GeoRePORT Case Study Examples: Reporting Using the Geothermal Resource Portfolio Optimization and Reporting Technique (GeoRePORT)

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ABSTRACT

The Geothermal Resource Portfolio Optimization and Reporting Technique (GeoRePORT) was developed with funding from the U.S. Department of Energy Geothermal Technologies Office to assist in identifying and pursuing long-term investment strategies through the development of a resource reporting protocol. GeoRePORT provides scientists and nonscientists a comprehensive and quantitative means of reporting: (1) features intrinsic to geothermal sites (project grade) and (2) maturity of the development (project readiness). Because geothermal feasibility is not determined by any single factor (e.g., temperature, permeability, permitting), a site's project grade and readiness are evaluated on 12 attributes pertaining to geological, technical, or socio-economic feasibility. In this paper, we present case studies showing how GeoRePORT can be used to compare geological, technical, and socio-economic attributes between geothermal systems. The consistent and objective assessment protocols used in GeoRePORT allow for comparison of project attributes across unique locations and geological settings. GeoRePORT case studies presented here outline the geological, socio-economic, and technical features of four individual geothermal sites: Coso, Chena, Dixie Valley, and White Sands Missile Range. The case studies illustrate the usefulness of GeoRePORT in evaluating project risk and return, identifying gaps in reported data, evaluating R&D impact, and gathering insights on successes and failures as applicable to future projects.

1. Introduction

The Geothermal Resource Portfolio Optimization and Reporting Technique (GeoRePORT) system was developed to address the need of the U.S. Department of Energy (DOE) Geothermal Technology Office (GTO) to track and measure the impact of its research, development, and deployment funding for geothermal projects (Young et al. 2016a). The National Renewable Energy Laboratory (NREL) led the development of the GeoRePORT protocol in collaboration with Lawrence Berkeley National Laboratory, with support from GTO. Over a 3-year period between 2013 and 2016, the concept was designed and the geological (Young et al. 2016b), technical (Young et al. 2016c), and socio-economic (Levine and Young 2016) assessment tools were developed with input from one-on-one phone calls with industry experts as well as regular, repeated industry workshops to solicit targeted feedback. GeoRePORT 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 12 attributes of geothermal resources (such as temperature, permeability, and land access) to indicate potential for geothermal development. GeoRePORT was developed to provide consistency among the user community in *reporting*; it is neither a prescription for conducting exploration and field development nor a replacement for expertise and conceptual or reservoir models.

The GeoRePORT protocol was designed to be able to distill massive amounts of geothermal project data into a concise, communicable summary that can be understood by project experts (e.g., geochemists, permitting experts) and by those in management. It can be used to establish country baseline information, for project-specific reporting, or for summarizing project development portfolios. It can also be a useful tool for:

- Project managers (e.g., leaders in the military looking to develop geothermal resources on military installations);
- Countries, states (e.g., California's Geothermal Resources Development Account), or other entities looking to fund research and development projects; and
- Geothermal risk mitigation funds (e.g., Geothermal Risk Mitigation Fund in East Africa, Geothermal Development Facility for Latin America) or a bilateral or multilateral development entity (e.g., World Bank) looking to finance geothermal projects.

These protocols can be useful to help quantitatively ***identify*** the greatest barriers to geothermal development, ***develop*** measurable program goals that will have the greatest impact on geothermal deployment, objectively ***evaluate*** proposals based (in part) on a project's ability to contribute to program goals, ***monitor*** project progress, and ***report*** on project portfolio performance.

Previous publications (Badgett, Young and Dobson 2015) have discussed the aims of GeoRePORT and the details of the protocol. This paper provides a brief introduction to GeoRePORT, then summarizes four case studies developed to illustrate the implementation of GeoRePORT: Coso (California), Chena Hot Springs (Alaska), Dixie Valley (Nevada), and the White Sands Missile Range (New Mexico). Full details about GeoRePORT and the protocols can be found on the GeoRePORT website.

2. Overview of the Protocol

GeoRePORT is based on the concept that a geothermal system can be described both in terms of the quality of the geothermal resource as it relates to the potential to extract heat (resource grade), and the progress of research and development efforts over the lifetime of the project (project readiness).

2.1 Resource Grade

Traditionally, a description of the grade of a natural resource includes a combination of 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).

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. A few examples are:

- Some developers may be interested in average temperature resources and poor fluid chemistry to take advantage of secondary mineral recovery potential from the geothermal brine.

- Near-field resources (resources located near operating plants) may have high temperatures but low permeability and may be candidates for the application of enhanced geothermal system techniques.
- 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 attribute grades equaling A rarely exist.

2.2 *Project Readiness*

Like resource grade, the GeoRePORT protocol breaks the concept of project readiness level into ordered categories. These project readiness levels are not directly related to the grades and are an independent assessment of the project progress (grades are an assessment of the resource). As projects progress from one development phase to the next, they pass through activity thresholds, which are minimum activities required to qualify for the next category. 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.

3. Methodology

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 (highest) through E. A full description of the protocol is given in Young et al. 2016a. GeoRePORT also considers the activities conducted to assign grades for each attribute and what is known about the quality of the data collected. Geological attributes include temperature, volume, permeability, and fluid chemistry. For the geological attributes, activity and execution indices are developed to address uncertainty in the reported data (for full description of the geologic assessment protocol, see Young et al. 2016b). Technical attributes include logistics, drilling, power conversion, and reservoir management (Young et al. 2016c). Socio-economic attributes include land access, transmission, permitting, and market demand (Levine and Young 2016). Uncertainties in technical and socio-economic attributes are addressed via activity indices.

GeoRePORT is a tool for experts familiar with the area to communicate their research and knowledge to others. For this reason, it was important to get experts (when available) in each case study area to participate in these case studies—not only to provide years of knowledge and experience to the case study, but also to test and provide feedback on the software tool developed to facilitate reporting. Publicly available information was used to complete the case studies prior to review. The data were collected using the best practices as lined out in the geological assessment tool protocol document (Young 2016b).

The case study sites were chosen in part for their diversity in characteristics (early-stage exploration vs. operation; low temperature vs. high temperature) as well as the willingness of participating partners. For the Coso case study, David Meade of the Navy Geothermal Program provided data for GeoRePORT. The Chena Hot Springs case study was initiated by co-author John Bednarek during his student internship with NREL and was completed by NREL geothermal analyst Amanda Kolker. Amanda Kolker completed the Dixie Valley case study from publicly available information, relying heavily on the GeoRePORT Analysis tool on NREL's Geothermal Prospector developed by NREL for certain socio-economic attributes. The White Sands Missile Range (WSMR) was one of the sites in the GTO Ruby Mountain play fairway analysis portfolio. Data for WSMR were provided by Adam Brandt, a student at the University of Utah, and Greg Nash, both who were working on the Ruby Mountain play fairway analysis project. Even with engaged site experts, because of information sharing restrictions, data availability, and/or knowledge gaps, some site data inputs are unavailable. This is to be expected for most case studies; the GeoRePORT tool allows more visibility into these data gaps. NREL developed a spreadsheet tool to facilitate reporting using the GeoRePORT protocol. The spreadsheet is available for download at no charge on the GeoRePORT website. Full details about the protocol can be found on the GeoRePORT website.

4. Summary Overview of Four Case Studies

4.1 *Coso Case Study*

4.1.1 Site Description

The Coso Geothermal Field is located in east-central California, within a dextral strike-slip fault system. Thin crust in the area results in a shallow (~2 kilometers [km]) and hot (>200˚C) reservoir (Monastero 2002). The Coso Geothermal Field has been producing power continuously since 1987 on the military-owned Naval Air Weapons Station China Lake. Exploration activities including heat-flow holes, geophysical, and geological data were conducted in the 1970s, and the Navy awarded a contract to the California Energy Company to develop the resource in 1979. Since initial development, production capacity has grown from 20 megawatts (MW) to greater than 200 MW. Coso Operating Company's current power purchase agreement is good for more than 15 years.

High temperatures allow for the use of double-flash technology for power generation. The field is liquid-limited and requires injection of liquids to maintain production (Monastero 2002). Produced fluids exhibit total dissolved solids ranging 7,000 to 18,000 parts per million, and a noncondensable gas content of 6% (gas fraction) (Monastero 2002). High noncondensable gas content and total dissolved solids concentrations required modifications to the power production process at Coso, and in general can cause environmental and safety hazards if unmitigated (Nagl 2009). Coso was developed cooperatively between the Navy and private industry, a business model that enabled the Navy to develop the resource at a lower initial risk of investment.

4.1.2 Resource Grades

Figure 1 shows the GeoRePORT resource grade totals for the Coso Geothermal Field. Overall, the field displays attributes generally favorable to project development, with geological, technical, and socio-economic attributes all scoring a C grade or better.

Geologically, Coso was graded A in volume and temperature, meaning the site has "ideal conditions" for geothermal production. Coso received a B in permeability, resulting from generally favorable fault/fracture permeability but some uncertainty about certain attributes (e.g., orientations of faults and fractures with respect to the local stress field). In fluid chemistry, Coso was given a C, representing challenging conditions, mostly because of high silica and total dissolved solids concentration in reservoir fluids. Note that the activity grades for some of these geologic measurements are low, likely because most of the assessment was done in the 1970s and 1980s and modern sampling and analysis methodologies were not available.

In the technical category, Coso received an A in power conversion because of its large temperature difference from the inlet to condenser (ΔT) and an A in drilling primarily because of its shallow depth. A grade of B was assigned for site logistics because Coso is located between two mountain ranges that create a certain degree of isolation, limiting transportation and potential for future expansion. Lastly, Coso received a grade of C in reservoir management because the project exhibits moderate system permeability, low risk of cold-water breakthrough, and a lack of readily available supplemental injectant (sub-attribute grades C, A, and E respectively). Together, the reservoir management sub-attributes considered for Coso resulted in a weighted grade of C.

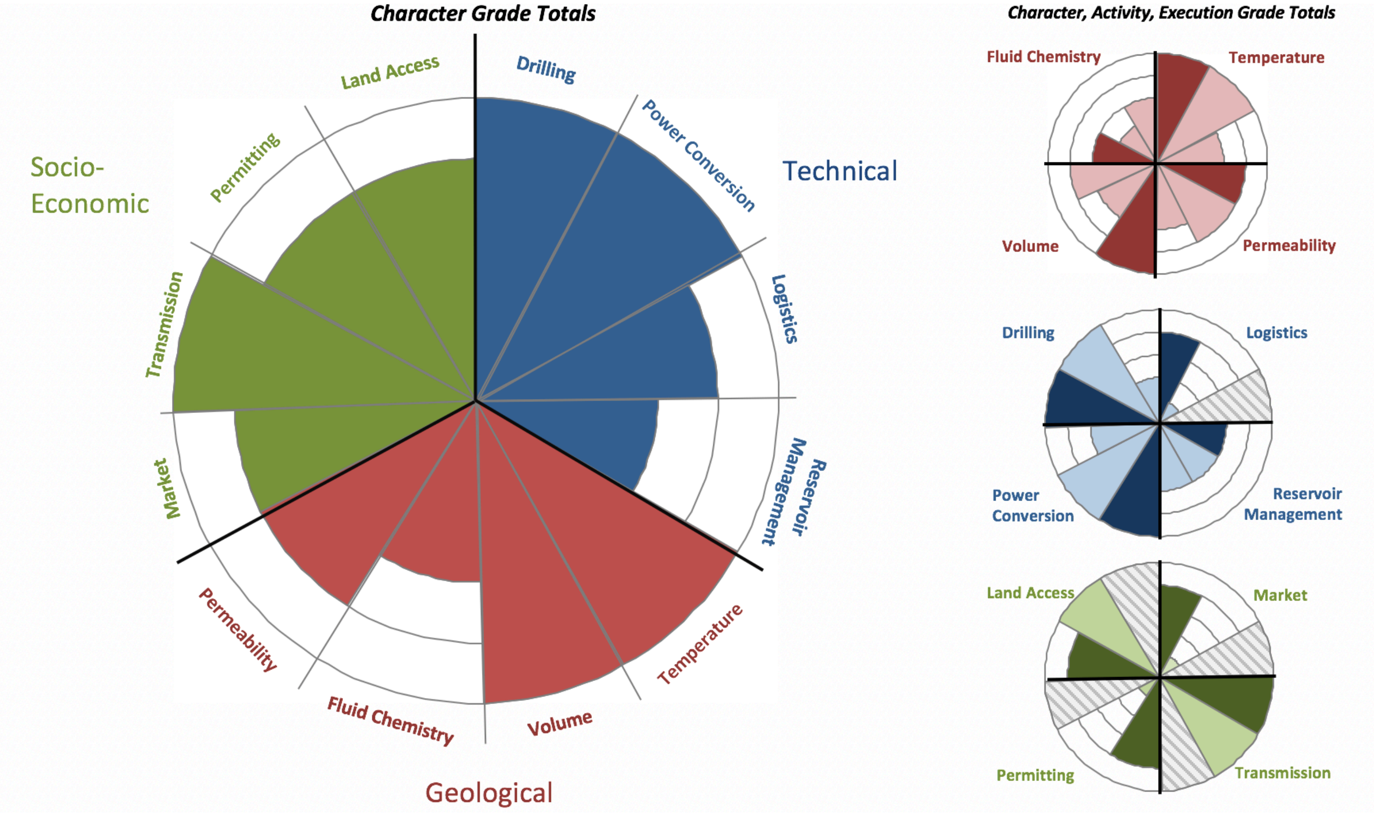

Figure 1. Case study GeoRePORT grade overview for Coso. Left: Character grade totals by geological, socio-economic, and technical attributes. Right: Attribute grades broken down into sub-attributes. Character of each sub-attribute shown in darker colors; activity and execution indices shown in lighter colors (crosshatch = N/A).

In the socio-economic category, Coso received an A in transmission because of existing transmission lines with excess capacity capable of handling expansion at estimated zero cost factor (GeothermEx Inc. 2004). Despite this high grade, it is important to note that Coso is still limited in terms of transmission because of its geographic isolation (see logistics grade of C). Coso received a B in land access because of minimal environmental, biological, and tribal impacts in the area. Permitting received a B grade because permitting may have been an issue *prior* to production; however, no current issues have been located in the public record at this time. Market conditions received a grade of B because there is strong local demand for baseload geothermal power generation. It is important to note that the certainty of the socio-economic grades reported for Coso vary. Land access and transmission received high activity grades because they are known from on-site experience, whereas permitting and market grades were estimated from publicly available records.

4.1.3 Project Readiness

Geothermal power production from the Coso Geothermal Field has been successfully underway since the late 1980s. Over the course of its more than 30 years of production, all required geological, technical, and socio-economic activities have been conducted and completed. Figure 2 shows Coso's project readiness level, G5, T5, S5, which is highest for all three categories.

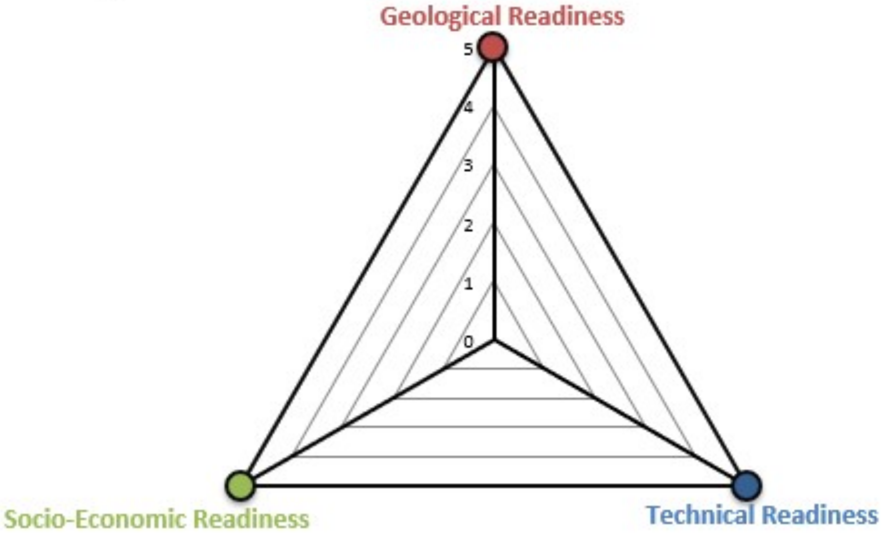

Figure 2. Coso geothermal site's total project readiness score, demonstrating G5 ("examined"), S5 ("secured"), and T5 ("demonstrated") readiness levels.

4.2 Chena Case Study

4.2.1 Site Description

The Chena geothermal area is located within the Yukon-Tanana Upland, a composite tectonic terrane extending from central Alaska to northern British Columbia, bound by large-scale strike-slip faults (Hansen and Dusel-Bacon 1998). The Chena Hot Springs are one of approximately 30 hot springs found in a 2,000-mile-long thermal belt, the central Alaskan hot springs belt, extending from the Seward Peninsula to the Yukon Territory in association with granitoid plutons of Cretaceous to Tertiary age (Kolker et al. 2007). The majority of the thermal springs along this trend are low- to moderate-temperature systems (Holdmann et al. 2006).

The Chena geothermal area has received significant recognition for successful utilization of low-temperature geothermal resources (Holdmann 2007). A readily available supply of cold river water on-site enables Chena to utilize organic Rankine cycle power generation systems at temperatures that are typically too low for organic Rankine cycle generation.

4.2.2 Resource Grades

Figure 3 shows the GeoRePORT resource grade totals for the Chena geothermal project. Many of Chena's attributes are unconventional for a commercial geothermal power project. Chena is a high permeability, shallow geothermal system with a low overall temperature. These unique attributes can be seen in three of the character grades reported in Figure 3: temperature, drilling (the high drilling grade is driven largely by the system's shallow depth and low temperature), and low power conversion grade.

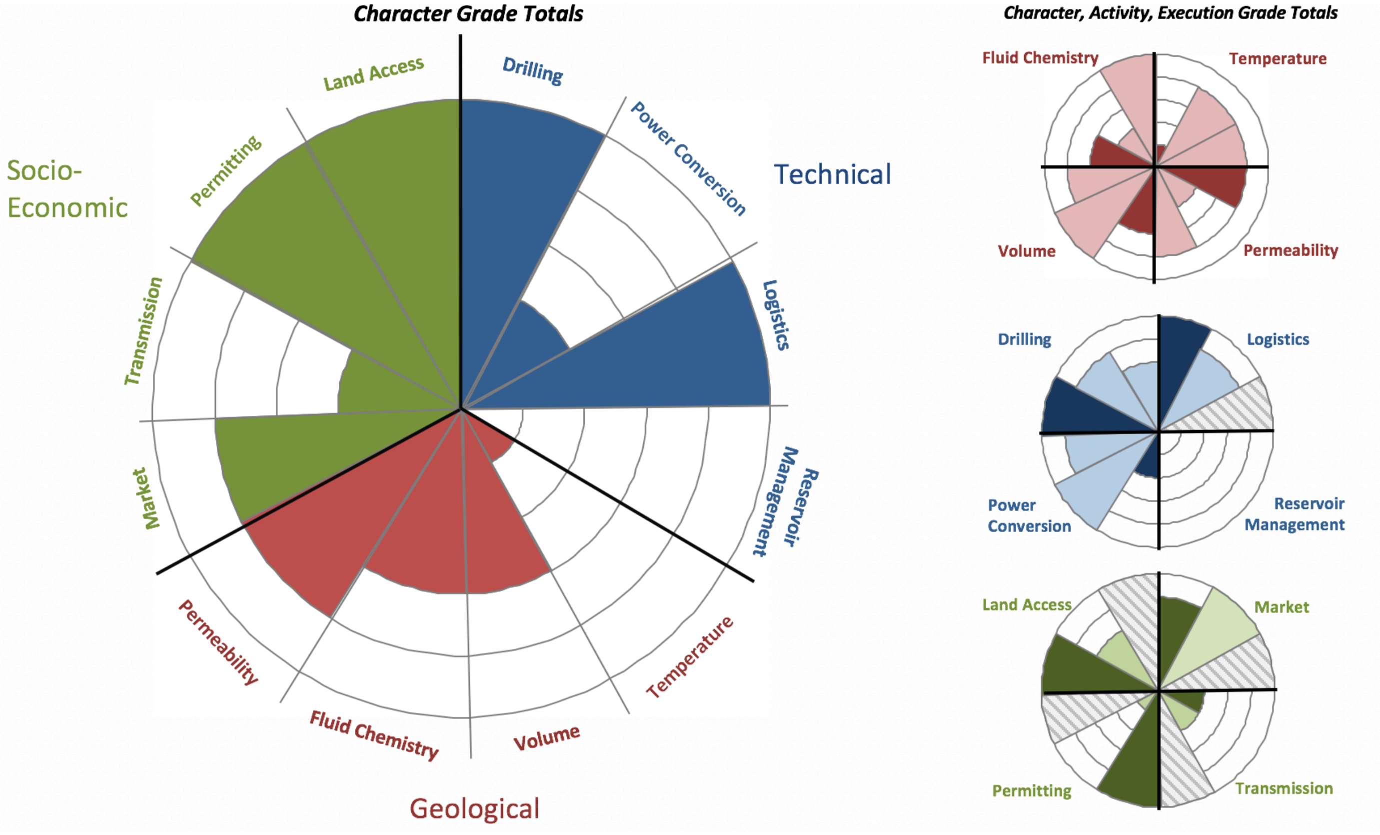

Figure 3. Case study GeoRePORT grade overview for Chena. Left: Character grade totals by geological, socio-economic, and technical attributes. Right: Attribute grades broken down into sub-attributes. Character of sub-attribute shown in darker colors; activity and execution indices shown in lighter colors (crosshatch = N/A).

Chena's geologic attributes are unusual: while permeability is high (grade B), fluid temperature received an E grade because of its low temperature of 74°C. Though the deeper reservoir is thought to have higher temperatures as estimated from geothermometry (Kolker 2008; Erkan et al. 2008), the fluids used for power production come from relatively shallow wells and do not attain these predicted reservoir temperatures. Because the volume of the system is moderate and the fluid chemistry is dilute but alkaline, both the volume and fluid chemistry received a grade of C.

In the technical category, Chena scored an A in logistics and a B drilling, both being relatively easy because of the nature of the site. In the power conversion category, a grade of D was assigned because the delta-T—the temperature difference between the heat source and the heat sink, which determines the efficiency of power generation—is less than 100°C for most of the year, with exceptions during the winter when ambient temperatures can dip below -40°C. There are no publicly available data for reservoir management activities at the site, hence the character grade for this attribute was omitted in Figure 3.

Chena scored well in most socio-economic attributes. Land access and permitting both received an A grade because the development is on private property and there are no permitting barriers. Market conditions are generally favorable and received a B; there is a strong demand for geothermal energy in this region resulting from high costs of power. In the transmission category, the project received a D because of the distance of the nearest transmission line; however, in this case the absence of transmission was a key driver of geothermal development because of high fuel costs in off-grid communities in Alaska (Kolker 2008).

4.2.3 Project Readiness

Drilling is complete at the Chena geothermal site and the Chena Hot Springs Resort is currently powered by the geothermal energy produced there. Alongside the many shallow wells, there are currently three generators installed that provide 680 kilowatts of energy. Given the level of maturity at Chena, the total project readiness is relatively high (Figure 4). Its geological readiness received a score of G5 ("examined"), meaning that two or more full-scale wells have been drilled and flow tested. Chena also secured a power purchase agreement, which allowed for a score of S5 ("secured") in its socio-economic readiness. Though the organic-Rankine-cycle-type generation units produce sufficient geothermal power for the developer's needs, they do not produce at or above the initial power production estimates because none of the drilled wells have achieved estimated reservoir temperatures of between 90°C and 130°C (Kolker 2008; Erkan et al. 2008). Hence, Chena scored a T4 grade ("confirmed") in its technical readiness, a step below the readiness grade of T5 ("demonstrated"), despite the fact that power has been produced from the geothermal site since 2006.

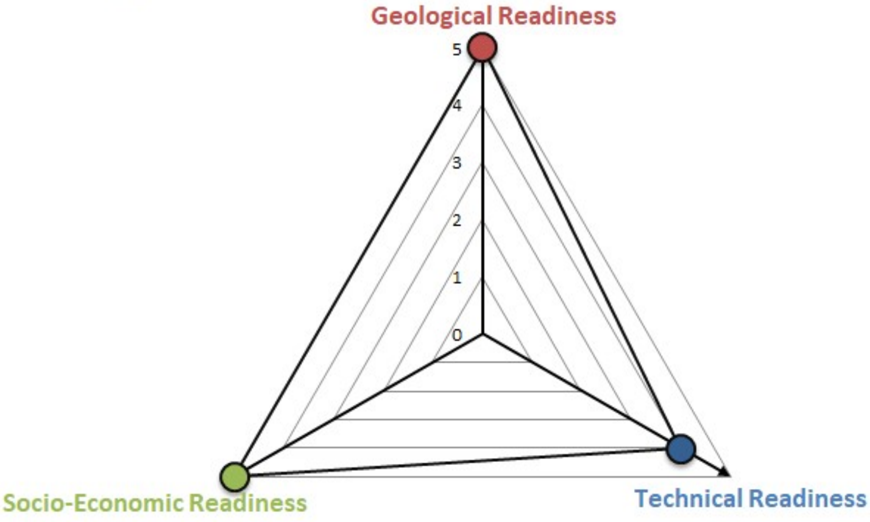

Figure 4. Chena geothermal site's total project readiness score, demonstrating G5 ("examined") geological readiness, S5 ("secured") socio-economic readiness, and T4 ("confirmed") technical readiness.

4.3. Dixie Valley Case Study

4.3.1 Site Description

The Dixie Valley geothermal area is near Fallon, Nevada, located in a 30-mile-long active fault zone. It is the hottest and largest known geothermal system in the Basin and Range Province (Blackwell et al. 2002). The heat source is deep circulation in a high heat flow, the highly fractured upper crust resulting from crustal thinning (Blackwell et al. 2009), or possibly accompanied by deep magmatic input (Jarchow et al. 1993).

The geothermal production area is divided into two groups of production wells, with injection wells located between the two production zones. Geothermal fluids with temperatures of ~285°C are produced from depths of ~2.8–3.1 km (Goff et al. 2002; Blackwell et al. 2009). As of 2009, a total of 20 deep drill holes and over 100 thermal gradient wells had been drilled at the site, with 63 megawatts electric of electric power being produced from only part of the identified geothermal field. The plant has been functioning for over 30 years. Between 1985 and 1998, a decline in reservoir pressure was observed, because approximately 31% of the fluid produced was lost to evaporation (Benoit et al. 2000). This was mitigated by a substantial augmentation to the existing reinjection scheme.

4.3.2 Resource Grades

Figure 5 shows the GeoRePORT resource grades for the Dixie Valley geothermal project. The project ranks moderate to high in most attributes, with a few exceptions.

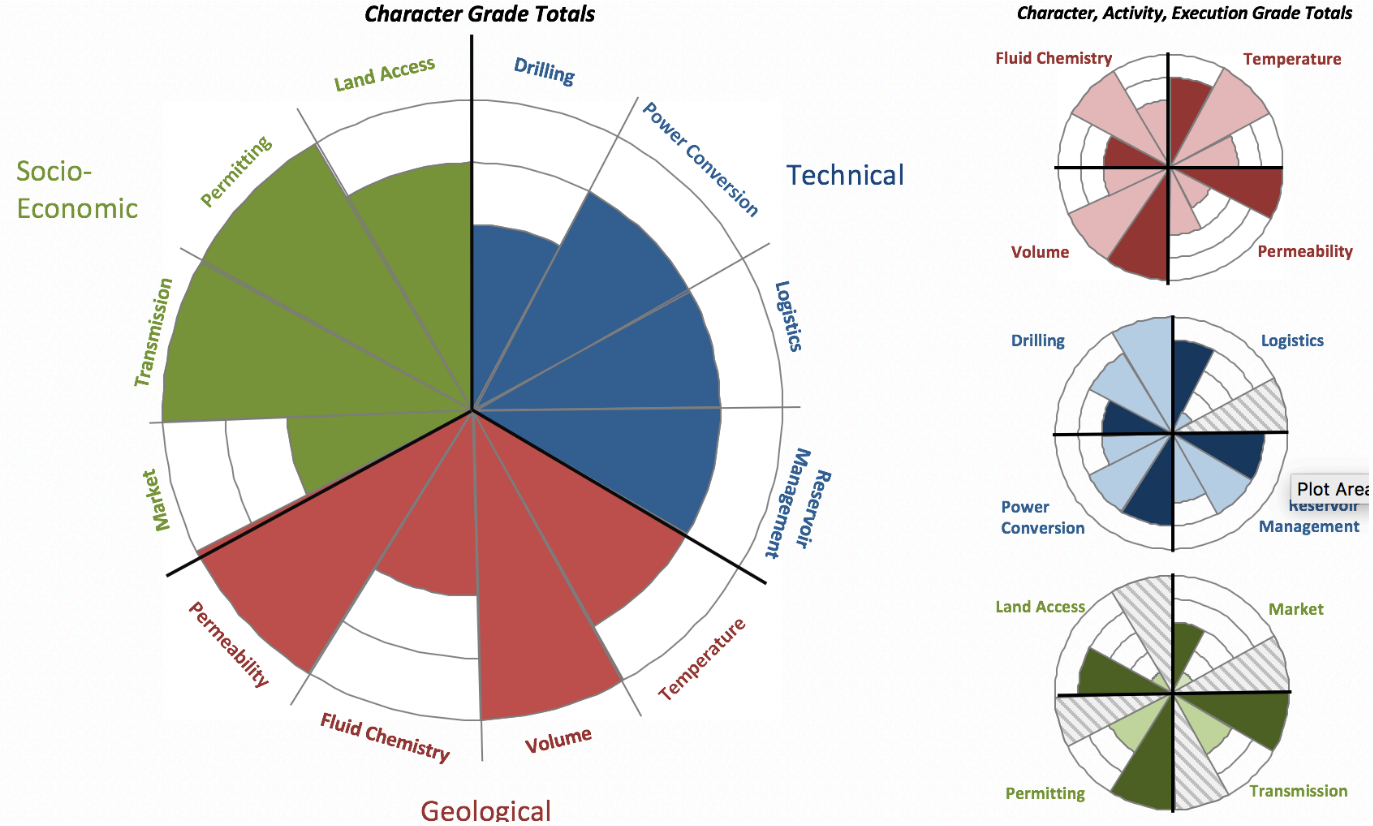

Figure 5. Case study GeoRePORT grade overview for Dixie Valley. Left: Character grade totals by geological, socio-economic, and technical attributes. Right: Attribute grades broken down into sub-attributes. Character of sub-attribute shown in darker colors; activity and execution indices shown in lighter colors (crosshatch = N/A).

Dixie Valley is a two-phase, liquid-dominated system with high temperatures, which results in a B in temperature (only steam-dominated resources get an A grade in GeoRePORT). Because of very favorable results from flow tests, the field received an A in volume. Dixie Valley also scored an A in permeability because of its association with a 1- to 2-km-wide fault zone, stretching over 20 km, that serves as the main conduit for geothermal fluid circulation (Blackwell et al. 2007). In contrast, the site only scored a C in fluid chemistry, because of challenging conditions for geothermal production (fluids are saturated to supersaturated in silica) (Goff et al. 2002). While this can be an issue for the power production process because of silica scaling in pipelines, the operator at Dixie Valley has mitigated this issue by isolating and marketing the silica (Bourcier et al. 2003). This again demonstrates the idea that lower grades (in this case, fluid chemistry grade of C) can be targets for some business models.

From a technical standpoint, Dixie Valley is more complicated. It is the only liquid-dominated field requiring augmentation of its injection program to maintain reservoir pressure (Benoit et al. 2000), resulting in a B grade for reservoir management. The use of air-cooled generators not only causes evaporitic cooling but also reduces the efficiency of power conversion, putting the power conversion at a B (though still favorable for power conversion because of the high resource temperature). Drilling conditions were given a C, resulting primarily from the depth of drilling (~3 km) and high temperatures. Logistics for the Dixie Valley are mostly favorable but not ideal because of the site's isolated location and its proximity to potential earthquake hazards. These combined factors result in a B grade.

In terms of socio-economic attributes, Dixie Valley scored A and B in permitting and land access, respectively. The state of Nevada is generally favorable to geothermal development in terms of these two attributes. Power transmission at Dixie Valley received an A, with nearby transmission lines currently delivering electrons to the grid. The C grade for market conditions reflects a mix of factors in Nevada affecting the power market. On one hand, there is strong current and long-term electricity demand in Nevada, and the geothermal project is eligible for both state and federal tax and financial incentives for renewable energy sources. On the other hand, the state of Nevada has purchasing requirements that favor other renewables over geothermal, such as a renewable portfolio standard that has preferential consideration or set-aside for nongeothermal renewables. Additionally, the regional wholesale price of power in 2015 was less than half the average levelized cost of energy for geothermal. It is worth noting that the market conditions reported here do not necessarily reflect the market conditions at the time of project commissioning over 30 years ago. The socio-economic grades reported for Dixie Valley all exhibit activity scores less than C, because they were sourced primarily from publicly available datasets and not detailed, site specific studies.

4.3.3 Project Readiness

The project readiness for the Dixie Valley geothermal site is shown in Figure 6. This plot indicates that all geological, technical, and socio-economic activities have been conducted and completed, with positive results for development. This is unsurprising considering that geothermal power production from Dixie Valley has been successfully underway for over 30 years.

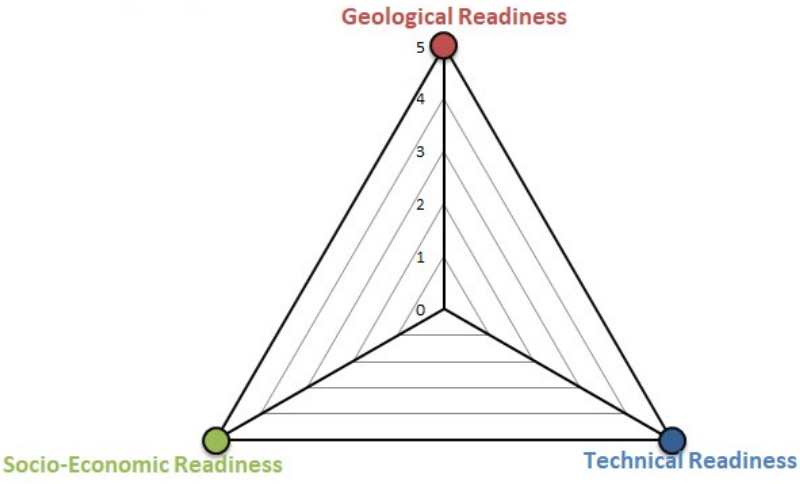

Figure 6. Dixie Valley Geothermal Field's total project readiness score, demonstrating G5 ("examined"), S5 ("secured"), and T5 ("demonstrated") readiness levels.

4.4 White Sands Missile Range Case Study

4.4.1 Site Description

The White Sands Missile Range (WSMR) reservoir was identified by a play fairway analysis in the Tularosa Basin of south-central New Mexico. This play fairway analysis was conducted by a team of scientists from the Energy and Geoscience Institute at the University of Utah, with on-site coordination operated by Ruby Mountain Inc. (Ruby Mountain Inc. 2017), and collaboration with other universities and government agencies around the United States. A geothermal reservoir was inferred through extensive greenfield exploration using data sets representative of heat, groundwater, and permeability. Fluid chemistries and reservoir volume are relatively unknown attributes at this time, given limited data availability and quality; however, temperature and permeability show positive indicators of a low-temperature, hidden geothermal system. Because data are limited, wells are shallow, and assumptions uncertain, many attributes of this reservoir cannot be graded with confidence.

4.4.2 Resource Grades

Figure 7 shows the GeoRePORT resource grade totals for the WSMR geothermal prospect. While its geologic and socio-economic attributes are generally favorable to development, the GeoRePORT highlights that this project's sparse data makes its technical attributes difficult to assess with a high degree of certainty at this time.

Geologically, the WSMR area's low activity indices reflect the fact that no wells have been drilled on-site, which means that most attributes are extrapolations from surface measurements. Reservoir temperatures have been estimated from geothermometry on surface water samples. Geothermometry estimates range between 90°C and 98°C, implying that the WSMR is likely to be a lower-temperature geothermal system, and was assigned a D grade in temperature, although the activity and execution indices for the temperature grade are low, indicating low certainty in these estimates. WSMR received relatively high character grades in the permeability, fluid chemistry, and volume, attributes—scoring B, A, and C, respectively. Again, it is important to note that the activity indices for all these parameters are low (d), meaning that there is substantial uncertainty in all these estimates. The volume estimates were based on local structure and stress field extrapolations, and the extrapolation of the reservoir's chemical character from surface samples can be misleading (e.g., if there has been substantial mixing with groundwater). This highlights how the GeoRePORT tool makes explicit the uncertainty of data in early stages of exploration.

The GeoRePORT for WSMR also shows the lack of data and the high degree of uncertainty in technical attributes. Drilling received a C because of a lack of nearby wells, but without solid knowledge of anticipated well depth. Several drilling sub-attributes did not have data available to assign grades, therefore the drilling grade is reported with a low activity index. A grade of E was assigned for the power conversion attribute due to the low resource temperature and likelihood of air-cooling. No data were available to assess reservoir management potential at this early stage of exploration. However, WSMR scored well in logistics, receiving an A, indicating that the site has no known logistical hurdles that would compromise access or project development.

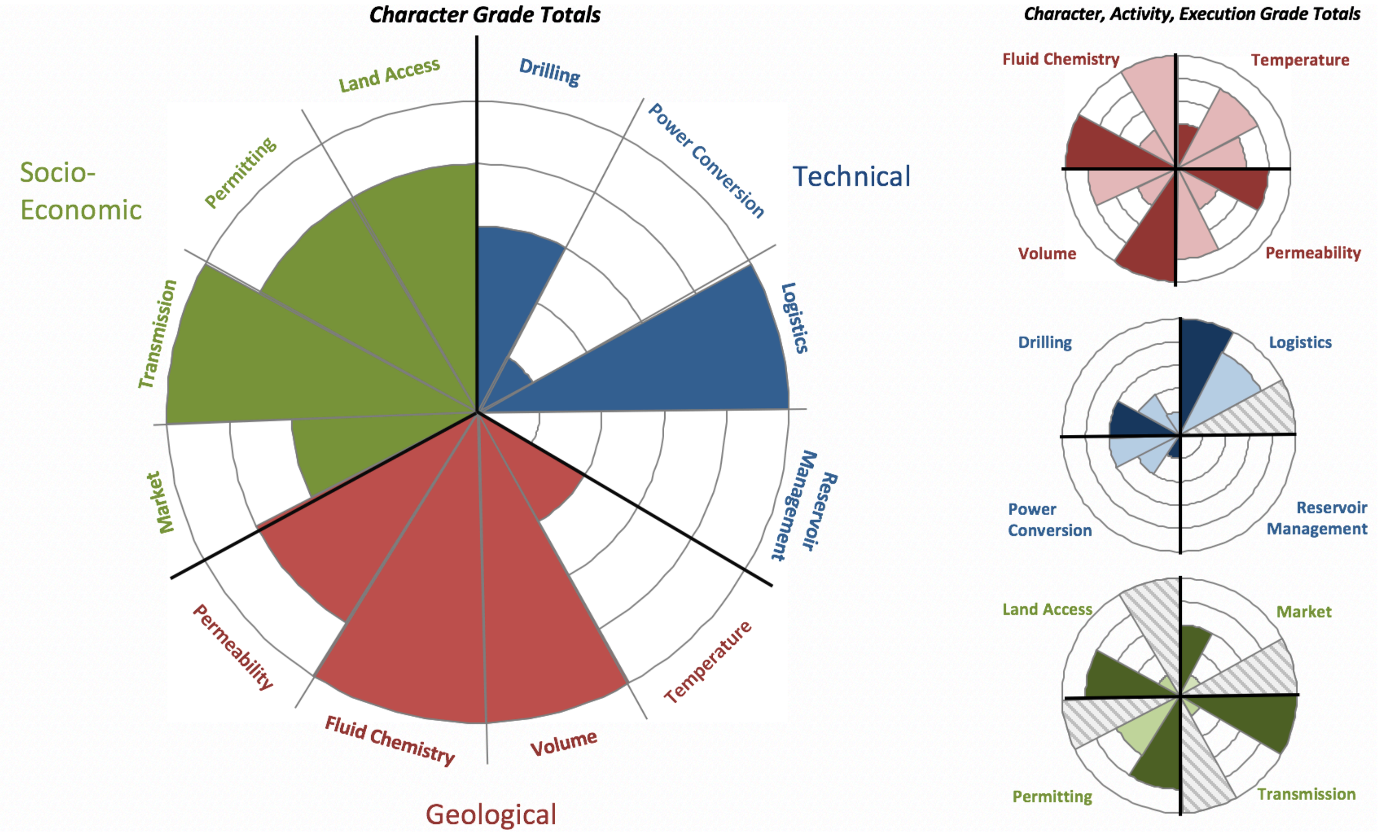

Figure 7. Case study GeoRePORT grade overview for White Sands Missile Range. Left: Character grade totals by geological, socio-economic, and technical attributes. Right: Attribute grades broken down into sub-attributes. Character of sub-attribute shown in darker colors; activity and execution indices shown in lighter colors (crosshatch = N/A).

With respect to socio-economic grades, WSMR received a B in land access and permitting, and an A grade in transmission. These high grades demonstrate characteristics such as little to no environmentally sensitive areas, manageable species concerns, and mature state and federal regulatory frameworks and review processes. The cost of electricity is highly variable in this area as a result of its isolation and high demand. A transmission line exists within 5 km of the site; therefore, transmission received an A, though the activity for this attribute is very low since data were all gathered from publicly available data, showing high uncertainty. The state of New Mexico has renewable purchasing requirements under the New Mexico Renewables Portfolio Standard, and although it identifies targets for solar and wind technology, it does not for geothermal (although it is a qualified renewable energy resource). For these and other reasons, market attributes received a C. Again, uncertainty is high on these attributes because they were estimated via public records and not via detailed site analysis.

4.4.3 Project Readiness

The total project readiness for the WSMR geothermal site is shown in Figure 8. The readiness level of this project is low. Its geological project readiness is level G2 ("inferred"), the technical readiness level is T1 ("undiscovered"), and the socio-economic readiness level is S0 ("unassessed"). The geological readiness reflects the fact that some geologic assessment of the resource has been conducted via desk studies and/or limited field campaigns, with a modest amount of acquisition of new data. The score of T1 in technical readiness reflects a very limited extent of site evaluation for the geothermal project. The socio-economic readiness level reflects the absence of project-specific studies on socio-economics for this site.

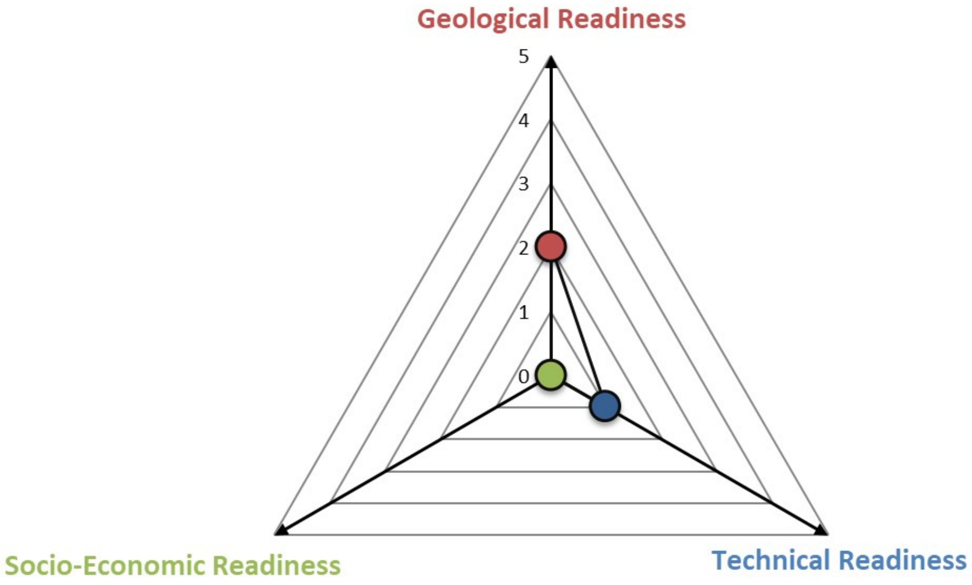

Figure 8. WSMR geothermal site's total project readiness score, demonstrating G2 ("inferred") geological readiness, T1 ("undiscovered") technical readiness, and S0 ("unassessed") socio-economic readiness.

5. Resource Grade Comparison

5.1 Summary Comparison

In this section, we present and discuss GeoRePORT resource grades for the four case study sites. Figures 9–11 depict character grades from the geological, technical, and socio-economic aspects of the GeoRePORT tool for the four case study areas. These figures depict character grades for each attribute, with "A" represented as the tallest bar. Bar transparency is scaled by activity grade from A–E grades and low to high transparency. Those attributes without bars indicate data gaps. These figures allow for a quick comparison of relevant sub-attributes among multiple sites.

5.2 Geological Assessment Tool Sub-attribute Comparison

Figure 9 illustrates not only geological character grades for the four case study sites (bar graphs) but also the relative uncertainty in the grade (color transparency). The degree of confidence is illustrated by indexing the *activity* (the type of methodology used) indices for each attribute.

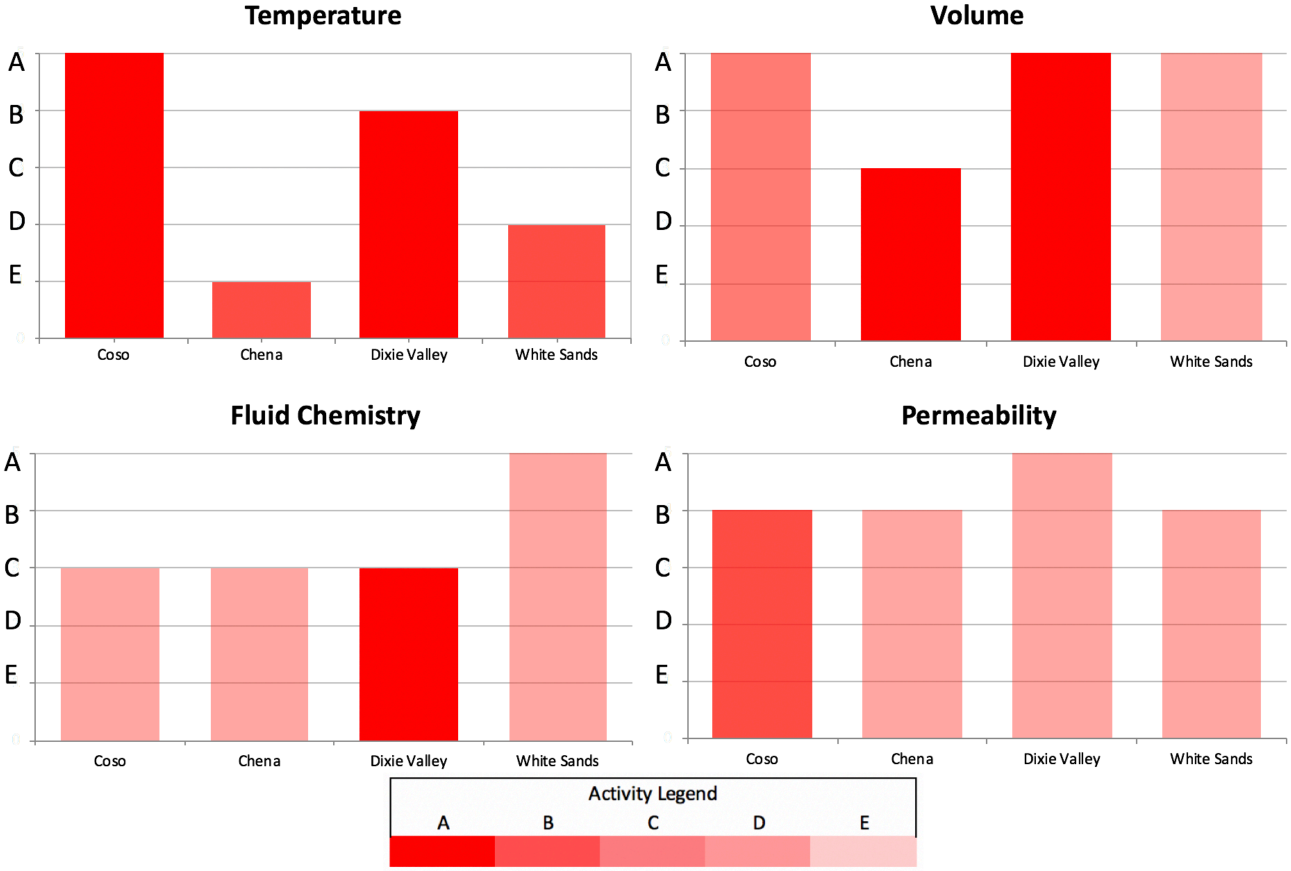

Figure 9. Geological sub-attribute comparison among four case study sites. More transparent colors indicate more uncertainty (i.e., lower activity index).

Figure 9 shows that while there is a high degree of variability in resource temperature for these four case studies, this attribute tends to have relatively high activity indices (i.e., low uncertainty). This is unsurprising because temperature is one of the first parameters targeted when evaluating geothermal resources; therefore, the methodologies have been better streamlined and/or more consistently applied. There is slightly less variability and slightly higher uncertainty in resource volume estimates. Contrarily, fluid chemistry and permeability display generally lower activity indices (less certainty) for nearly all of the four case studies. Interestingly, the chemistry grades for Chena, Coso and Dixie Valley are all grade C, despite the vastly different chemistry characteristics. Recall that Chena's fluids were alkaline, Coso's fluid had high silica and total dissolved solids concentration, and Dixie Valley's fluids are saturated to supersaturated in silica. This demonstrates how GeoRePORT normalizes grades between different geological attributes within the fluid chemistry sub-attributes (Young et al. 2016b). The geological assessment tool framework gives the user flexibility to identify which aspect of the system will drive the character grade, streamlining assessment of areas with different fluid geochemistry.

5.3 Technical Assessment Tool Sub-attribute Comparison

Figure 10 illustrates not only technical character grades for the four case study sites (bar graphs), but also the relative degree of uncertainty in the grade (color transparencies).

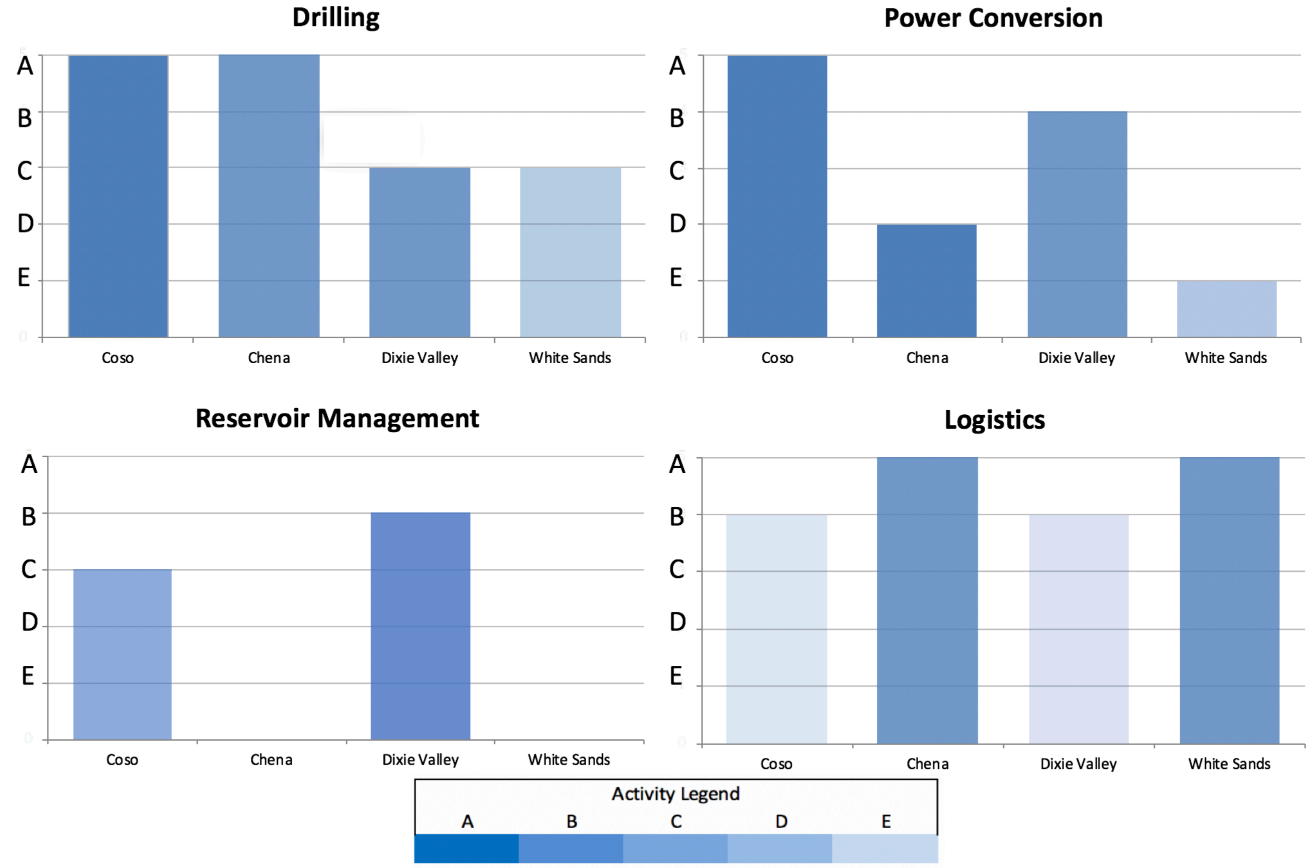

Figure 10. Technical sub-attribute comparison among four case study sites. More transparent colors indicate more uncertainty (i.e., lower activity levels).

Coso, Chena, and Dixie Valley all exhibit higher technical grades and generally higher activity indices than WSMR (Figure 10), the case study with the lowest readiness level (Figure 8). Many of the data needed to assign technical grades may not be available in early stages of exploration within a reasonable range of certainty, hence the gap shown for WSMR reservoir management grade. In the case of Chena, this same gap exists due to a lack of publicly available data available to the authors for reporting.

Figure 10 shows that logistical factors for all the four case studies are generally manageable, but there is a high degree of uncertainty in these assessments, even for developed projects. This is due to the fact that we used publicly available information for these reports; project developers with inside knowledge of these sites would almost certainly be able to report these factors with higher certainty. The four projects display variable grades in terms of drilling attributes, but these attributes have generally higher certainty. The difficulty in obtaining public data in the power conversion and reservoir management parameters is reflected by the high variability and moderate to high degree of uncertainty.

5.4 Socio-Economic Assessment Tool Sub-attribute Comparison

Figure 11 illustrates the socio-economic grades for the four case study sites (bar graphs), as well as the relative degree of confidence in the grade (color transparency).

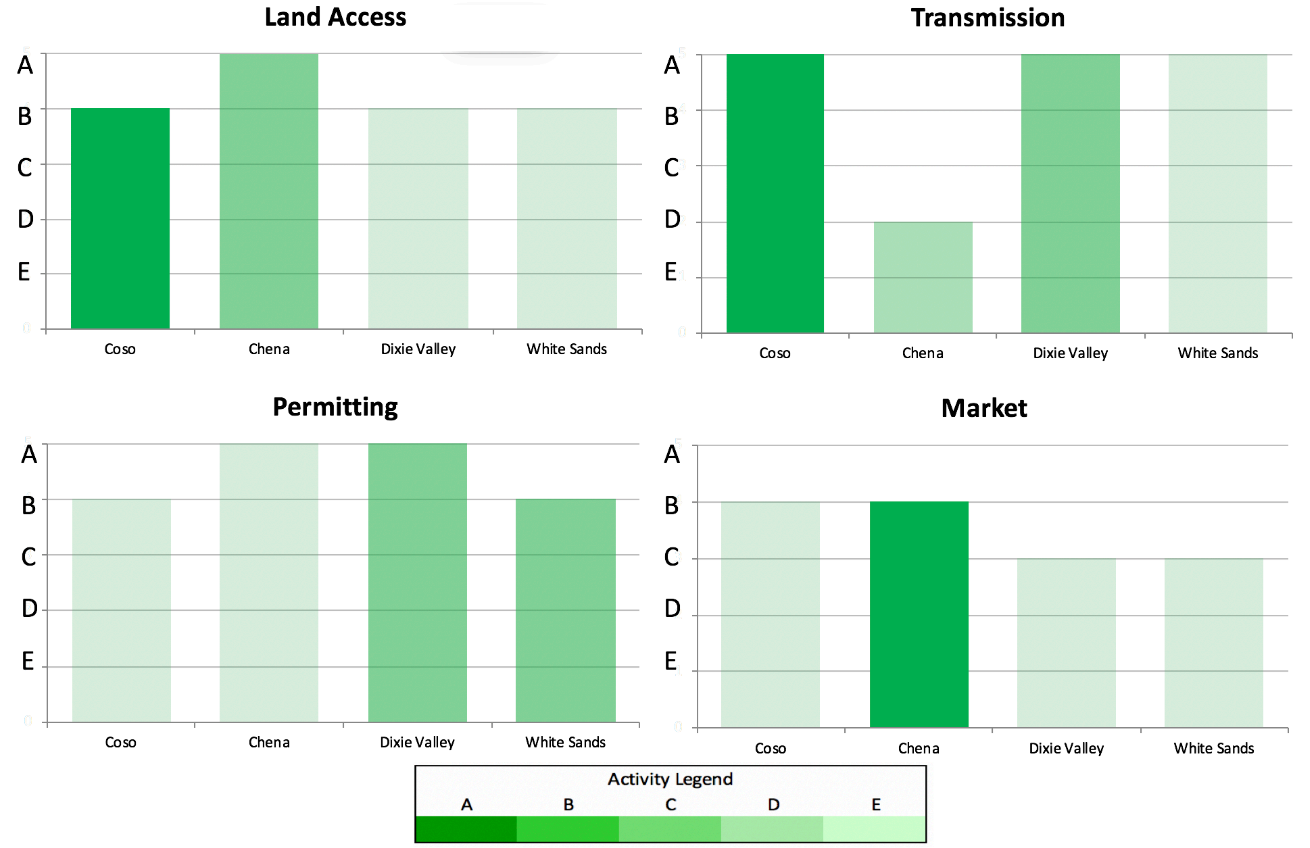

Figure 11. Socio-economic sub-attribute comparison among four case study sites. More transparent colors indicate more uncertainty (i.e., lower activity levels).

Figure 11 shows that most of the case studies rank relatively high in the socio-economic attributes, even the undeveloped WSMR site. This may reflect the fact that socio-economic attributes do not typically require site development and evaluation prior to assigning grades, and therefore can be evaluated in projects with low readiness levels (though at low certainty levels as indicated by the transparencies in Figure 11). Baseline maps for socio-economic sub-attributes were developed for the GTO GeoVision Study and are available on NREL's Geothermal Prospector tool, making assessment of these attributes (using publicly available information) relatively easy. These maps were useful in assessing undeveloped and younger sites; however, they are less appropriate for older projects because they reflect present-day conditions and not conditions at the time of project development. For example, Dixie Valley received a C grade in market, despite the fact that geothermal power has been delivered to the grid from this site for over 30 years. This is because data used in these assessments were taken from public records and reflect present-day conditions—in which geothermal fares poorly in the face of low fuel costs and other factors—and not market conditions at the time of project development. This then, is a better indication of the market potential for any additional power developed at this location, though the transparency in Dixie Valley's market grade reflects a moderate uncertainty in the in the methodology used (in this case, that the given conditions were estimated through public records).

Chena received a D in the transmission category because of the lack of nearby transmission lines. However, this was not a hindrance to development; quite the opposite—the absence of transmission was in fact a key driver of project development because of high fuel costs for the off-grid community at Chena Hot Springs Resort. This illustrates a point made earlier in Section 2.1: low grades do not necessarily imply that projects are not feasible.

6. Discussion

One observation that emerges from examining the project readiness plots is that commercial geothermal power projects do not necessarily need to be at T5 in order to be developed. Three out of four case studies are already producing geothermal power. While Coso and Dixie Valley are "ready" (that is, all geological, technical, and socio-economic activities have been conducted and completed that would normally lead to project development), the Chena site has been developed despite its ranking at a T4.

The two case studies of older projects, Coso and Dixie Valley, highlight the usefulness of developing activity and execution indices alongside resource grade. With older projects, resource evaluation activities were carried out prior to certain refinements to many of the widely used exploration techniques. For example, volume estimates made prior to the 2000s frequently rely on the U.S. Geological Survey heat-in-place method, which has since been reevaluated in light of systematic overestimates of resource volume (Garg and Combs 2015). Geochemical sampling techniques, geothermometry calculations, and the way certain geophysical data sets are interpreted have also changed significantly since the 1970s and 1980s. The use of old and/or outdated methodologies are brought to light by the activity and execution indices of projects in GeoRePORT. Keeping those indices separate from resource grade is an elegant way to avoid downgrading older projects, where the data quality may be compromised even though the resource may be high grade.

Examination of the four geologic sub-attributes (temperature, volume, fluid chemistry, and permeability) shows that the fluid chemistry and permeability generally display lower activity and execution indices (less certainty) than temperature and volume. This may reflect a general industry-wide need to streamline and/or improve methodologies for measuring fluid chemistry and permeability; or it may be a reflection that these data simply are not as publicly reported. This may be less important for fluid chemistry because it is not as much of a showstopper for development as other resource attributes. For example, Dixie Valley scores a C on the fluid chemistry attribute, but this has been mitigated. Permeability, on the other hand, is notoriously difficult to estimate even in developed fields; however, this parameter has high impact on resource capacity and sustainability (Sanyal 2004). This implies a need for industrywide improvement in estimating and measuring system permeability for a given geothermal field.

The high degree of uncertainty and absence of data in the reservoir management attribute may reveal something about the way these data are collected and reported. Younger and/or less developed projects do not appear to collect these data. Older projects may receive low reservoir management grades due to complex reservoir behavior in response to long-term production, demonstrating that grades can change over time. Geothermal systems produced for long periods of time often experience changes to the reservoir conditions (typically pressure declines).
Taken together, these case studies show that reservoir management parameters may be under-reported and even overlooked in many geothermal operations.

Chena's GeoRePORT demonstrates that low-graded resources can have development potential. Figure 3 shows that Chena's low-temperature resource is utilized despite low-efficiency (but technologically possible) power conversion because technical and socio-economic conditions are very favorable, including the absence of a transmission line. Similarly, Dixie Valley's GeoRePORT demonstrates how the operators took advantage of its low fluid chemistry grade to produce and sell silica.

Many of the GeoRePORTs show a lack of publicly available data, and the high uncertainty of several of their attributes. This illustrates the power of GeoRePORT to distill the key information from a given geothermal project. It also shows how the tool illuminates otherwise concealed pieces of the story, such as missing data, key drivers, and uncertainty.

7. Conclusions and Next Steps

Initial progress has been made in developing a geothermal resource reporting methodology to aid in reporting for geothermal development. This paper briefly summarizes and compares four geothermal sites and their GeoRePORT grades and provides the framework for how these concepts are recorded at different stages of geothermal exploration and development.

Close examination of trends within GeoRePORT's outputs for these four case studies has revealed certain industrywide areas for improvement and/or streamlining (such as permeability estimations/measurements and reservoir management reporting). These case studies also illustrate the success of GeoRePORT's activity indices in making explicit the degree of uncertainty in the data. This is an important part of de-risking geothermal development.

Future work includes updating the GeoRePORT website, publishing the updated assessment tools, and completing the case study document. Additional future potential expansions include adapting the socio-economic tool for international use, developing a resource size assessment tool, and making adjustments to allow for reporting of low-temperature direct-use and enhanced geothermal system projects. The development of a resource size tool would allow GeoRePORT grades to be translated into quantifiable outputs, such as megawatts electric/megawatts thermal potential, power conversion efficiency, levelized cost of energy, and/or other such numbers that would be highly useful to the geothermal industry. Additional case studies should be completed as the protocol would benefit from a large library of GeoRePORT case studies to better show its effectiveness at characterizing geothermal reservoirs of a wide variety of types. The authors welcome feedback and suggestions from all users and potential stakeholders of the protocol.

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