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Establishing a Baseline for Global Geothermal Drilling Rates

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ABSTRACT

Geothermal is a promising source of renewable energy with almost zero emissions. However, there remains untapped geothermal potential around the world. This is largely because geothermal projects have high development costs and high resource-value uncertainty, and returns on initial investments can be slow to materialize. Increasing drilling efficiency of geothermal wells is one way to decrease development costs, as drilling accounts for up to 50% of the upfront costs of a geothermal power project. Currently, little quantitative information exists about how fast geothermal drilling occurs on a global scale. This paper was originally intended to be an extension of Frone and Boyd's 2018 report on geothermal drilling rates in California and Nevada. Our project includes global data and considers additional measures, such as flat time. Data for the project was limited to published papers and drilling reports that are publicly available online. The goal of our project was to establish a baseline geothermal drilling rate that is representative of current global geothermal drilling practices can be used to gauge the impact of future improvements in geothermal drilling technology. We recorded the number of days from beginning to end of a project, the number of days spent drilling, and the number of days considered to be flat time. We found the average global rate at which a drilling project is completed (including non-drilling activities) to be 160 ft/day, and the average drilling rate (including only time during which active drilling occurred) to be 360 ft/day. Our data shows no clear trend in rate change from 2000 to 2017 and significant variability in drilling rates between countries and within countries.

1. INTRODUCTION

Geothermal potential exists around the globe, yet much of it remains untapped. This is a result of unfavorable economics. In contrast with the oil and gas industry, geothermal resource areas are much more heterogeneous, resulting in higher development costs and resource-value uncertainty, and geothermal production has a much longer return on investment[1]. Drilling costs are estimated to account for up to 50% of upfront capital costs of a geothermal project (Tester et al., 2016). To a large extent, drilling costs are time-dependent, as rig rental and labor costs are charged per unit time.

Increasing drilling efficiency is one way to reduce time dependent drilling costs. In fact, drilling efficiency is one of the only controllable factors affecting drilling costs (Lowry et al., 2017), as opposed to the price of rig rental and labor costs, which are more or less market controlled. While it is well-documented that geothermal drilling occurs at a much slower rate than oil and gas drilling (Eustes et al., 2015), little information is available about the exact rates at which geothermal drilling occurs globally. In 2018, Frone and Boyd published a paper estimating geothermal drilling speeds within the US, based on data from wells drilled in California and Nevada (Frone and Boyd, 2018). This paper expands upon their research, considering global geothermal drilling data and addressing details of drilling that were not included in Frone and Boyd's paper, such as the distinction between time spent drilling (time during which drilling equipment is used to actively increase the depth of the well) and flat time (for the purposes of our paper, defined as the time during which the activities performed did not increase the depth of the well).

Ultimately, this paper strives to establish a baseline geothermal drilling rate that is best representative of current global geothermal drilling practices. This rate can hopefully be used as a baseline against which to gauge the impact of future improvements in geothermal drilling technology.

2. METHODS & DATA

In our analysis of drilling speed, we considered the total depth of a well, the number of days from spudding the well to reaching total depth, and the number of days considered to be flat time versus the number of days spent drilling. For the sake of our project, "flat time" is a count of days during the drilling project in which the depth of the well did not increase. This includes days spent on activities such as cementing, running casing and resolving lost circulation event, and does not include time spent mobilizing and demobilizing the drilling operation. We defined "days drilling" as a count of days in which the depth of the well is actively increased.

We used these measures to calculate a spud to TD rate ("spud-TD rate") and a "drilling rate" for each individual well. The spud-TD rate acts as a measure of total project efficiency, and it is important when considering drilling costs that are dependent on total number of project days. The drilling rate more accurately represents the efficiency of actual drilling activities. We defined the two rates as follows:

$$spud - TD\ rate = \frac{total\ depth}{days\ from\ spud\ to\ total\ depth}$$

Equation 1

$$drilling\ rate = \frac{total\ depth}{days\ drilling}$$

Equation 2

Frone and Boyd's "drilling rate" refers to the total well depth in feet divided by the number of days from spud to completion of a well[4]. Their "drilling rate" is equivalent to our "spud-TD rate", while our "drilling rate" measures a value not included in Frone and Boyd's paper, as they did not consider flat time. Any reference to "drilling rate" or "spud-TD rate" within this paper refer to our definitions of the rates, even when they are used to discuss Frone and Boyd's published results.

To best represent current drilling practices, we included only data from wells drilled during or after the year 2000. In order to maximize the sample size, data was included from sources that did not provide an exact date when it could be reasonably assumed that the well was drilled during or after the year 2000. The data used in this project was pulled from various online sources, including publicly available drilling reports and published papers, listed in Appendix A. We found data reporting within the geothermal industry to be extremely irregular and unstandardized. The following paragraph explains the resulting possible sources of error or bias within our sample.

Due to the limited amount of information available online, all useable data found was included in the project and no effort was made to assure that the sample was geographically or chronologically representative of the actual global distribution of geothermal drilling projects. Additionally, for the data to be found online, it must have been knowingly released by some entity that participated in the drilling project. As such, we must consider the possibility of a reporting bias in the data – that is, that companies would be more likely to release information about a drilling project that was successful and efficient than one that was slow and inefficient. The data found was expressed in different formats depending on the type of publication. In some cases, days to TD, days drilling and flat time were estimated from a days vs. depth graph of a drilling project, while in others, the variables were reported explicitly within the text or in a table. Because all data was collected manually, there is likely some human error present in our data set, especially in measuring variables directly from a graph. To ensure that the analysis was not significantly swayed by human error, we double checked all significant drilling rate, spud-TD rate and flat time outliers. Finally, some sources reported information on all three variables, while others excluded flat time information. As a result, our sample includes almost twice as many measures of spud-TD rates than of drilling rates.

Figure 1 displays the distribution of available spud-TD rate data and drilling rate data by country. Figure 2 displays the distribution of our sample by year(s) associated with the data point. A single data point is defined as all information about a single well, including spud-TD rate and drilling rate (if available). Some source correlated a drilling project with an exact date or exact year, while others associated multiple drilling projects with a span of years and others included no information about the year a well was drilled. The different reporting styles are reflected in Figure 2 by color.

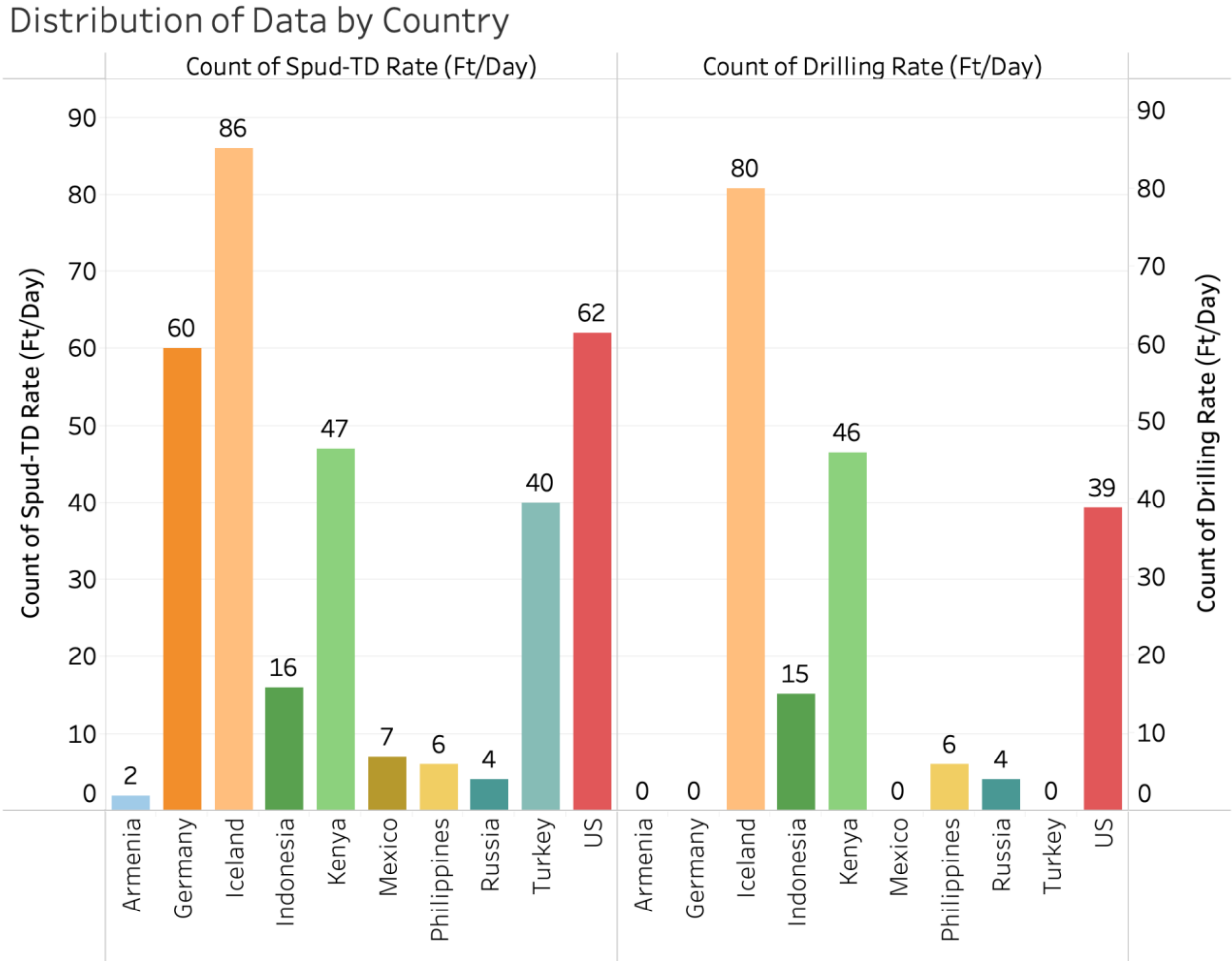


Figure 1: Distribution of data included in our sample to calculate spud-TD rates and drilling rates by country.

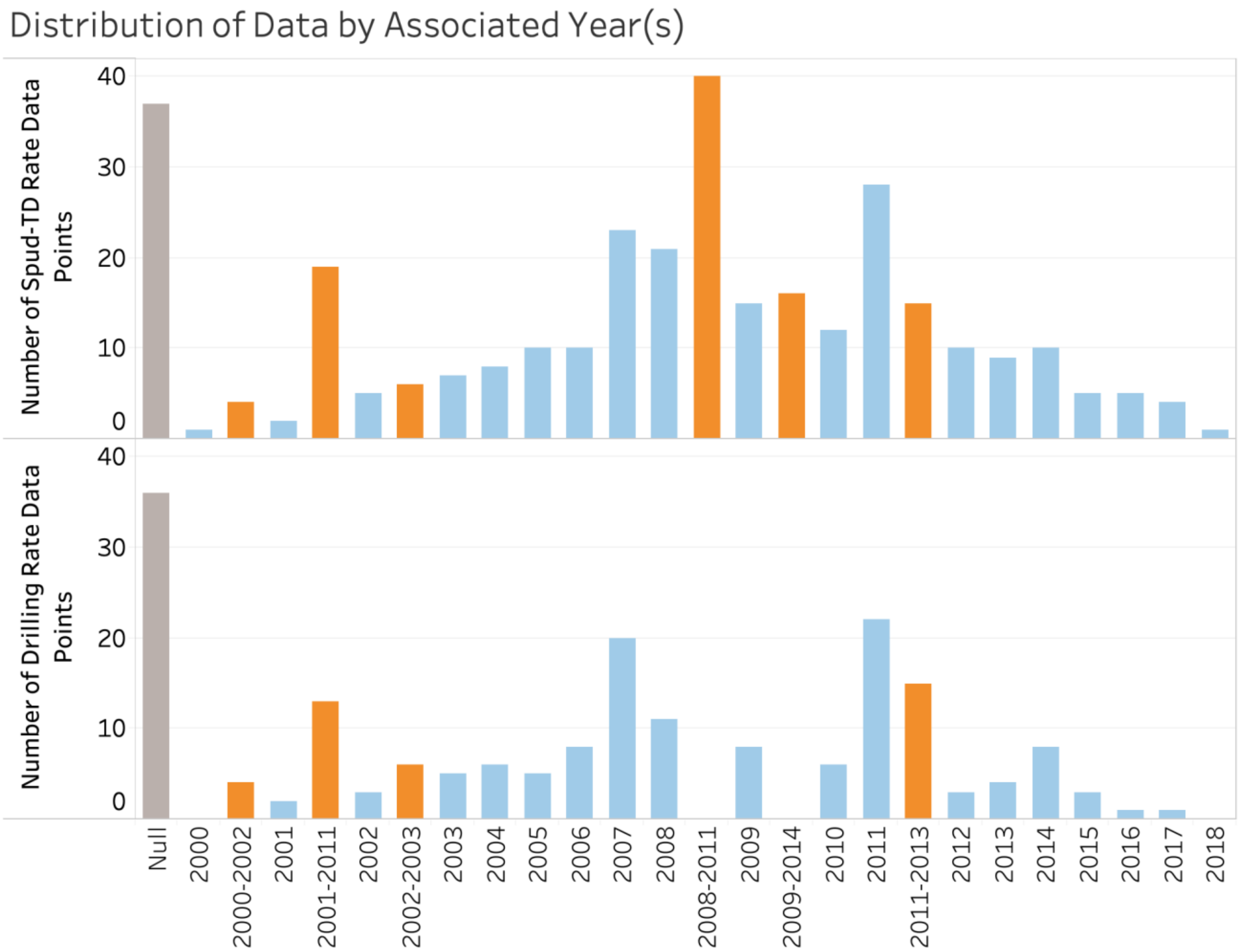


Figure 2: Distribution of data included in our sample to calculate spud-TD rates and drilling rates by associate year(s). Counts of data reported by exact year in blue, counts of data reported by groups of years in orange, and count of data with no associated date in grey.

3. RESULTS & DISCUSSION

3.1 Spud-TD Rates and Drilling Rates Over Time

Figure 3 plots spud-TD rates and drilling rates over time. It includes all data in our sample for which an exact year of drilling was given. Spud-TD rates are in orange and drilling rates are in blue. The plot shows no discernable trend or change in rates since the year 2000, which suggests that geothermal drilling rates have seen no recent improvement. In contrast, average oil and gas spud-TD rates more than doubled between the years 2006 to 2014 – from about 350 ft/day to 750 ft/day (EIA, 2016). Furthermore, the variability in rates remains high and relatively constant from the year 2000 to 2017.

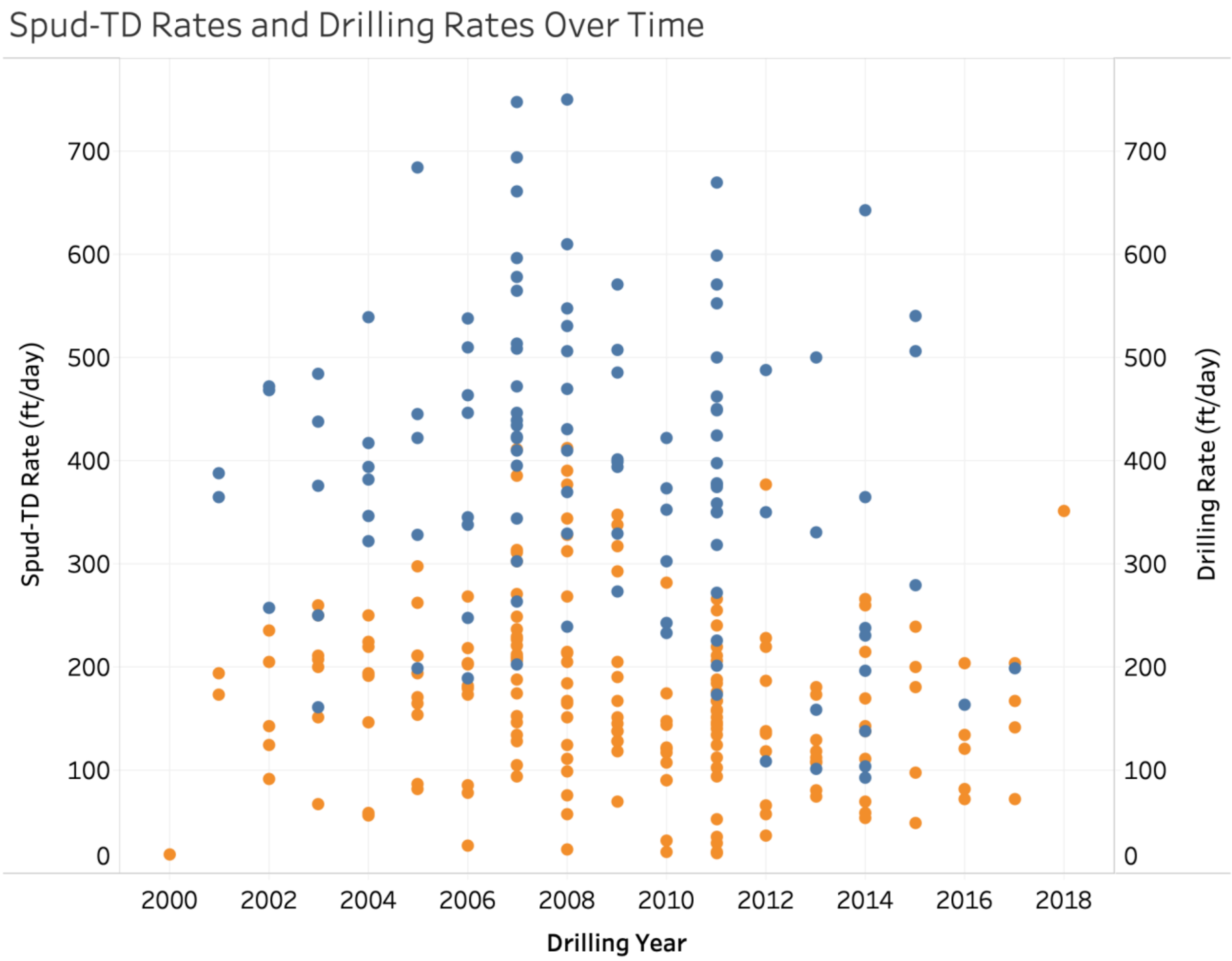


Figure 3. Scatterplot of spud-TD rates and drilling rates over time. Spud-TD rates are in orange and drilling rates are in blue. Both are given in ft/day.

3.2 Distributions of Spud-TD Rates and Drilling Rates

As seen in Figure 3, there is great variability in the current rate at which geothermal wells are drilled. To better represent this variability, Figure 4 displays a histogram of spud-TD rates and drilling rates. The distribution of spud-TD rates is almost normally-shaped, although it is skewed right by a few high outliers. Table 1 reports that the mean global spud-TD rate is 159 ft/day while the median is 151 ft/day, confirming a slight right-ward skew. The distribution of drilling rates appears to be less skewed than that of spud-TD rates, confirmed in Table 1 by a mean global drilling rate of 359 ft/day and a median of 356 ft/day. The standard deviations of the spud-TD and drilling rates distribution are 79 ft/day and 160 ft/day, respectively – there is larger variation in drilling rates than in spud-TD rates. The high spud-TD rate outliers are labeled by field and country, as are the highest four drilling rates. One of the high spud-TD outliers represents a well in the US (shown in Figure 5), but the field is unknown. It is worth noting that the exact wells with the four highest drilling rates were among the high spud-TD rate outliers as well.

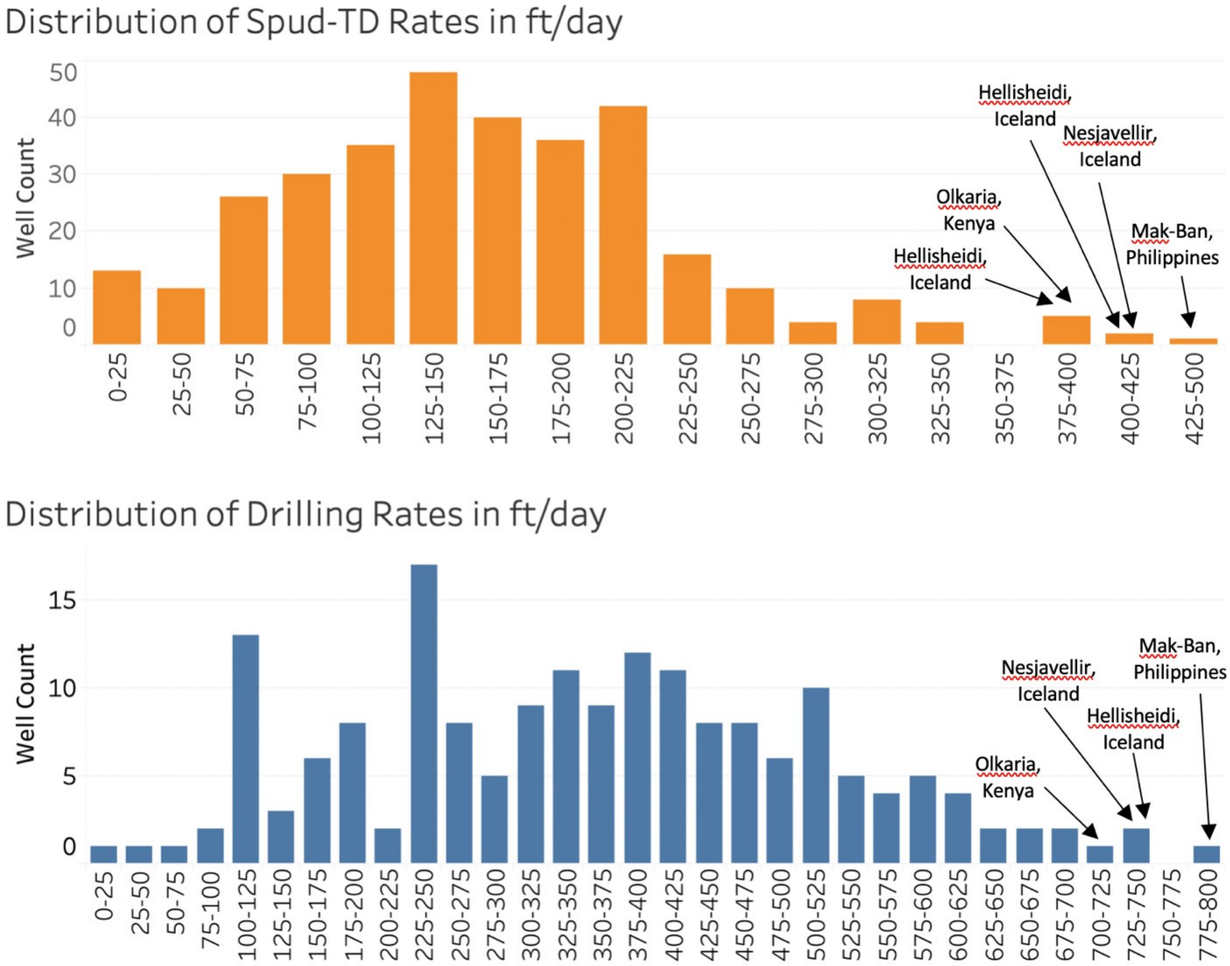


Figure 4. Histogram of spud-TD rates and drilling rates. Intervals of spud-TD rates and drilling rates are given along the x-axis in ft/day. Field and country the wells came from are labeled for the highest rates.

The discrepancy in sample sizes by country is clearly illustrated in Figure 1, and our sample is not distributed in a way that accurately represents the true global distribution of geothermal wells. For example, our sample includes 86 spud-TD rates from Iceland and only 6 from the Philippines. In reality, Iceland's installed geothermal capacity is only 755 MWe, while the Philippines is much higher at 1,868 MWe (ThinkGeoEnergy, 2019). It is worth sorting spud-TD rates and drilling rates by country in order to understand how the distribution is influenced by countries like Iceland that make up a disproportionate amount of the sample. Figure 5 suggests that Iceland's data points may be upwardly inflating both the spud-TD rate and drilling rate distributions. Counts of Iceland spud-TD and drilling rates from 2000 to 2017 are in light orange, most of which fall on the higher half of each distribution. The average drilling rate calculated without any data from Iceland is 138 ft/day, over 20 points below the average global rate when Iceland is included. The average global drilling rate surprisingly drops by 50 points when data from Iceland is excluded. These values are represented in Table 1.

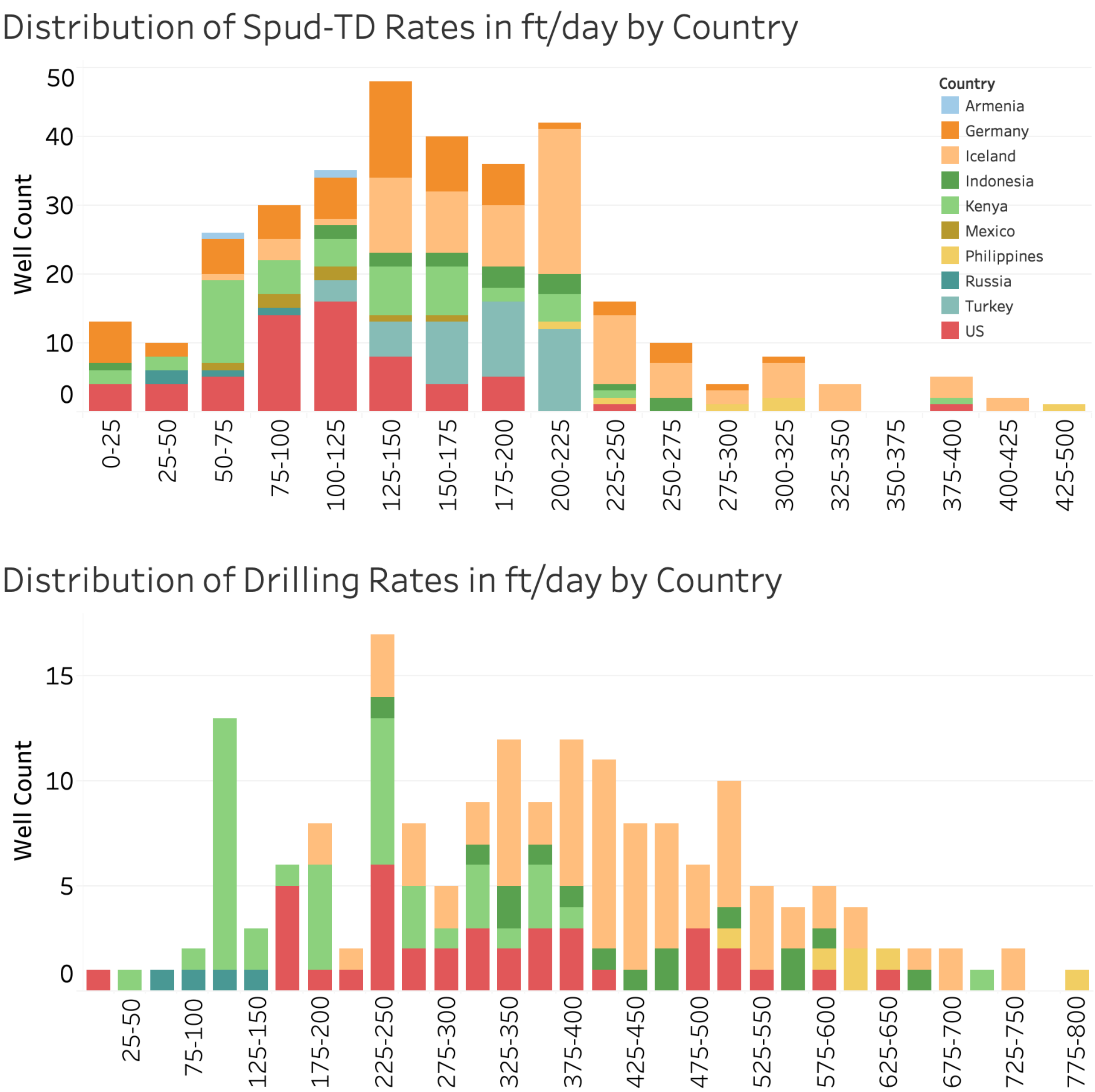


Figure 5. Histogram of spud-TD rates and drilling rates with color used to divide counts by country.

Frone and Boyd report an average domestic geothermal spud-TD rate of about 130 ft/day[4]. Their results are displayed in Figure 6. Globally, our data suggests average spud-TD rates to be slightly higher – about 159 ft/day. Table 1 reports the mean and median drilling and spud-TD rates given by Frone and Boyd and the same values calculated from our data both globally and within the US using the data included in Figure 5. The discrepancy between Frone and Boyd's reported values and our reported values for the US is likely explained by the differences in geographic distribution and sample sizes of the data sets. Frone and Boyd only include data from California and Nevada while our data includes wells drilled throughout the country, and Frone and Boyd's data includes 245 data points while our calculation of US spud-TD rates includes only 62. Nevertheless, both our US spud-TD distribution and Frone and Boyd's spud-TD distribution have peaks around 75-125 ft/day, and both US spud-TD averages are lower than the global average. US drilling rates calculated from our data fall only slightly behind global drilling rates, but are higher than the average global rates excluding Iceland. This is reiterated in Figure 5 – US spud-TD rates are clustered towards the lower end of the global distribution while US drilling rates fall within the middle of the global distribution.

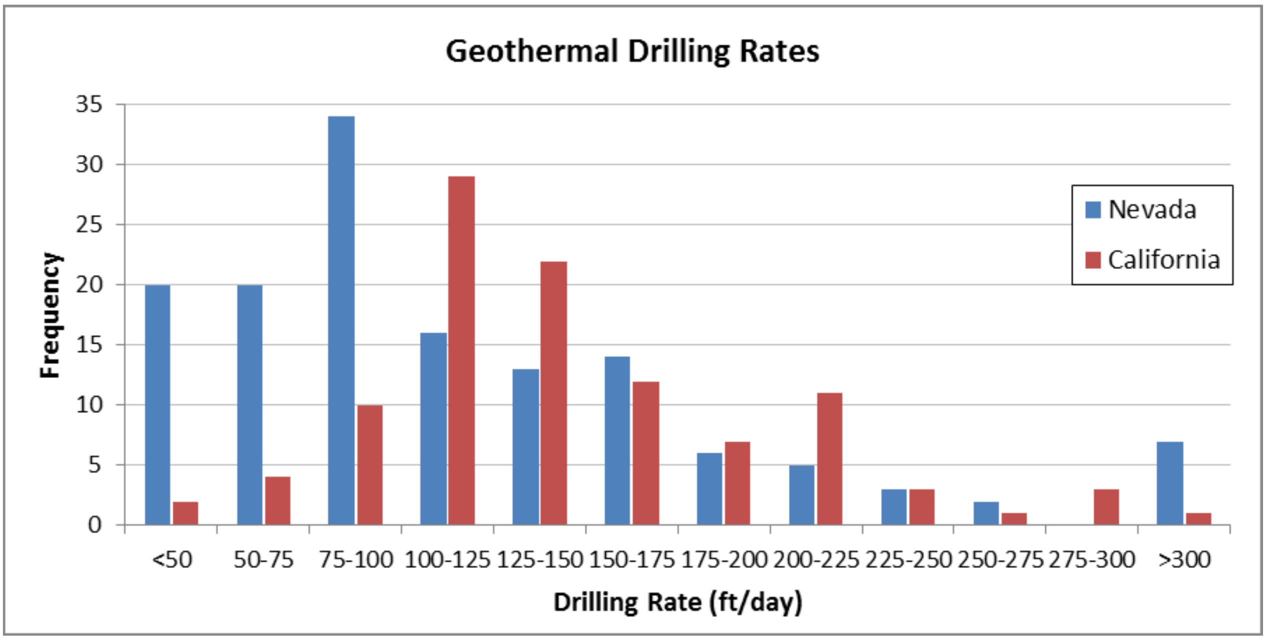


Figure 6. Histogram of geothermal drilling rates determined for California and Nevada (Source: Frone and Boyd 2018). Their "drilling rate" represents the same measure as our spud-TD rate.

Table 1: Comparison of our results to Frone and Boyd (2018)'s Results. All rates expressed in ft/day.

	Mean spud- TD rate	Median spud- TD rate	Number of Observations	Mean Drilling Rate	Median Drilling Rate	Number of Observations
Frone and Boyd	130	119	245	-	-	-
United States	112	107	62	323	304	39
Global	159	152	330	359	356	190
Global, excl. Iceland	138	135	244	306	273	110

3.3 Percentages of time spent

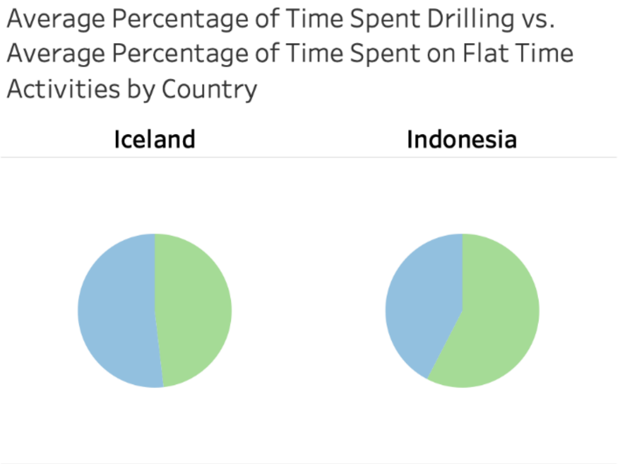
In this paper, we considered all time from spud to reaching total depth of the well to be either time spent drilling (days drilling) or flat time. We defined "days drilling" as days in which drilling equipment was used to actively increase the depth of the well. We defined "flat time" as time in which activities were performed that did not actively increase the depth of the well, essentially the number of days in which a days vs. depth graph of a drilling project is flat. This includes days spent on activities such as cementing, running casing and resolving lost circulation events, and does not include time spent mobilizing and demobilizing the drilling operation. Due to the nature of our sources, days drilling and flat time were measured as full days. While it is possible that drilling and flat time activities occurred within the same day, our data does not account for this.

Figure 7 shows how time is spent differently during a drilling project by country. It includes all countries for which flat time/drilling days data was available. The distribution and counts of data included by country can be seen on the right side of Figure 1. The pie charts show average percentage of time spent drilling and the average percentage of time spent on flat time activities by country. As we considered all time spent on a drilling project to be either drilling time or flat time, the two percentages add up to 100% for each country. On average, Indonesia, the Philippines and the US spend more time on flat time activities than drilling activities, while the reverse is true for Iceland, Kenya and Russia.

Figure 5 shows that US spud-TD rates is lower than the global average while US drilling rates fall around the global average. This is a result of the high percentage of time spent on flat time activities in the US. While US drilling rates are comparable to the global average, high amounts of time spent on flat time activities result in lower spud-TD rates.

The variable inputs to spud-TD rate are drilling rate and flat time. Figure 7 includes a table that shows average drilling rate, flat time and spud-TD rate by country to illustrate how drilling rate and flat time work together to determine spud-TD rate. It also includes average days drilling by country. It illustrates that of the countries included, countries with higher drilling rates also tend to have less flat time and vice-versa, implying that there may be factors affecting the efficiency of drilling and flat time activities simultaneously.

The ratio of average days drilling to average flat time should not necessarily correspond to the average percentages of time spent on each activity. The average percentages were found by first calculating time percentages for each individual well (days drilling/total days, flat time/total days) and then averaging all days drilling and flat time percentages within a given country.



Country	Avg. Days Drilling	Avg. Flat Time (days)	Avg. Drilling Rate (ft/day)	Avg. Spud-TD Rate
Iceland	17.7	18.3	430.9	218.1
Indonesia	13.3	18.9	446.1	142.5
Kenya	44.5	38.5	221.8	122.9
Philippines	16.2	18.8	629.5	298.4
Russia	60.0	66.3	100.0	53.9
US	28.7	40.3	305.2	107.6

Measure Names
Avg. percentage of time spent on flat time ..
Avg. percentage of time spent drilling

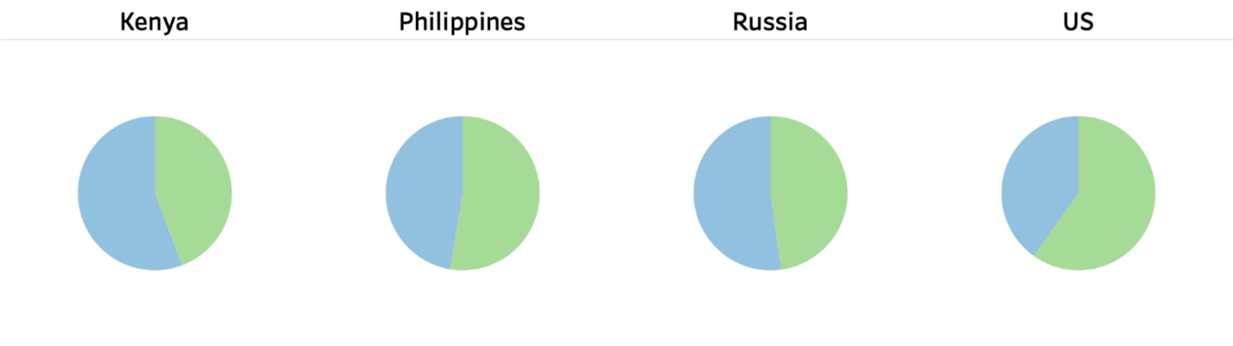


Figure 7. Pie charts showing average percentage of time spent drilling and spent on flat time activities and table displaying average drilling rates and average flat time by country. The green in the pie chart represents the percentage of time spent on flat time activities, while the blue represents the percentage of time spent drilling.

3.4 Assessing the Viability of Spud-TD Rates as a Measure of Drilling Efficiency

Ultimately, improvements in spud-TD rates are important in order to minimize the number of days spent on a geothermal drilling project and as a result – minimize time-dependent costs. Future improvements in spud-TD rates could be achieved in two ways: a reduction in flat time and/or an increase in drilling rate. Flat time includes activities like cementing, running casing and resolving lost circulation events, and improvements in the efficiency of the technologies used in such activities could reduce total flat time. The greatest potential source of improvements in drilling rate is through developments in bits for drilling through hard or abrasive rock, as is often the case in geothermal drilling.

Figure 8 displays average spud-TD rates by intervals of drilling rates and flat time. The intervals along the x-axis represent either drilling rate or flat time, the height of the bars represents the number of wells within the given drilling rate or flat time interval, and the numbers above the bars and the color of the bar show the average spud-TD rate for the given interval. As expected, wells drilled at higher drilling rates have higher spud-TD rates, and wells that experience fewer days of flat time have higher spud-TD rates.

From our data, flat time made up an average of 50.5% of total drilling project time, and days drilling made up an average of 49.5%. As such, we should expect improvements in either to have similar effects on spud-TD rates. In terms of Figure 8, we should expect the spud-TD gradients should be similar (but flipped) between the two graphs. This is the case for the most part, although the two highest drilling rate intervals display spud-TD almost double those of the lowest flat time intervals. Because the third highest drilling rate interval displays an average spud-TD rate similar to those observed in the lowest flat time intervals, we can likely attribute the high spud-TD averages in the top two drilling rate intervals to the small size of the sample they represent.

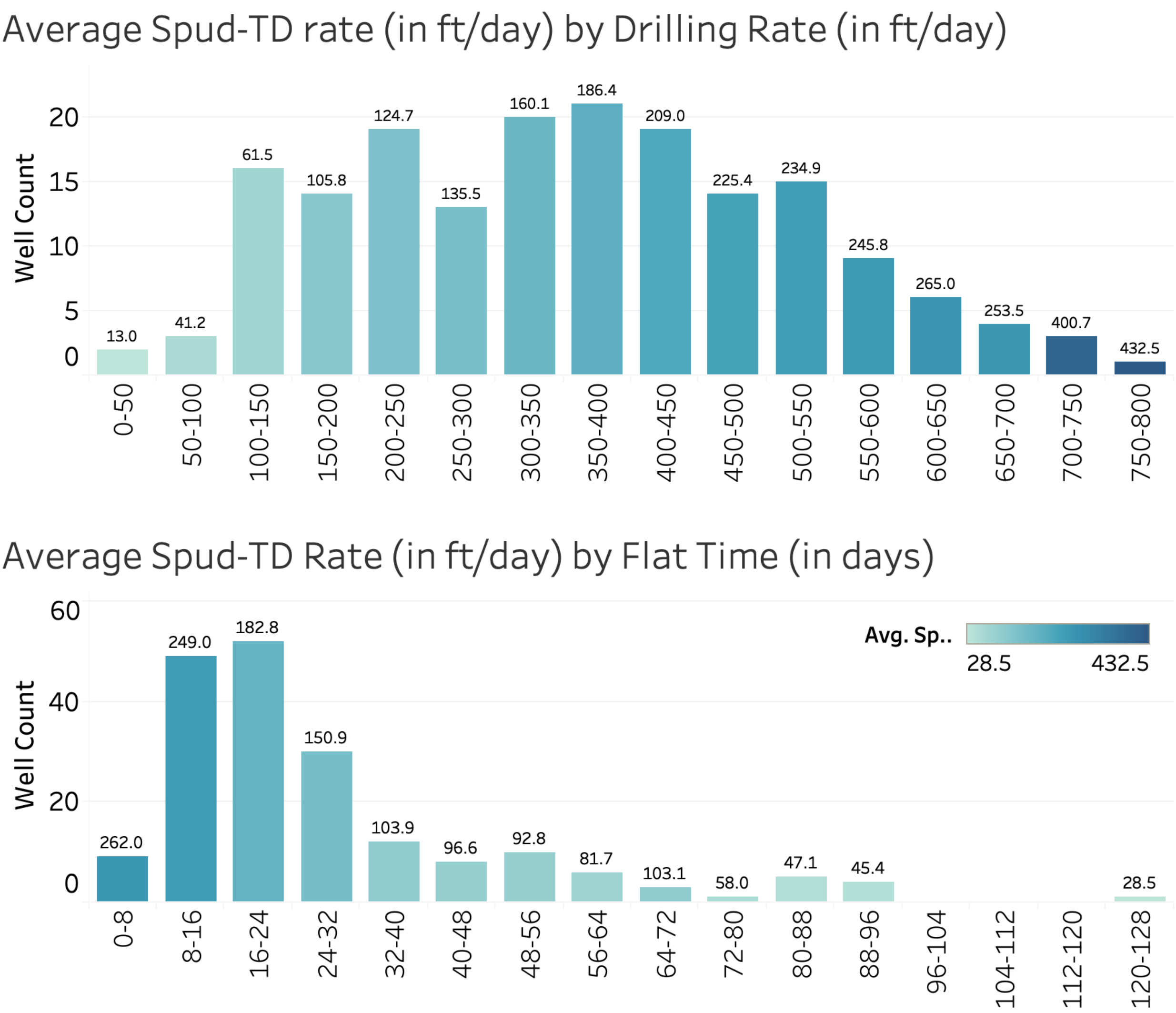


Figure 8. Histogram of spud-TD rates by intervals of drilling rates and flat time. Average spud-TD rate is overlaid both as a number and by the color of the bar. Bar height represents the number of wells included in the average calculations.

It is tempting to use spud-TD rates as a measure of efficiency in geothermal projects for two reasons: 1) they reflect changes in both flat time and drilling rates, and 2) they are directly correlated to the amount of time spent on a project. However, they may also be influenced by the depth of a well. Oftentimes, time spent on flat time activities like casing and cementing is relatively fixed no matter the depth of the well. At minimum, changes in flat time are not always proportional to changes in depth. As the depth of a well increases, any “fixed” flat time is distributed among a larger depth, resulting in an artificially inflated spud-TD rate.

Our data reflects this effect. Figure 9 is a scatterplot of spud-TD rate versus total depth of the well, sorted in color by high or low drilling rate. Among wells drilled at similar drilling rates, we see that spud-TD rate increases as total depth increases. The depth-dependency appears to be more extreme for wells drilled at higher drilling rates.

If spud-TD rates are to be used as a measure of future improvements in geothermal drilling efficiency, their depth dependency should be noted. If we observe the depth of wells to increase significantly as time goes on, the reported spud-TD rates may be artificially inflated. In this case, considering both drilling rate and flat time separately may be a better gauge of drilling efficiency. Additionally, this would allow us to distinguish between improvements in drilling technologies and reductions in flat time activities.

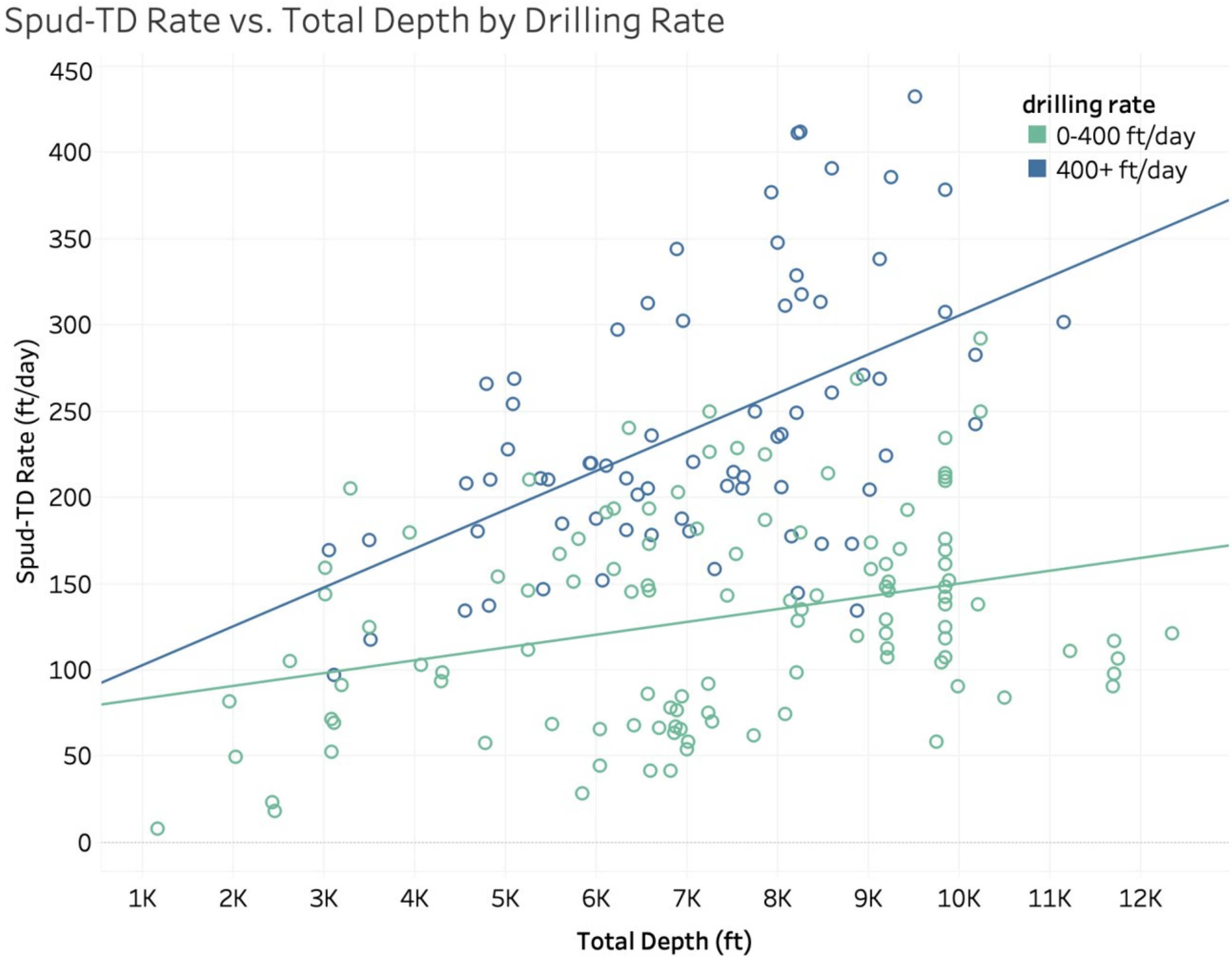


Figure 9. Scatterplot of spud-TD rate versus total depth distinguished by drilling rate. Wells with drilling rates above 400 ft/day are shown in blue and wells with drilling rates below 400 ft/day are shown in teal.

3.5 Hellisheidi's Learning Curve Effect

Multiple sources point to the existence of a learning curve effect in both geothermal drilling and oil and gas drilling (Sanyal and Morrow, 2012; Lukawski et al., 2014). With more experience drilling in the same area, there is potential to improve drilling rates by gaining a better understanding of the lithology and how best to address any geological challenges. Lukawski et al. suggest that there may be more potential for improvement within a geothermal field than in a hydrocarbon field because the rock formations are initially less predictable (Lukawski et al., 2014). The learning curve effect should be easily detected by comparing drilling rates within a given field over time.

To assess the learning curve effect, we use data about drilling in Iceland's Hellisheidi geothermal field from a Reykjavik University study. (Sveinbjornsson 2010). Of the data compiled for this project, it was the only source to supply the exact dates of drilling for multiple wells in the same field. All Hellisheidi wells were included except for those drilled in multiple intervals or whose drilling dates information was too ambiguous to confidently interpret.

Figures 10 is a scatterplot of spud-TD rates and drilling rates versus the date of the beginning of the drilling project for wells in Hellisheidi. Spud-TD rates are in orange and drilling rates are in blue. For each well, an individual spud-TD rate and drilling rate is plotted. The plot are overlaid by linear regressions of spud-TD rates and drilling rates over time for the given field.

Figure 10. Scatterplot of spud-TD rates and drilling rates over time for Hellisheidi. Spud-TD rates are in orange and drilling rates are in blue. Each rate is plotted against the beginning date of its corresponding drilling project.

There is too much variability in the data for the trend lines in Figure 10 to be used as predictors of spud-TD rates and drilling rates based on year. However, the scatterplot illustrates that drillers were able to achieve increasingly faster maximum drilling rates and spud-TD rates over time, even if slower rates were not completely eliminated. We do not observe this effect after the year 2000 in the global data displayed in Figure 3. Hellisheidi illustrates the potential to achieve higher spud-TD rates and drilling rates over time within a single field, where information about drilling and complications, etc. from previous wells is presumably shared among those working in the field to a greater extent than drilling information is shared globally.

The comparison between Figures 3 and 10 suggests that sharing data and drilling information more freely among the global geothermal industry could improve global spud-TD rates and drilling rates. However, wells in individual fields have relatively similar geology and may experience similar complications. As the same cannot be said for wells globally, it is that sharing information globally would not have as much as an effect as it does within an individual field.

3.6 Country-level Case Studies

Our data is not complete enough to understand numerically how different variables affect spud-TD rates and drilling rates. Nevertheless, case studies of countries with plentiful available data can help us understand the roles of certain geologic and industry-level factors: geologic/tectonic setting, type of rock typically found at geothermal sites, beginning of geothermal drilling, overview of major geothermal drilling operators, number of geothermal wells drilled, and drilling contract structure. Our analysis compares geothermal drilling in Germany, Iceland, Indonesia, Kenya, and Turkey. These countries were chosen for their large sample sizes, differences in tectonic settings, and high amount of publicly available geothermal information.

Before beginning the case study comparisons, we theorized that spud-TD rates and drilling rates may be influenced in the following ways:

1. Harder rocks may make it harder to drill, resulting in slower rates
2. The learning curve effect may exist on a country-level scale; countries that have been drilling for a longer amount of time and have drilled more wells may observe faster rates as it gives them a chance to figure out what works and what doesn't

3. Oil and gas companies may be more likely to invest in expensive equipment than smaller geothermal drilling companies. Oftentimes, initial expensive investments such as better rigs, the use of downhole tools, a focus on drilling efficiency, etc. can mitigate risk in geothermal projects and result in fewer complications later on. For countries where significant amounts of geothermal drilling is done by oil and gas companies, this could result in faster rates because the drilling equipment may be more efficient.

4. Contract structures enforced on a national level may affect the way that drilling contractors make choices during drilling projects. Hagen Hole outlines two different contract structures: unit-time contracts and unit meter contracts. Under a unit-time contract, drillers are paid based on how long a project takes. Under a unit-meter contract, drillers are paid based on the depth of the well (Hole, 2006). Under the later contract structure, drillers may be more incentivized to minimize the time spent on a project, as extra time spent on a project will be in no way reimbursed.

While our results can neither confirm nor deny our hypotheses, we can use the logic outlined above to better understand and provide context for our results.

Figure 11 shows the distributions of spud-TD rates and drilling rates for each of our case study countries. The middle line within each box represents the median value of the given data, and the other lines divide the sample into quartiles, excluding outliers. The means and medians of both rates by country are given in Table 2. Iceland and Indonesia have the highest average drilling rate, much higher than both Kenya's average drilling rate and the global average drilling rate. However, their average spud-TD rates are not significantly higher than those of other countries.

Additionally, Table 2 includes both means and medians of rates by country, the number of wells included in each calculation, and the average well depth by country. Based on our data, Germany is drilling the deepest wells while Indonesia is drilling the shallowest wells.

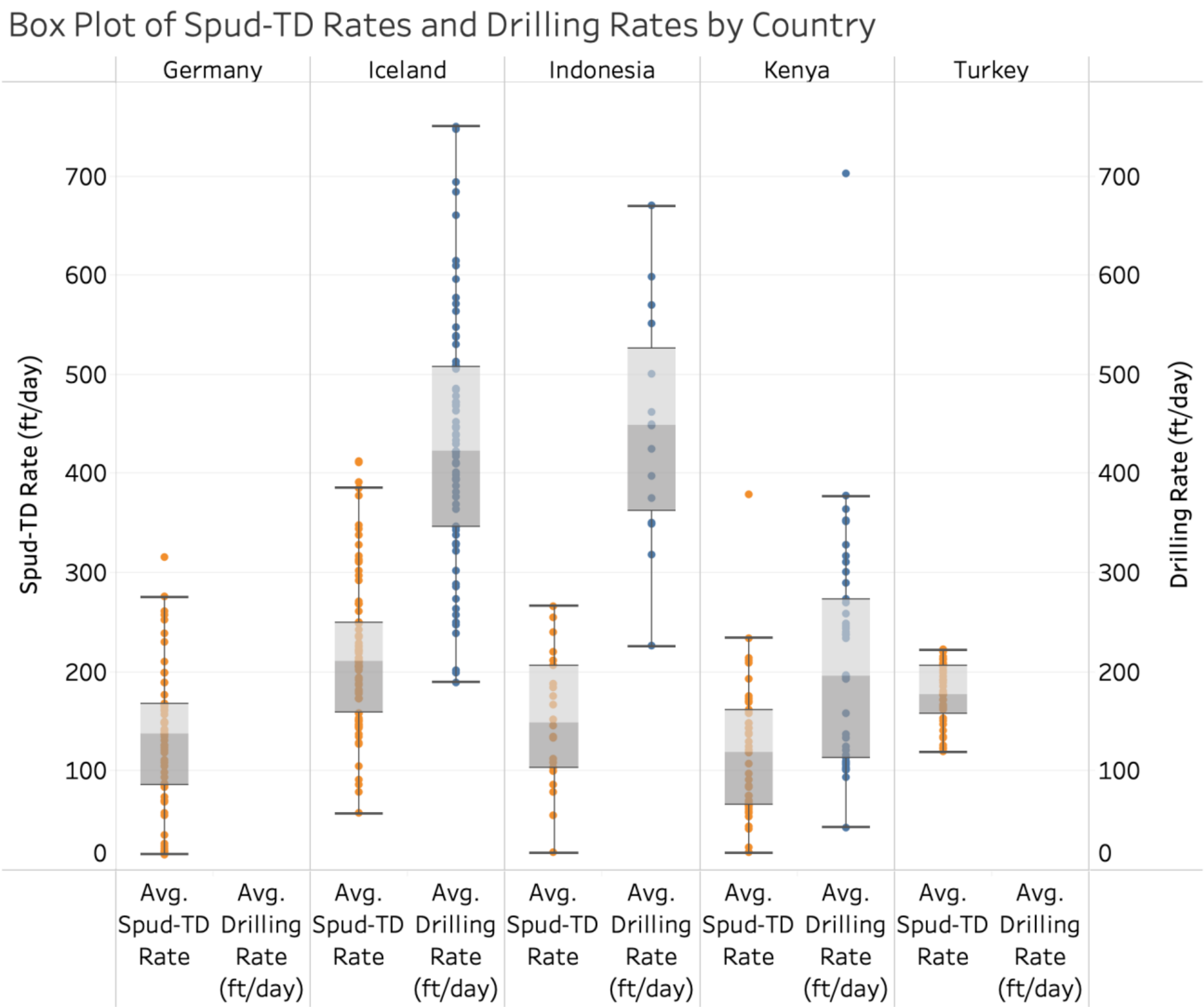


Figure 11. Box plots displaying the distribution of spud-TD rates and drilling rates by country for each case study country. Spud-TD rates are in orange and drilling rates are in blue. Both rates are given in ft/day.

Table 2: Spud-TD rate and drilling rate results and average total depths of wells for case study countries. Both rates given in ft/day.

	Mean spud-TD rate	Median spud-TD rate	Number of observations	Mean drilling rate	Median drilling rate	Number of observations	Avg. Total Depth
Iceland	218	210	86	431	422	80	7188
Kenya	123	121	47	222	236	46	8379
Indonesia	174	180	16	446	448	15	5056
Turkey	178	178	40	-	-	-	7104
Germany	135	137	60	-	-	-	9085

Tables 3 and 4 assess the following geologic and industry-level factors that may influence spud-TD rates or drilling rates: geologic/tectonic setting, type of rock typically found at geothermal sites, beginning of geothermal drilling, overview of major geothermal drilling operators, number of geothermal wells drilled, and drilling contract structure. The data sources for the information in Table 3 and Table 4 are listed in Appendix B. Each is relevant to one of the theories outlined at the beginning of the section. Publicly available information about Germany's geothermal industry was limited; in the place of information not found is a dash.

Table 3: Geologic Factors. Comparison of geological conditions that may affect drilling speeds for case study countries.

	Geologic and tectonic setting	Type of rock found at geothermal sites
Iceland	• Located on the Mid-Atlantic Ridge, spreading at about 2 cm/year[1] • Volcanoes and hot springs[1] • Relatively young rock; bedrock age of most high temperature fields is < 0.8 Ma[2]	• Hyaloclastites[3] • Basaltic rock[3] • Intrusive rock[4]
Kenya	• Located on a divergent continental plate boundary in the East African Rift System, rifting at about 2 cm/year[3] • Volcanoes[5]	• Basaltic rock[3] • Felsic rock[3] • Trachtyte[3]
Indonesia	• Located on a subduction zone where the Pacific, Indo-Australian and Eurasian plates meet[6] • Tectonism, magmatism and earthquakes[6]	• Mafic rock[7] • Andesite[7,8] • Lava[7,8] • Tuffs[7,9] • Breccia[7,9]
Turkey	• Located on the Alpine-Himalayan orogenic and tectonic belt[10] • Tectonism and volcanism[10] • All data taken from wells in and around the Menderes Massif, a mountain range in Western Turkey created as a result of orogenic uplift	Menderes Massif: • Core made of gneiss and other metamorphic rock [11] • Core covered by schist and marble envelopes[11] and sedimentary rock[12]
Germany	• Located on the Alpine orogenic belt[13] • All data taken from wells drilled in the Molasse Basin, located in the North Alpine Foreland Basin[14] created as a result of the collision of the Adriatic and European plates[15]	Molasse Basin • Limestone[14] • Shale[14] • Siliciclastic rock[14] • Calcareous rock[14] *Most geothermal drilling occurs through carbonate rock*[14]

Table 4: Industry Factors. Comparison of industry conditions that may affect drilling speeds for case study countries.

	Start of geothermal drilling	Number of wells	Major drilling operators	Contract structure
Iceland	1920s [16]	340 [17]	• Iceland Drilling[18] (private, Iceland-based, international geothermal drilling company)	"unit meter rate" contracting[19]
Kenya	1950s [20]	> 345 [21]	• KenGen[22] (state-owned) • Geothermal Development Company[22] (state-owned)	"unit time rate" contracting[19]
Indonesia	1920s [23]	> 711 [24]	• Star Energy[25] (UK oil company) • Pertamina[25] (state-owned oil and gas company) • Supreme Energy[26] (private, geothermal only)	"unit time rate" contracting[19]

Turkey	1960s [10]	~ 700 [27]	• all exploration done by MTA (General Directorate of Mineral Exploration and Research), some drilling licenses leased out to private companies[28]	"unit time rate" contracting[10]
Germany	-	~ 300 [29]	-	-

Both Iceland and Indonesia report drilling rates much higher than the other countries. Figure 7 shows that Iceland and Indonesia have the lowest flat time averages of the six countries for which flat time data was available. Iceland ranks #1 in spud-TD rates, while Indonesia falls only slightly above the global average. Both countries have a long history of geothermal drilling, suggesting the possibility of improved drilling rates and lowered flat time through a learning curve effect. A singular company (Iceland Drilling) does most of the geothermal drilling in Iceland, which most likely expands the information-sharing potential between geothermal operators. Indonesia has drilled the greatest number of wells, which could also be conducive to a learning curve effect.

Iceland's conditions are most favorable to high spud-TD rates and drilling rates, at least according to our initial theories. Many of its geothermal sites are located on relatively new rock, which makes them much more permeable and easier to drill (Ragnarsson, 2013). Iceland is also the only one of the case studies to operate geothermal drilling under a unit-meter contract. As previously explained, this gives drillers more of an incentive to minimize the number of days spent drilling, possibly by investing in more efficient drilling equipment. They are being paid a fixed price for their drilling services no matter how long it takes them to complete the project, and so additional days spent on the project would incur additional time-dependent costs without any increase in the amount they are being paid to complete the project.

Indonesia's geothermal drilling is dominated by oil and gas companies. Such companies are often larger than typical geothermal drilling companies and have more capital to invest in the most up-to-date drilling equipment. Additionally, these oil and gas companies drill both oil and gas wells and geothermal wells, giving them more experience drilling wells in general. This additional capital and experience may contribute to Indonesia's high spud-TD rates and drilling rates.

Turkey and Germany's wells are located in similar tectonic settings – within an orogenic belt. However, Germany reports drilling geothermal wells through softer sedimentary rocks (such as Limestone and Shale) in the Molasse Basin, while geothermal drilling in Turkey's Menderes Massif encounters harder igneous and metamorphic rock. In the case of Germany and Turkey, rock type is likely not the only determining factor of spud-TD rates, as Turkey reports higher rates (mean spud-TD rate of 178 ft/day) than Germany (mean spud-TD rate of 135 ft/day). Unfortunately, information about Germany's industry factors is limited.

Harder rock is often alleged to be the reason geothermal drilling fall behind oil and gas drilling rates. Oil and gas drilling commonly occurs through sedimentary rock similar to shale and limestone, and the industry reports average spud-TD rate of 750 ft/day (EIA 2016). Germany's geothermal drilling occurs through rock similar to that encountered in oil and gas drilling, yet its spud-TD rates remain low. Germany's case suggests that other characteristics of the geothermal industry may be limiting its spud-TD rates.

4. CONCLUSIONS & IMPLICATIONS

1. Our data reveals no global improvement in either geothermal spud-TD rates or drilling rates throughout the 21st century.
2. From our data, the average global spud-TD rate is 159 ft/day, and the average global drilling rate is 359 ft/day.
3. Global variation in both rates remains high. Distributions of spud-TD rates and drilling rates are relatively normally shaped, with standard deviations of 79 ft/day and 160 ft/day, respectively.
4. The United States' spud-TD rates appear to be lower than the global average, but its drilling rates appear to be closer to the global averages. This is a result of high percentages of time spent on flat time activities in the US.
5. Spud-TD rates may be a good measure of drilling efficiency because they reflect both drilling rates and flat time, but there is potential for spud-TD rates to be upwardly inflated by high total well depths. Considering drilling rates and flat time individually may eliminate a depth-dependency and allow us to measure improvements in drilling efficiency and flat time activities seperately.
6. There is potential for maximum spud-TD rates and drilling rates to improve over time within a single field through a learning curve effect. We did not observe this effect within our global data, possibly due to limited global information sharing within the geothermal industry.
7. Our study would have benefitted from improved availability and standardization of global geothermal data. From our experience conducting this study, we believe these would be the most ideal conditions for future monitoring of spud-TD rates and drilling rates: standardized, mandatory and publicly-shared reporting of drilling information for every future well drilled, including total depth of well, time spent drilling, time spent on various flat time activities, well lithology, drilling operator, bottom-hole temperature and a record of any unexpected challenges encountered. Such a reporting system would probably be difficult to initiate and enforce.
8. Rock type and well lithology are likely not the only determinants of spud-TD rates and drilling rates. Industry conditions and characteristics likely affect the ways that drilling decisions are made and the potential for a learning curve effect.

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7. APPENDICES

Appendix A: List of sources used to compile data set

Source	Year of Publication	Geographic Scope of Data	Number of Data Points
Balamir, Rivas, Rickard, McLennan, Mann, Moore: Utah FORGE Reservoir: Drilling Results of Deep Characterization and Monitoring Well 58-32, *Proceedings,* 43rd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2018).	2018	Utah	1
Changole and Kivure: Investigating the Effect of Nozzles on the Rate of Penetration in Drilling Geothermal Wells – A Case Study Of Menengai Geothermal Fields, *GRC Transactions*, **41**, (2017).	2017	Kenya	9
Cole, Young, Doke, Duncan and Eustes: Geothermal Drilling: A Baseline Study of Nonproductive Time Related to Lost Circulation, *Proceedings,* 42nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2017).	2017	United States	38
Flechtner and Aubele: A brief stock take of the deep geothermal projects in Bavaria, Germany (2018), *Proceedings*, 44th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2019).	2019	Germany	60
Geothermal Resource Group, AK-3 End of Well Report, *report,* (2016).	2016	Alaska	1
Gilliland, Austin, Wilmarth, Daskin, Babayan and Adams: Karakar, Armenia – Slimhole Drilling and Testing Results and Remote Project Management Overview, *Proceedings,* 39th New Zealand Geothermal Workshop, Rotorua, New Zealand (2017).	2017	Armenia	2
Jaffe: summary of TGW submitted to DOE, *Geothermal Data Repository* (2011).	2011	Oregon	6
Jonsson, Gudmundsson and Palsson: The Hagongur High-Temperature Geothermal Field, Central-Iceland. Surface Explorations and Drilling of the First Borehole: Lithology, Alteration and Geological Setting, *Proceedings,* World Geothermal Congress, Antalya, Turkey (2005).			
Karimi: Rotary Steerable Systems to Reduce the Cost and Increase the Energy Value of Drilling Directional Wells in Olkaria Geothermal Field, *GRC Transactions,* **41, (**2017).	2017	Indonesia	15
Kaya: Geothermal Project Development in Turkey – An Overview With Emphasis on Drilling, *GRC Transactions*, **36**, (2012), 159-164.	2012	Turkey	40
Lopez, Silva, Saldago and Cecilia: Results of Geological – Geophysics Drilling of the Well H-43 the Geothermal Field in	2010	Mexico	7

Humeros, Pue. Mexico, *Proceedings,* World Geothermal Congress, Bali, Indonesia (2010).			
Nyota and Murigu: Analysis of Non-Productive Time in Geothermal Drilling Operations – A Case Study of Olkaria, Kenya, *Proceedings,* 42^{nd} Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2017).	2017	Kenya	11
Okwiri: Geothermal Drilling Time Analysis: A Case Study of Menengai and Hengill, *Proceedings,* Geothermal Training Programme, Orkustofnun, Iceland (2013).	2013	Iceland and Kenya	34
Raymond, Knudsen and Blakenship: PDC Bits Outperform Conventional Bit in Geothermal Drilling Project, *Proceedings,* Geothermal Resources Council (2012).	2012	United States	1
Richmond Energy Services: Well KS-5 Completion Report for the Hawaii Department of Land and Natural Resources, 2003 (unpublished).	2003	Hawaii	1
Sitorus, Nanlohy and Simanjuntak: Drilling Activity in the Matalko Geothermal Field, Ngada – NTT, Flores - Indonesia, *Proceedings,* 5^{th} Inaga Annual Scientific Conference & Exhibitions, Yogyakarta, Indonesia (2001).	2001	Indonesia	1
Southon and Gorbachev: Drilling Geothermal Wells Efficiently, With Reference to The Mutnovsky, Mak-Ban and Lihir Geothermal Fields, *Proceedings,* 25^{th} NZ Geothermal Worshop, New Zealand (2003).	2003	Russia and the Philippines	10
Sveinbjornsson: Cost and Risk in Drilling High Temperature Wells in the Hengill Area In Iceland, *MSc. thesis*, Reykjavik University, Reykjavik, Iceland (2010).	2010	Iceland	66
Thorhallsson, Sveinbjornsson and Ongau: Geothermal Drilling Effectiveness, *Proceedings,* "Short Course on Geothermal Drilling, Resource Development and Power Plants", Santa Tecla, El Salvador, (2011).	2011	Kenya	12
Visser and Eustes: FY14 AOP 3.3.0.6 SURGE Geothermal Drilling and Completions: Petroleum Practices Technology Transfer, *final report*, National Renewable Energy Laboratory, (2014).	2014	United States	14

Appendix B: List of sources used to compile information for Table 3 and Table 4

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