grade	Weighted Ranking	Description
A	1	Very High
B	2	High
C	3	Medium
D	4	Low
E	5	Very Low

A.1.2 Density of Heat Source

The concentration of power per unit area is important for consideration in a geothermal development as a higher value places more power within the accessible reservoir area. This concentration is referred to as power density, and is considered in the grade table as megawatts per square kilometer (Wilmarth and Stimac 2015). High power densities allow for plants to access more heat energy with a lower well density.

Grade	Weighted Ranking	Power Density
A	1	>35 MW/km ²
B	2	>25-35 MW/km ²
C	3	>15-25 MW/km ²
D	4	>5-15 MW/km ²
E	5	0-5 MW/km ²

A.1.3 Calcite Saturation Index

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 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).

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 affect the temperature has on calcite precipitation as well as the overall concentration of silica within the fluid, the Calcite Saturation Index is used to grade the presence of calcite.

Grade	Weighted Ranking	Calcite Saturation Index
A	1	0
B	2	>0 to 0.5
C	3	>0.5 to 0.75
D	4	>0.75 to 1
E	5	>1

A.1.4 Bicarbonate Content

Bicarbonate mineralization poses similar issues to geothermal power plants as is seen from calcite (Siratovitch 2016). Carbonate mineralization within operating infrastructure of a geothermal power plant results in reduced efficiency and the increased need for precipitant removal within piping.

Bicarbonate content is considered within the fluid chemistry aspect of the geological axis; therefore the same grading scale was utilized.

Grade	Weighted Ranking	Ryznar Stability Index
A	1	6.5 to 7.5 RSI
B	2	6.0-6.5 or 7.0-7.5 RSI
C	3	5.5-6.0 or 7.5-8.0 RSI
D	4	5.0-5.5 or 8.0-8.5 RSI
E	5	<5.0 or >8.5 RSI

A.1.5 Silica Saturation Index

Silica presence in thermal fluids can result in scaling in plant infrastructure and reservoir fractures. This mineralization restricts fluid flow and requires removal for the system to continue to effectively produce fluid. Common methodologies used for managing silica precipitation include, but are not limited to: not re-injecting geothermal brines, the use of silica removal equipment, pH modification, and dilution with steam condensate. As an example, Mighty River Power manages brine silica with pH modification to prevent precipitation within power plant infrastructure. At the Kawerau power station, this management technique allows for increased electricity generation of 17-18% (Addison 2015).

The concentration of silica as well as the temperature of the reservoir fluid controls the likelihood of silica precipitation. Low temperature fluids are more likely to precipitate silica from solution than fluids with high temperatures. To account for the affect the temperature has on silica precipitation as well as the overall concentration of silica within the fluid, Silica Saturation Index (SSI) is used to grade the presence of silica.

Grade	Weighted Ranking	Silica Saturation Index
A	1	0
B	2	>0 to 0.5
C	3	>0.5 to 0.75
D	4	>0.75 to 1
E	5	>1

A.1.6 Energy Conversion System Fluid Loss

Water is necessary to convert recovered heat energy into usable electric power, whether it is flashed to steam or worked through a heat exchanger with a secondary working fluid. In some instances all of the fluid recovered at the wellhead may not be available for re-

injection due to losses during cooling or as a result of the geofluid flashing to steam during power conversion. Water is subsequently used to condense vapor for re-injection and/or to cool the working fluid (Clark 2015).

Losses of fluid during the power conversion cycle create the need for supplemental water to maintain injection rates. The Geysers geothermal field in California is a high-temperature system, and most of the produced geofluid is steam dominated. When this steam is converted to power, a high percent of the steam mass is lost to power generation processes. To provide sufficient water to maintain optimal power production, water is now supplied via pipeline from surrounding municipalities (Khan 2010). Geothermal systems able to minimize the percentage of water lost during power conversion allow for more effective management of the reservoir.

Fluid flow rates through geothermal plants are dependent on a number of reservoir and power plant characteristics and are best considered in terms of percentage loss rather than bulk volume.

Grade	Weighted Ranking	Water Loss Percentage
A	1	0-5%
B	2	5-15%
C	3	15-25%
D	4	25-35%
E	5	>35%

A.1.7 Water Available for Reservoir Management

This sub-attribute considers both the anticipated need and availability of water to effectively manage the power production of the geothermal reservoir. Economical and local sources of water are crucial to the power plant operation as they allow for increased injection to mitigate pressure drawdown or decreased fluid recovery rates.

Grade	Weighted Ranking	Description	Water Needed
A	1	No supplemental water is needed	
B	2	Water is needed and is available (and identified) for injection	>0-5 gal/kWh
C	3	Water is needed and is available (and identified) for injection	>5-10 gal/kWh
D	4	Water is needed and is available (and identified) for injection	>10 gal/kWh
E	5	Water is needed and is not available for injection	

A.1.8 Pressure Support

When a well is drilled into a geothermal system, the production of the geofluid may cause a decrease in overall reservoir pressure. Lower pressure can result in a number of effects including mineralization (in plant infrastructure or reservoir itself) and decreased flow rates through production wells (Taylor 2007).

Pressure drawdown occurs on varying timescales for different thermal systems; it can operate on terms of days or years. To consider the overall pressure trend, grades were developed in terms of percent pressure drawdown per year.

Grade	Weighted Ranking	Pressure Drawdown per Year
A	1	0%
B	2	>0-2%
C	3	2-3%
D	4	3-5%
E	5	>5%

A.1.9 Injectate Breakthrough

When water is injected into a geothermal system, it is intended that the injectate work itself through the fractures of the system while gaining heat energy. At times it may shortcut or breakthrough the normal flow path and interact with production fluid before the injectate has reached maximum enthalpy. The colder injectate lowers the overall enthalpy of the other fluid when the two mix and results in an overall lower enthalpy of the fluid recovered at the wellhead. Lower enthalpy production fluid means that less heat can be extracted during power conversion and subsequently less power can be produced from that fluid.

Identifying and optimizing injection rates is important to managing the power production of any geothermal reservoir. Developing an injection plan is best achieved through reservoir and well field modeling, and using resulting model outputs for designing an injection schedule (Juliusson 2013).

To characterize how these breakthroughs affect the overall reservoir enthalpy, injectate breakthrough is graded in terms of annual decline in enthalpy of production fluid.

Grade	Weighted Ranking	Description
A	1	No noticeable change in geofluid enthalpy
B	2	0-5 kJ/kg per year of enthalpy change
C	3	>5-7.5 kJ/kg per year of enthalpy change
D	4	>7.5-10 kJ/kg per year of enthalpy change
E	5	>10 kJ/kg per year enthalpy change

A.1.10 Cold Water Breakthrough

Secondary to injectate breakthrough described in §A.1.9, Cold Water Breakthrough considers the entrance of non-injected fluids into the active geothermal reservoir volume. Potential breakthrough sources range from ocean and lake waters to nearby subsurface aquifers. The likelihood of these fluids breaking into the reservoir is a function of both the reservoirs proximity to these bodies of water as well as the orientation of fractures within the reservoir itself. If the fractures are optimally oriented for intersection with the body of water in question, the potential for fluid breakthrough is increased.

Beginning in 1985, the Tiwi Geothermal Field in the Philippines experienced cold-water breakthrough in the production area of the field. This sudden entrance of cold water drastically affected the power production of the system, and was eventually mitigated by relocating the production area further west (Menziés 2010). Although it is necessary for water to enter the geothermal system to collect stored heat energy, the rate at which water enters the system is important to maintaining the areas productivity. This sub-attribute considers the likelihood that excess water will enter the reservoir.

Character grades for this sub-attribute consider both the proximity of large bodies of water to the thermal system as well as the orientation of fracture networks within the system.

Grade	Weighted Ranking	Description
A	1	Low susceptibility to cold water breakthrough (reservoir located greater than 2.5km horizontally or vertically from lake, ocean and fracture orientation and size/lithological characteristics do not suggest aquifer interaction is possible)
B	2	Low susceptibility to cold water breakthrough (reservoir located greater than 2.5km horizontally or vertically from lake, ocean, HOWEVER fracture orientation and size/lithological characteristics do suggest aquifer interaction is possible)
C	3	Moderate susceptibility to cold water breakthrough (reservoir located greater than 1.5km horizontally or vertically from lake, ocean, HOWEVER fracture orientation and size/lithological characteristics do suggest aquifer interaction is possible)
D	4	High susceptibility to cold water breakthrough (e.g., reservoir located within 1 km horizontally or vertically to a large cold water body-lake or ocean) OR fracture orientation and size suggest cold water breakthrough or drawdown from aquifer is possible
E	5	High susceptibility to cold water breakthrough (e.g., reservoir located within 1 km horizontally or vertically to a large cold water body- lake or ocean) AND fracture orientation and size suggest cold water breakthrough or drawdown from aquifer is possible

A.2 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, several publications and industry research were reviewed (e.g., Fairbank and Niggeman 2004, Augustine et al. 2006 Entingh 2006, International Finance Corporation 2013, and Finger and Blankenship 2010, Denninger 2015, Eustes et al. 2015). To reflect multiple physical, geological, and logistical aspects that contribute to drilling difficulty, nine 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 down time. Grades were developed for each of the nine sub-attributes.

Not every aspect considered in the sub-characters affects drilling difficulty equally. To take this into account, a weighted ranking system was developed. This weighting system can be seen in the tables below, where the weighted rankings assigned to each sub-character represents how it is weighted relative to other sub-attributes that contribute to drilling difficulty. The drilling character grade is determined by the sum of the weighted sub-attributes.

A.2.1 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 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 overall 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.

Grade	Weighted Ranking	Description	Quantification
A	4	Shallow well	<1000m
B	8	Moderately deep well	1000-2000m
C	12	Average depth well	>2000-3000m
D	16	Deep well	>3000-4000m
E	20	Extremely deep well	>4000m

A.2.2 Bottom-hole Well Completion Diameter

In the case of geothermal power plants, the amount of power that can be produced is dependent on the flow rate of geofluid at the wellhead. To maximize flow rates, plants use well designs with large production diameters (defined as the well diameter at the bottom of the well). When a large production zone diameter is desired, it requires an increased diameter beginning at the top of the well and may require additional casing strings (Finger and Blankenship 2010). As both depth and production zone diameter increase, elapsed drilling time and difficulties are likely to increase along with cementing costs and casing costs, driving the overall well cost higher.

Grade	Weighted Ranking	Description	
A	2	<20cm	<7.87in
B	4	20-25cm	>7.87-9.84in
C	6	26-30cm	>9.84-11.81in
D	8	31-35cm	>11.81-13.78in
E	10	>36cm	>13.78in

A.2.3 Number of Casing Strings

Well design requires the use of casing strings to ensure structural integrity of the wellbore. After drilling is completed, a series of casings strings are inserted into the wellbore to prevent it from collapsing. The number of casing strings required increases with depth and subsequently increases overall well cost (Tester et al. 2006).

Grade	Weighted Ranking	Description
A	3	<4 casing strings needed
B	6	<5 casing strings needed
C	9	<6 casing strings needed
D	12	<7 casing strings needed
E	15	<8 casing strings needed

A.2.4 Drilling Angle

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 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. 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). Therefore, it is best to consider the angle of adjustment required to meet the well design specifications rather than the overall well angle in the drilling angle character index. Angle of adjustment can be defined as the difference between the angle the drill bit takes naturally and the angle needed to meet the well design.

Grade	Weighted Ranking	Description
A	1	Unrestricted drilling angle (no angle of correction)
B	2	Slight alterations to drilling angle necessary 0-10°
C	3	>10-15° drilling angle adjustment needed to access resource
D	4	45-60° angled drilling OR >15-20° drilling angle adjustment necessary
E	5	60-90° (horizontal drilling) OR drilling angle adjustment is >20°

A.2.5 Rock Properties

The rock properties sub-attribute is aimed to assess any difficulties caused by geologic properties of the reservoir. The specific properties considered here include formation composition/hardness and lost circulation zones. By nature, geothermal wells are more likely to encounter harder and more abrasive rock formations. More brittle formations create extreme stresses on drill bits and their supporting equipment. Slower drilling speeds also result from drilling in harder formations. Also to be considered is the level of consolidation exhibited in the rock; soft and unconsolidated formations will crumble and fracture, potentially collapsing the well (Eustes 2015).

Drilling engineers consider lost circulation one of the most frequently encountered problems in geothermal drilling (Carson 1982). Drill rigs pump mud at the drill bit to lower heat generated from friction and to remove fractured rock from the drill bit. A zone of lost circulation occurs when drilling intersects with a fracture or open space in the rock and the pumped mud is lost within that void. The increased drilling times and equipment wear caused by these zones is assessed within the rock properties sub-attribute. However, it is important to note that encountering such zones within the geothermal reservoir is a requirement for a successful geothermal well.

Grade	Weighted Ranking	Description
A	3	Soft/Medium soft formation (shale, clay, limestone, sandstone); no anticipated areas of lost circulation
B	6	Medium hard/hard formation (hard limestone, sandstone, dolomite); no areas of lost circulation known
C	9	Sedimentary rock with occasional layers of shallow, swelling clays, or lost circulation zone
D	12	Crystalline basement formation OR unconsolidated sediments OR shallow swelling clays OR multiple lost circulation zones
E	15	Crystalline basement formation OR unconsolidated sediments AND shallow swelling clays OR multiple lost circulation zones

A.2.6 Heterogeneity of Rock Types Encountered

Also to be considered during well drilling operations is the variance in lithological units to be encountered during drilling. Different rock types may require different drill bits, mud types, and other operational adjustments while drilling. These changes can be costly (e.g., tripping out of a well to change the drill bit) and challenging (e.g., utilizing a mud weight that is sufficient to hold one formation open while not plugging up another).

Sharp variances in lithology can also influence the number of casing strings used in the well. While transitioning between lithologies with varying degrees of consolidation, putting into place a casing string can help prevent any collapse or structural deformations within the well.

Grade	Weighted Ranking	Description
A	3	4 or fewer distinct changes in rock types are to be encountered during drilling
B	6	5 distinct changes in rock types to be encountered during drilling
C	9	6 distinct changes in rock types to be encountered during drilling
D	12	7 distinct changes in rock types to be encountered during drilling
E	15	>7 distinct changes in rock types to be encountered during drilling

A.2.7 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 is not always applicable to geothermal drilling. To garner useful information from these wells, they 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-character index and the comparable depth, geology and the density of nearby wells is considered in the activity index.

Grade	Weighted Ranking	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

A.2.8 Water for Drilling

When a geothermal well is being drilled, water is typically mixed with some form of clay or mud to be pumped down to the drill bit. This drilling mud helps to cool the bit, hold the formation open, reduce wear on drilling equipment, and carry the rock cuttings back up the well. Large amounts of water are therefore needed for well drilling.

Depending on the geographical location of the geothermal system, water may be difficult to appropriate, and therefore the overall amount of water needed for the well to be constructed is a factor that should be considered in any geothermal development. Grades for the *Water For Drilling* sub-attribute are defined in total water needed for complete drilling of the considered well/well field in acre-feet.

Grade	Weighted Ranking	Description
A	2	<1 AF
B	4	1-2 AF
C	6	2-3 AF
D	8	3-4 AF
E	10	> 4 AF

A.2.9 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 mechanical issues with the well itself (Callis 2015).

Grade	Weighted Ranking	Description
A	0	No drilling restrictions in place
E	10	Drilling restrictions present

A.3 POWER CONVERSION

When geofluid is recovered at the wellhead, there exist several different power conversion techniques to convert that 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.

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

A.3.1 Temperature Difference: Inlet to Condenser

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 areas ambient temperature is, the more efficiently a plant can operate. 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:

$[\text{Reservoir temperature} - 5^\circ] - [95^{\text{th}} \text{ percentile of ambient air temperature (from cumulative distribution function of hourly temperature for a year)}]$ (Turchi 2016).

Grade	Weighted Ranking	Conversion Technology	Quantification
A	2	Double flash	$\Delta T > 180^\circ\text{C}$
B	4	Single flash	$\Delta T > 150^\circ\text{C}$
C	8	Binary cycle; working fluid: geothermal fluid	$\Delta T > 125-150^\circ\text{C}$
D	10	Binary cycle, working fluid: isobutane, etc.	$\Delta T > 125-100^\circ\text{C}$
E	14	Binary cycle, working fluid: isobutane, etc. OR direct use	$\Delta T < 100^\circ\text{C}$

A.3.2 Non-Condensable Gas Content

One impact on power plant efficiency is non-condensable 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 results 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. 2015) is assigned a NCG ranking of “A.”

NCGs are an important consideration for many geothermal areas around the world. Common NCG compositions consist of greater than 90% CO₂, 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). Proper management of any NCGs in a geothermal area is important for ensuring a productive reservoir and power plant.

Grade	Weighted Ranking	Description
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%

A.3.3 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 effective than air-based systems, but require water nearby to operate. 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 are hybrid cooling technologies, which use a combination of water and air to cool the working fluid.

Grade	Weighted Ranking	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

A.4 LOGISTICS

Logistics grade considers the physical ease of access of the geothermal area. Multiple factors must be considered when determining logistical grade. Not only can it be determined by the presence of geological hazards, but also by geographical location and topographical features. Assessment of logistical accessibility required the use of multiple sub-attributes.

A.4.1 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 (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.

In considering the development of a geothermal resource, the availability of materials for development is necessary (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.

Grade	Weighted Ranking	Description
A	3	Land-locked system; no major continental boundaries or barriers present in accessing resource and area is within reach of existing infrastructure
B	6	Land-locked system; long distances necessary to travel to access resource, but area is without continental barriers (mountains, large lakes, arctic landscape etc.)
C	9	Area isolated by continental barrier-mountain, large lake, arctic landscape, etc.
D	12	Area isolated by less than 500 miles of ocean
E	15	Area isolated by more than 500 miles of ocean

A.4.2 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.

The geothermal system’s proximity to any volcanic hazards is considered in terms of zones developed and mapped for the continental United by the USGS (Mullineaux 1976).

Grade	Weighted Ranking	Description
A	2	Site not located within 10 km of any identified volcanic hazards
B	4	Site within 2 km of a USGS identified "Area Subject to Specific Volcanic Hazard"
C	6	Site located within a USGS identified "Area Subject to Specific Volcanic Hazard"
D	8	Site Located within a USGS classified "Vent Area"
E	10	Site located within 3 km of a USGS classified "Large Volcano"

A.4.3 Landslide Hazards

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

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

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

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).

Grade	Weighted Ranking	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

A.4.4 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 earthquake probability of occurrence. Units used are peak acceleration as a fraction of standard gravity (Petersen et al. 2014).

Grade	Weighted Ranking	Description
A	2	Site located in an area with a value of peak acceleration less than 0.04
B	4	Site located in an area with a value of peak acceleration 0.04-.1
C	6	Site located in an area with a value of peak acceleration >0.1-.2
D	8	Site located in an area with a value of peak acceleration >0.2-.4
E	10	Site located in an area with a value of peak acceleration >0.4

A.4.5 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 overall 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).

Grade	Weighted Ranking	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

A.4.6 Severe Weather Events

Harsh weather conditions at the geothermal site restrict construction windows and inhibit access to the site during extreme weather events. Climate considers severity of precipitation events and the areas average overall climate. Arid and arctic 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.

Grade	Weighted Ranking	Description
A	2	No annual days of prevented access (as a result of severe weather events)
B	4	1-15 annual days of prevented access (as a result of severe weather events)
C	6	>15-30 annual days of prevented access (as a result of severe weather events)
D	8	>30-45 annual days of prevented access (as a result of severe weather events)
E	10	>45 annual days of prevented access (as a result of severe weather events)

A.4.7 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).

Grade	Weighted Ranking	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

A.4.8 Topography

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

Grade	Weighted Ranking	Description
A	2	Flat, accessible resource area
B	4	Terrain with slopes up to 10°
C	6	Terrain with slopes up to 20°
D	8	Rugged terrain with slopes up to 30°
E	10	Rugged topography with slope >30°