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Refining the Definition of a Geothermal Exploration Success Rate

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ABSTRACT

The geothermal exploration process impacts project development timelines, costs, and overall perceived risk. However, the success in the exploration phase of a geothermal project—and the calculation of a success rate—is universally ill-defined. In previous studies, the success of a geothermal process is loosely defined as the number of wells that result in commercially-viable production. This work focuses on refining the definition of success for the exploration process to represent an upper bound to the likelihood a project will proceed into commercial production. This research examines the topic of success from both a top-down and bottom-up approach: a review of previous assessments of success rate that identifies common conditions leading to successful exploration, and a project-level review of geothermal sites in the western United States focused on decision points in the geothermal exploration process. The analysis not only considers the impact of factors outside of the geothermal reservoir (i.e. delays due to financing or permitting), but also touches on the length of the exploration process and the symbiosis between exploration methods. Using a combination of these analyses, future work will investigate which levers within the geothermal exploration process have the strongest influence on overall project success.

1. INTRODUCTION

The Department of Energy's Geothermal Vision Study aims to understand the current landscape of geothermal development in order to develop future scenarios for growth of the geothermal industry. As part of this effort, this exploration task force has identified that an understanding of the current industry probabilities of project success is a crucial piece to evaluating the current the business as usual situation. By developing a methodology that investigates the current exploration decision points of the geothermal industry, this work seeks to identify ways to improve exploration success in the future, which may then increase deployment of geothermal resources in the US.

Confirmation and exploration well drilling and the associated exploration methods used to locate a geothermal resource are attributable to nearly 40% of the cost of a geothermal project (International Finance Corporation (IFC), 2013). However, a single project unavoidably incurs multiple phases of drilling and exploration in order to find a resource (exploratory drilling) and to confirm that a resource exists on a commercial scale (confirmational drilling). At each step in the process, the possibility exists that the project will be abandoned entirely – or revisited by a new owner.

All previous studies on geothermal drilling risk and success rate have focused on defining "success" by using a combination of qualitative and quantitative performance criteria that must be met to continue with project development. These criteria are not universally accepted for multiple reasons, such as:

- *Change in Intended Use*: A well originally intended for power production could be repurposed as an injection well.
- *Change in Technology:* Advances in technology, such as in binary lower temperature limits and downhole treatments, may allow for production of previous wells that were once technically infeasible.
- *Change in External Economic Conditions:* A well's production characteristics (such as flow rate, temperature, corrosion/scaling, potential or gas content) or technology may not currently meet a project developer's economic hurdles, but may be adequate in the future if market conditions change (e.g. if power prices increase).
- *Differences in Internal Developer Economic Conditions*: A well's production characteristics may not fit the financial profiles of its current developer but could be attractive for development by a different developer.
- *Changes in Available Prospects:* As the most attractive prospects are tested and developed, remaining prospects with the same geologic and return profiles become scarcer.

All previous studies on geothermal drilling risk and success rate known to date have focused on defining success rate by the single probability that a full-size production well meets sufficient performance criteria to continue with project development. This work seeks to define a conservative probability of exploration success as the combined probability of all stages in the project's workflow. Unlike today's measure of success, this probability aims to represent the average likelihood that the development project will not be continued (whether due to insufficient exploration results or the lack of development resources). Nevertheless, this "project oriented" success rate should not be substituted for an investor's success rate for a geothermal project; this rate would typically be lower to account for the idiosyncrasies of the specific project and developer.

We recognize that forecasting risk at any specific project is often a combination of data, experience, and educated guesses. Where possible, this work attempts to quantitatively construct the probabilities at each stage using empirical project or well data. While this work may aid the development of estimates at future project sites, the intent of this analysis is primarily to develop a standard definition of success rate that allows comparability across projects and developers in the industry. By refining the definition of a geothermal exploration success rate to include transparency into decision points, this work will aid in the development and improvement of project risk assessments (see diagram in Appendix, Deloitte 2008). Since investor confidence of geothermal project development estimates is understood to be prohibitively low during these early phases due to a lack of transparency into a project's uncertainty, future implications of this work may be an improvement in investment decision making.

2. METHODS OF DEFINING SUCCESS

In general, a geothermal project under development is considered successful if the project proceeds into commercial production. Embedded in this definition are three conditions:

- The area (and/or well) meets minimum reservoir performance criteria (e.g. temperature, flow rate) for its intended use.
- The area meets minimum operational feasibility criteria for power project development (e.g. lease availability, transmission access, and power purchase agreement partners).
- The developer is able to secure financing for further development, including any additional exploration and confirmation phases.

To highlight the challenges in addressing these conditions at each development phase, the following section reviews the assumptions used in previous studies of success rate. The latter half of the section presents assumptions and boundaries of the methodology used for this paper's comprehensive exploration success rate.

2.1 Methods of Previous Studies

Previous assessments have defined the success rate as the proportion of successful full-size production wells out of the total number of wells attempted (IFC, 2013; Sanyal and Morrow, 2012; Shevenell, 2012; Combs, 2006). Simplifying assumptions that address the conditions listed above have been developed, with mixed results:

- ***Lower limit to a well's power generation capacity***: Previous reports suggest that wells under 3 MWe are not successful for use as production wells (IFC, 2013; Sanyal and Morrow, 2012). To eliminate temporal and geographic homogeneity of developer project criteria, these studies placed a 3MW floor on the well capacity in order for it to be categorized as successful. However, wells under 3 MWe could be categorized as either successful or unsuccessful, depending on the intended use (IFC, 2013).
- ***Adjustments for changes in intended use:*** The International Finance Corporation (IFC) rates any change that led to a well being used in some capacity (i.e., a well originally drilled as a production well used as an injection well) as a success (2013). In contrast, the existing version of the Geothermal Electricity Technology Evaluation Model (GETEM) used by the U.S. Department of Energy (DOE) Geothermal Technologies Office (GTO) does not consider changes in intended well use after drilling to be relevant to calculations of success rate; any wells deemed unsuccessful are assumed to be abandoned entirely.

Even though a resource is not discovered, exploration wells can still be deemed "successful" if they provide the information needed to help characterize the resource. However, the boundary of what encompasses the exploration phase, including the exploratory phases of drilling, is also contentious. In GETEM, exploration drilling success is based on the number or total cost of exploration wells drilled prior to proceeding to drill a well sufficient for production (i.e. all wells in the exploration phase smaller than a full diameter well). For example, a deep exploration well may be considered to be a partial success if it encounters high temperatures but does not intersect permeable fractures. After exploration drilling, GETEM has a confirmation well drilling phase, based on the number of wells required to confirm production capacity estimates, with a separate confirmation well success rate. Other published reviews of exploration success appear to be more closely related to GETEM's confirmation phase. IFC (2013) and Sanyal and Morrow (2012) defines the exploration phase as the first five wells drilled, regardless of size.

A complication resulting from these assessments' definitions is that the success of an exploration program is often determined by the ability to replicate drilling success. A given exploration well may find both temperature and permeability (which would make it a successful discovery well) but subsequent wells may have difficulty in replicating this success, resulting in a cancelled project. For example, this scenario was the case at Baca (Goldstein et al., 1982; Goldstein & Tsang, 1984) and Rye Patch (Benoit, 1994).

2.2 Method Proposed In This Analysis

The geothermal exploration process results in a final decision to drill only after passing multiple go/no go decision nodes (Figure 1). When combined, these decisions incorporate the operational uncertainty of receiving leases and permits, the geologic (and execution) uncertainty of finding a resource by exploration methods, and the financial uncertainty of funding additional exploration and development activities.

Following the chain rule for the joint probability of multiple conditional events, Equation 1 for the project success of exploration (S^E) represents the combined probability of an exploration project with a lease reaching the production drilling stage:

Equation 1: $$P(S^E) = P(\text{P and EM and D}^\text{E}) = P(\text{P}) * P(\text{EM}|P) * P(\text{D}^\text{E}|\text{P and EM})$$

where P(P) = probability of receiving permitting, P(EM) = probability of continuing the project after applying exploration methods to develop a conceptual model, and $P(\text{D}^\text{E})$ = probability of continuing the project after exploratory drilling.

The $P(\text{S}^\text{E})$ of Equation 1 assumes the probability of receiving a lease is a prior condition to a project being able to apply for (and receive) permitting. This assumption may be an oversimplification and not a legal requirement. Many regional exploration activities are conducted on unleased lands; this work helps identify which areas are most prospective and where leases should be acquired. However, a company is usually not willing to invest in significant exploration activities if they do not already possess the lease rights to the area.

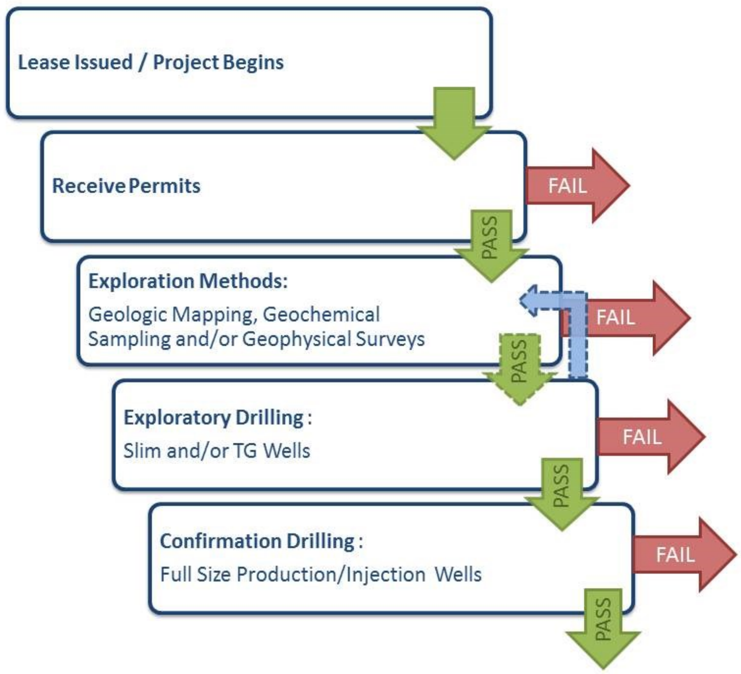

Figure 1: Diagram of decision nodes within a geothermal exploration project leading to resource production drilling. The option to abandon the project at each stage is depicted by the red arrows. The option to continue is represented by the green arrows. Options which may occur but which vary on a project by project basis (e.g. the choice to drill slim holes, or additional exploration after exploratory drilling) are represented by dashed arrows.

On the other end of the exploration process, the probability associated with project continuation from full-size production drilling may or may not be conditional on knowledge from the prior well drilled. If a well succeeds in meeting performance criteria because adjustments were made to the drilling approach or location, the "learning curve" effect would suggest each drilling event is conditional on the knowledge gleaned from the prior well. Conversely, if a second well is drilled based on the same prior information as the previous well, the drilling approach would suggest each drilling event is independent. Sanyal and Morrow's (2012) investigation of the impact of learning from prior drilling experiences on the drilling success of additional wells supports a conclusion that drilling results are independent events during the exploration phase (as they define it); there is minimal improvement in success during the first five wells drilled. The following equation provides transparency into the combined probability that a project will proceed past any given drilling event, assuming information from the prior event is not considered in the next drilling decision:

Equation 2: $$P(\text{S}^\text{C}) = P(\text{P and EM and D}^\text{E}\text{ and D}^\text{C}) = P(\text{D}^\text{C}) * P(\text{P and EM and D}^\text{E}) = P(\text{D}^\text{C}) * P(S^E)$$

where $P(\text{D}^\text{C})$ = probability of continuing the project after full-size production well drilling.

The conditional joint probability in this equation above, $P(\text{S}^\text{C})$, is not a universally true measure of the success rate of geothermal The conditional joint probability in this equation above, $P(\text{S}^\text{C})$, is not a universally true measure of the success rate of geothermal project exploration for any individual project, but provides an expectation ceiling. Note that for any given stage of drilling (exploration and confirmation), a project does not need to have 100% drilling success for the project to proceed to the next phase. Each company may have different thresholds of risk (i.e., number of drilling failures) that they are willing to accept for a given project.

The following sections discuss a potential approach to calculating this representative success rate for the geothermal industry, with the intention to vet this proposed probability-based method. Since no single repository of project information was identified that could satisfy all calculations for recent projects, this discussion includes a description of the datasets used for each of these probabilities. Where data were available, we examined the average of information over the last 10 years (e.g. 2005-2015), or the longest timeframe available in these datasets. Our later discussion of these examples addresses how our methods compare to probabilities calculated from a previous project-level study of exploration progress (Combs, 2005).

2.2.1 Leasing and Permitting

The Bureau of Land Management's (BLM) Land and Mineral Legacy Rehost 2000 System (LR2000) logs the existence of both non-competitive and competitive geothermal leases, as well as all associated permits, for all states. These records include all activity associated with these requests, such as when the permit was awarded, and includes comments on these activities, such as when additional information is required.

Permit applications include both of the following possible reasons for rejection and/or delays:

- Operator will not meet the paperwork requirements (e.g. the application does not provide sufficient information, or information is missing), and/or
- Area itself cannot pass the regulatory limits for exploration (e.g. the environmental impact statement (EIS) indicates the effects to an endangered species would be too significant to continue with exploration tests of any kind).

As a result, the "successful" permitting probability necessary before proceeding with exploration methods (i.e. P(P)) can be calculated for the industry as:

Equation 3: P(P) = (number of permits approved)/(total number of permits requested).

For the purposes of this current demonstration, only geophysical exploration permits with the last recorded activity between 2005-2015 are included in the P(P) ratio. Future work is necessary to investigate the relationships among different types of permits (such as projects that require a categorical exclusion (CX) versus an EIS), the impact of the NEPA process, and whether these probabilities differ by state. Future work should also investigate the difficulty and prevalence of permitting for private landowners, who may not be subject to the permitting requirements of BLM implied currently.

2.2.2 Exploration methods

Very little data are available on the exact types of research methods employed by geothermal developers during the exploration process, or the value of these methods in improving the likelihood of finding a geothermal resource. General instrumentation and methods can be gleaned from resource studies, such as Benoit (1994), Combs (2006), Shevenell & Zehner (2011), and Shevenell & Blackwell (2011). As a result, this analysis discusses project data from the Public Interest Energy Research (PIER) report issued on behalf of the California Energy Commission (GeothermEx, 2004). Due to the small sample size for any individual exploration method, the probability of proceeding with a project beyond exploration research is calculated as:

Equation 4(A): P(EM) = (number of projects proceeding to exploration or production drilling)/(number of projects with exploration methods).

To provide a more recent estimate of exploration method success, the Geothermal Energy Association (GEA)'s Annual Report was considered for its status of listed projects (2013, 2014, 2015) to calculate P(EM) from project records. GEA's Project Development Phase system considers a project to have applicable permits (and leases) if it qualifies for the Phase I categorization, and qualifies for Phase II only when drilling commences. For the purposes of this analysis, the success rate of exploration methods is approximated in a period as the probability:

Equation 4(B): P(EM) = 1-[(number of projects rejected or abandoned at Phase I)/(total number of projects categorized in Phase I)].

This probability is best calculated as an inverse because the timeframe of exploration methods differs significantly between projects. For example, two projects that receive permits at the same time may or may not be at a comparable stage in information gathering a year later to determine whether to proceed to drilling. Had all projects been considered, the rate would include the number of projects that are abandoned/rejected from any further development as well as the number of projects that have not yet succeeded (i.e. projects which are delayed or still undergoing exploration research, but not yet abandoned).

2.2.3 Drilling

The Nevada Bureau of Minerals tracks well-level records of temperature gradient, slim hole, production, injection and observation well drilling permits, as well as the intended use and dates associated with drilling. These records are kept confidential for the first five years after permits are initially issued. While other states have similar data systems for drilling records, such as California's Division of Oil, Gas, and Geothermal Resources (DOGGR), Nevada's records provide a level of detail on changes in intended use that makes this dataset more representative of both production and exploratory drilling success. For the purposes of this analysis, the success rate of a project's exploration drilling is approximated from data between 2005 and 2015 as the probability:

Equation 5(A): $P(D^E_w)$ = (number of operating or idle wellsfor exploration) / (number of wells permitted and drilled for exploration) for all wells w permitted for slim hole or thermal gradient hole drilling.

Since a well used for exploration (e.g. slim hole) is independent from a full-size production well, these probabilities are based on different samples. However, the projects themselves can be related; the choice to proceed to production drilling is dependent on a developer's knowledge of the project gained from exploration drilling. To capture this relationship, the probability that a project proceeds past exploration drilling can be approximated as the subset of projects with exploration drilling that also carried out full-size production drilling:

Equation 5(B): $P(D^E)$ = (number of projects with permitted and drilled for both production and exploration) / (number of projects with operating or idle wells permitted and drilled for exploration)

Similarly, the success rate of a project's production well drilling and progress onto commercial power development is approximated from data between 2005 and 2015 as the probability:

Equation 6(A): $P(D^C{}_w)$ = (number of wells in use for industrial production)/(number of wells permitted and drilled).

for all wells w permitted for production drilling.

Equation 6(B): $P(D^C)$ = (number of projects with commercial power under construction or installed) / (number of projects with operating or idle wells permitted and drilled for production)

The above approaches may either over or under-estimate the true probability of success due to a lack of insight into the individual project decision making. For example, this work assumes the number of idle wells are included as "successful" since the wells remain available for use; if the well were truly a "failure" for exploration purposes, it is assumed the well would be plugged and abandoned. To prevent artificially low measures of success, these calculations do not include the number of sites that were permitted but never drilled (which typically occurs for developers to mitigate permitting delays and hedge exploration site uncertainty).

3. PRELIMINARY FINDINGS

As previously defined, the proposed rate of success $P(S^C)$ is a combination of the probabilities of permitting, exploration methods, exploration drilling, and production drilling. Preliminary estimates of these individual probabilities of success from the datasets described above are:

$P(P) = 87.5\%$ (see Section 3.1)

$P(EM) = 60\%$ (see Section 3.2)

$P(D^E) = 31\%$ where $P(D^E{}_w) = 42\%$ (see Section 3.3)

$P(D^C{}_w) = 40\%$ (see Section 3.4)

If one can assume that projects move forward with development after finding successful production wells, regardless of the success rate in finding these wells, then $P(D^C)$ can be roughly approximated 1 and the total conditional probability could be estimated as:

$$P(S^C) = P(\text{P and EM and } D^E \text{ and } D^C) = 87.5\% \times 60\% \times 31\% = 16\%$$

Since these individual probabilities are provided primarily as a demonstration of this method, the above joint probabilities are calculated for illustrative purposes only; these current values are not meant to be definitive representations of the behavior of the industry. The above value for exploration project success is indeed lower than initial industry feedback of green field success rates of 25%. Instead, the expected value may be closer to the combined probability of success when considering exploration well drilling:

$$P(S^E) = P(\text{P and EM and } D^E{}_w) = 87.5\% \times 57\% \times 42\% = 21\%$$

As mentioned previously, this work seeks to vet an appropriate methodology that accurately represents results in the field; thus, further work and input will be integral to developing a consensus on the findings above.

3.1 Success of Leasing and Permitting

Leasing and permitting activities within the BLM are tracked by the date of the last activity related to the item. This work considers geophysical exploration permits with recent activity between 2005 and 2015. Within these records, the BLM also records the type of recent action, which may be that the permit is issued, that the application is rejected, or that the application has expired. To investigate challenges related to permitting, the same sample dataset of activity on geothermal exploration permits for the same locations was used. Of 24 exploration permit applications for land greater than one acre with activity between 2005 and 2015, three project applications (12.5%) were terminated (i.e. the applicant ended the request) or denied (i.e. BLM ended the permit application). Six other applications were rejected because the activity was deemed to be casual use, and thus did not require a permit; thus, these applications were considered successful because the project was able to proceed. With these factors in consideration, the likelihood of receiving a permit—when it is necessary—is determined to be 87.5%. Future work is planned to investigate whether this likelihood is consistent across different types of exploration permits, and further work is warranted to review the time required for obtaining permit types.

3.2 Exploration methods

Very little data have been systematically compiled and published that provide insight into all of the methods used during the exploration process. One example, the Public Interest Energy Research (PIER) dataset compiled in 2003 (GeothermEx, 2004), details the number and type of exploration methods likely necessary to complete a commercial power project. At the snapshot in time this dataset was created, 173 fields were analyzed for further exploration needs. Exploration on 15 projects was far enough into the process that no further exploration or well tests were required, 14 projects needed only to summarize previously collected data, and 56 projects had sufficient information to warrant exploration drilling (slim holes and/or well tests) (Figure 2). If exploration research success is calculated as the ratio of the number of projects that proceed to drilling (whether performed previously or needed in the future) to the number of projects with any exploration research, this dataset would suggest a success rate of approximately 49% (i.e. (15+14+56)/173). Since this dataset (published in 2003) is outside of the timeframe of other components of success rate (between 2005 – 2015), this analysis presents this rate only as a historical example of the method.

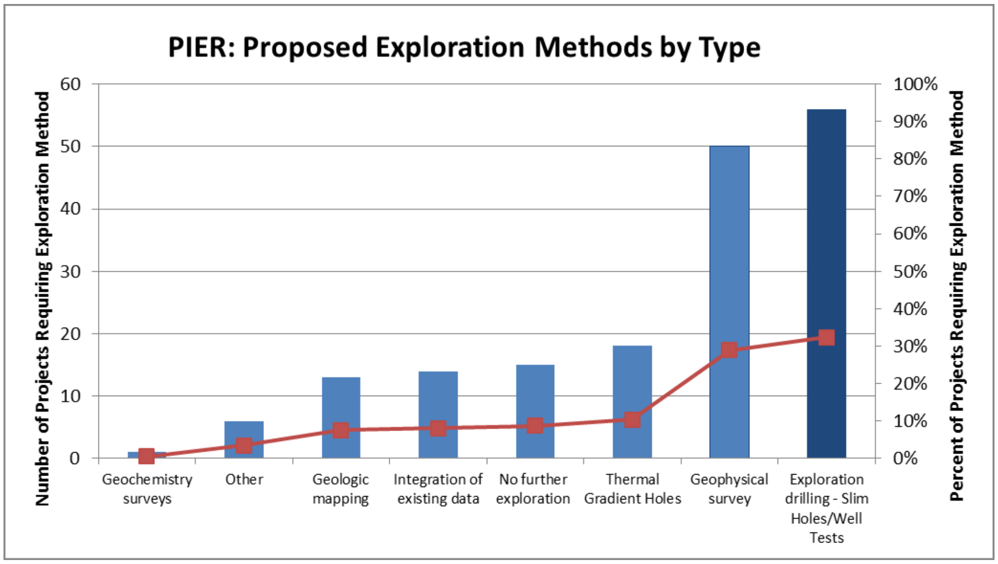

Figure 2: Types of exploration research analyses expected for geothermal exploration projects analyzed from the PIER (2004) report, by the number and percent of projects using these methods.

Alternatively, the success of exploration can be approximated by s an evaluation of the number of projects that have been explored and subsequently abandoned For this analysis, a database constructed of more than 260 project records from SNL Financial and GEA reports filed between 2012 and 2015 was used to track project progress through GEA's Development Phase categories (GEA 2010, SNL 2015, Wall and Young, 2016). Nearly one-third of the projects showed advancement in development that indicates active exploration (such as "Prospect" to "Phase 1"), but nearly 53% of projects made no advancement in development progress during this timeframe. However, progress alone does not indicate the fate of the projects – namely whether the projects continued, were stalled or postponed, or were discontinued entirely. In this sample, nearly 20% of the projects that remained in the same phase and approximately 7% of projects that advanced phases during these four years were ultimately discontinued by the end of this period. Figure 3 summarizes project development progress (i.e. advancing or remaining in a Phase) for projects which remain under development, and includes the outcome of those projects which are no longer under development (i.e. terminated or postponed). Since approximately 40% of projects were terminated or postponed, the overall success rate of these projects continuing exploration can be calculated as 60% (i.e. 1-40%).

For those projects which remain in development, this calculation may be an overestimate of the actual success rate because the outcomes of these projects are not yet known. Further refinement of this study to follow these projects is needed to determine whether the inclusion of projects in development institutes a bias in the success rate.

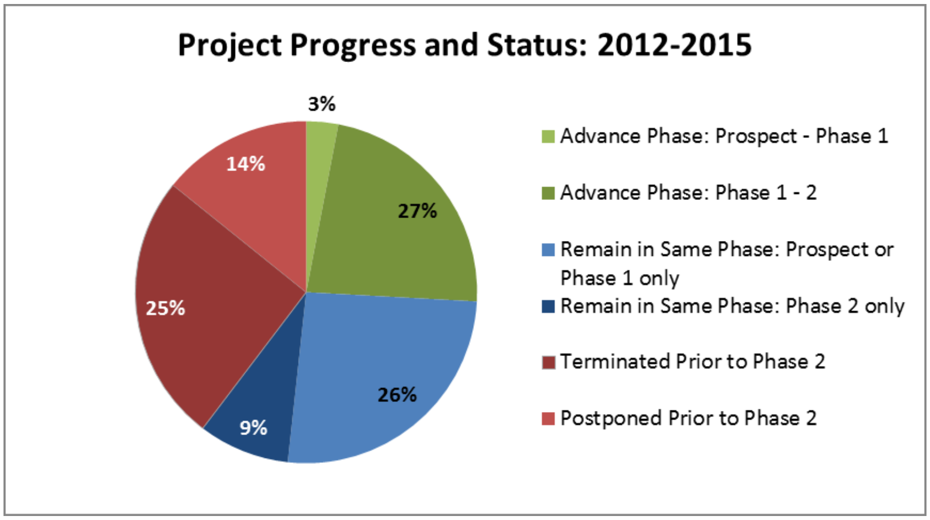

Figure 4: Proportion of projects within the U.S. GEA Annual Reports and SNL Financial records that remained in the same development phase, changed phase, or were otherwise stopped (terminated or postponed) prior to exploration drilling. If projects that remained in the same development phase over the 4 year period under evaluation are excluded, the success rate of exploration methods can be determined as the ratio: 1 - (number of projects that were terminated or postponed) = 60% (difference from figure due to rounding).

3.3 Exploration Drilling

In general, thermal gradient holes are not intended to discover a geothermal resource, but based on the results of these wells, deeper exploration wells are targeted with the intent of discovering a viable geothermal resource. The Nevada Bureau of Minerals monitored the permit and operational status of 292 thermal gradient holes (TGH) from 2005 to 2015. Of these permits, nearly 158 expired or were cancelled before drilling occurred, likely as a hedge against the time required to obtain permits when drilling sites are confirmed. Of the 134 thermal gradient holes that were drilled, the outcome of 14 TGHs were not available, and three TGHs changed their end use to observation wells. Figure 4 demonstrates differences in the success rate of this sample dataset with and without adjustments, and suggests a possible probability of exploration drilling success to be 42%. A caveat to Figure 4 is that these results only consider wells, and only those which are categorized as "in use." For a given project, the average drilling success rate for exploration wells in use is found to be 31% and the success rate for exploration wells both idle and in use is 36%.

Figure 4 suggests that considering changes in the end use of wells results in only minor adjustments to the calculation of the success rate. Then again, not considering the overall likelihood that a permit will be used could significantly over-estimate the success of exploration. Within this subset of the last 10 years, nearly twofold differences existed between the number of permits issued for drilling and the number of wells actually drilled.

When projects with exploration drilling are followed to identify whether full-size production wells were also drilled, only 10 of 32 projects with exploration drilling also obtained permits for production well drilling. This sample, although small, suggests a project success rate of exploration drilling may be 31%.

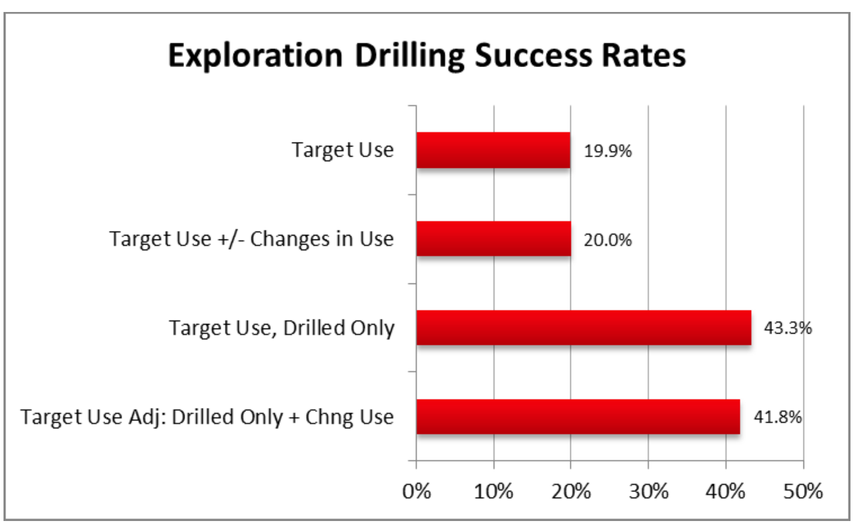

Figure 5: Distribution of slim hole and thermal gradient hole (TGH) drilling success rates calculated from the Nevada Bureau of Mineral's well production and permit records. "Target use" indicates TGHs that were drilled for their original use and includes all well permits that were abandoned, never in use, or never drilled. "Target use, drilled only" records the success rate of only TGHs that were drilled, and includes wells that were never in use. "Target use adj." records the success rate of TGHs when only considering wells drilled, and adjusts for the number of TGHs which were repurposed for other uses.

3.4 Confirmation Drilling

The Nevada Bureau of Minerals monitored the permit and operational status of 183 production wells, as well as 166 observation and 84 injection wells from 2005 to 2015. Of the 202 permits originally issued for production, 66 permits expired or were cancelled before drilling occurred. Of the 136 production wells which were drilled, the outcome of 17 wells were not available, and 19 production wells changed their end use to become injection or observation wells. However, 3 injection and 4 observation wells changed their end use to be used for production. Figure 5 demonstrates differences in the success rate of this sample dataset with and without calculation adjustments for changes in intended use.

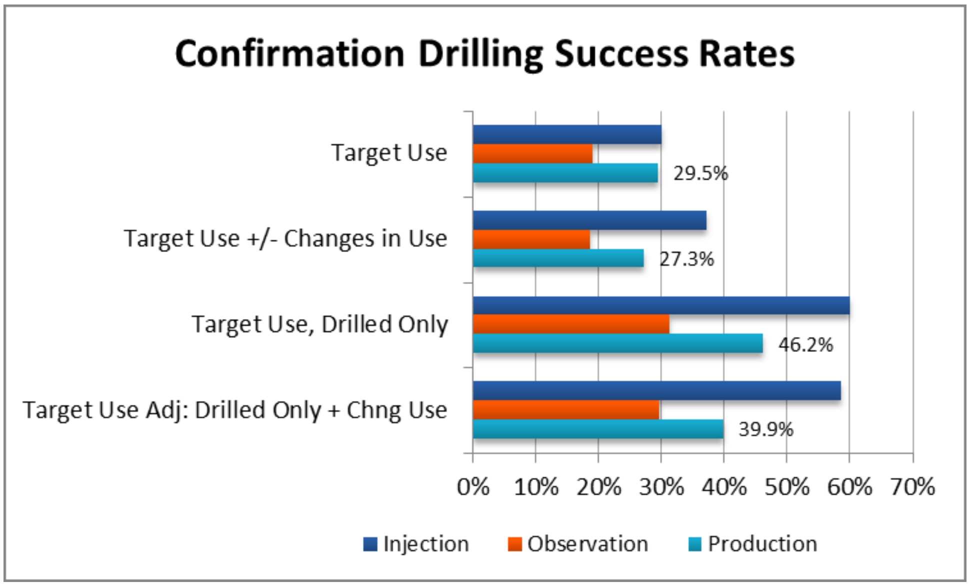

Figure 5: Distribution of injection, observation, and production well drilling success rates calculated from the Nevada Bureau of Mineral's well production and permit records. "Target use" indicates wells that were drilled for their original use and includes all well permits that were abandoned, never in use, or never drilled. "Target use, drilled only" records the success rate of only wells that were drilled, and includes wells that were never in use. "Target use adj." records the success rate of wells when only considering wells drilled, and adjusts for the number of wells which were repurposed for other uses.

Adjustments to calculations made to reflect changes in the end use of wells do appear to impact the overall success rate. Conversely, not considering the overall likelihood of whether a permit will be used or not is much more significant to understanding the success of the drilling process. In the 2005 to 2015 subset, there is nearly a 33% difference between the number of permits issued for full-size production drilling and the number of wells actually drilled. A caveat to Figure 5 is that these results only consider wells, and only those which are categorized as "in use." For a given project, the average drilling success rate for production wells in use is found to be 32% and the success rate for production wells both idle and in use is 60%.

In examining plant records where more than one production well was attempted, the outcomes of these wells appear to support previous research suggesting very little learning effects during initial full-sized production drilling (e.g. Sanyal and Morrow, 2012). For example, the Stillwater plant received six production well permits between 2005 and 2012, and drilled four wells. The first well that was drilled in September 2005 was idled, suggesting that it did not meet performance criteria. The second well that was drilled in July 2009 is currently in use. And, while the third well that was drilled in August 2009 was idled, the fourth well drilled in September 2009 was put in use. The probability of success in this case is equivalent to flipping a coin: 0/1 x 0.25% (i.e. first of four wells fails)+ 2/3 x 75% (i.e. 2 of three wells are used) = 50%. On the other hand, a striking example of a potential learning situation exists at the Wild Rose plant, where seven of the eight wells drilled were put to use after the first idled well.

4. LIMITATIONS AND NEXT STEPS

The analysis focuses on demonstrating an approach to calculating and combining success rates at multiple stages of the geothermal exploration process. It does not investigate causal factors or relationships between projects that could influence a project's likelihood. For example, this analysis does not replicate the work of the IFC to investigate the impact of differences in redrilling, enthalpy, or pumping on the likelihood the well was considered successful. IFC's work also points to a potential dependency/learning from redrilling full-size production wells that improves success rates from 77% to 87%—an improvement of nearly 13% to the probability of confirmation drilling. Validating the strength and magnitude of these other relationships would be important future work to understanding the variability in overall project success rates.

Proposed next steps include a careful deconstruction of the differences in success between projects having prior research (i.e. previous wells or development for any reason) and true green field projects with no knowledge or research in the area. Using these results, future work will investigate whether there is a significant distinction between green field and brown field exploration success rates. A recent analysis of geothermal project barriers suggests that areas that shift ownership are indeed able to move forward with project development after an acquisition, indicating that institutional knowledge of an area is not insurmountable (Wall and Young, 2016). IFC acknowledges significant differences in success due to prior information for the large fields of its 2012 study, but further research is required to validate whether this conclusion holds true for small projects and projects that do not survive to the drilling phase. Further research into DOE's Innovative Exploration Technology (IET) portfolio will also illuminate our understanding whether exploration wells drilled for specific purposes aided in future well siting decisions. Another way to look at this is to count the total number of geothermal systems that are commercial developments in the western US and the number of geothermal prospects that have been explored in the same region over the past 40 years. This would provide a crude overall exploration and development success rate. The USGS list of identified high temperature systems would give an initial estimate of the number of prospects – this could then be looked at to see which of these have undergone different degrees of exploration.

In practice, the true measure of project success is a combination of the operational feasibility (discussed in this paper) along with the likelihood of financial return. This work does not directly address the financial decision process being made during geothermal exploration, such as the financial model that ultimately determines whether an area can support commercial geothermal power production. Since exploration "failure" may be – and is often – due to a lack of financing, this model for project progress is currently missing the distinction of project success due to technical likelihood versus financial likelihood (Petty, 2016; Wall and Young, 2016). For example, Calpine experienced a project that was technically successful and ready to produce >30 MWe, but the company was forced to suspend this project after it was not able to obtain a PPA at a price needed to pay for the project development costs (Walters, 2016). Thus, a necessary improvement of this method would be to create a complimentary, distinct definition of success that outlines the likelihood of investor and developer returns.

These complimentary analyses can then directly support better projections. By applying the applicable probabilities to expected expenditures at each project stage, a developer can create a more accurate probability-adjusted cash flow that supports a risk-adjusted net present value (rNPV). Beyond a developer's financial stability, other factors that impact a project's valuation, such as the effect of variance in expected capacity on success rate, also deserve further consideration. IFC (2013) suggests that an understanding of enthalpy and resource type can explain 11% of the variance in capacity, but this analysis considered primarily large geothermal fields (only seven of 57 fields evaluated had fewer than 10 drilled wells).

The paucity of comparable data at the project level is a known weakness of the analytical results currently presented. For example, this analysis does not consistently follow the success of the same set of projects across the 10-year timeframe investigated, but instead aggregates the sample set at each stage to calculate a combined probability. To investigate whether this method creates a bias, future work will consider detailed case reviews of a set of individual projects as well as results from DOE's IET project portfolio. An initial review of project data collected in 2005 for the Battelle Energy Alliance – Idaho National Laboratory which was able to follow project progress to completion suggests similar rates of success: of the 318 projects in this study, 72 (22.6%) proceeded to exploration or slimhole drilling, and 24 (7.5%) completed successful confirmation drilling (Combs, 2005).

A known limitation of this work is also that it considers only hydrothermal project development – the primary type of geothermal power projects to be placed into commercial development in recent years. Other types of geothermal project development, such as deep sedimentary basins or EGS, may present significantly different risk profiles. Since these types of projects are not yet commercial, an investigation of the probability of success for these projects at this time would be based on expert opinion and projections. However, such an assessment might be valuable in order to direct future geothermal exploration to lower risk - higher return project options than the current project types.

5. CONCLUSION

The definition of success for geothermal projects—and the calculation of a success rate—are critical factors in understanding project risk at each stage of development. These probabilities have previously been narrowly defined as the number of wells that result in commercially-viable production, solely representing the ability of a drilling operation. This research refines the definition of success for the exploration process as the conditional probability of a geothermal project to reach consideration for commercial development. A method has been developed for applying this definition by constructing the conditional probabilities of each development stage from project-level and well-level data in in the western U.S. Due to these very different definitions, this work suggests that success rate for a geothermal exploration process should be considered as approximately 16-21% likelihood to proceed beyond confirmation drilling to actual commercial power production. This refined success rate better represents the symbiosis between exploration methods, the developer decisions, and the procedural hurdles required to pursue a geothermal development.

This analysis anecdotally investigates the length of the exploration process for projects started within the last 10 years. Further improvements of this method will consider differences in success rate based on the impacts of delays, whether due to research, capital budgeting, or external project barriers such as permitting delays and rig availability. Recent work on qualifying the impact of these factors on project deployment indicates significant differences in the type of delay as a project progresses toward commercial development (Wall and Young, 2016). Thus, further analyses of success would benefit from explicit study of the impact of time on the project's capital budgeting (i.e. project NPV). Using the combination of these analyses, future work will investigate which levers within the geothermal exploration process have the strongest influence on overall project success.

Applications of this revised definition of success place the geothermal industry in a better position to understand project risk—and its associated financial impacts. This work does not provide a financial measure of project risk, but presents a threshold to expectations for green field project development that could be developed into a risk analysis. Possible outcomes of this work could be improved decision-making during the exploration process, which could prevent unlikely projects from being drilled or push projects that may have been too quickly discarded otherwise. Moving the definition of exploration "success rate" closer to a common probability-adjusted framework may improve the transparency into geothermal project progress, and by association, the likelihood of development cash flows.

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APPENDIX:

Cumulative Probability of Success at Each Phase of Project Development (Deloitte, 2008)