

## SUCCESS AND THE LEARNING CURVE EFFECT IN GEOTHERMAL WELL DRILLING – A WORLDWIDE SURVEY

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### **ABSTRACT**

This paper investigates the success achieved in terms of well capacity and the presence of any “learning curve effect” in drilling geothermal wells. This investigation is statistical and is based on technical data from a majority of the more than 4,000 geothermal wells drilled worldwide to date. These well data have been retrieved from the accumulated data archives of GeothermEx with the data confidentiality maintained by withholding the names of individual wells and fields except where the relevant data are publicly available. Using an arbitrary definition of a successful production well as being of 3MW or higher in capacity, the database yielded 869 successful wells with reasonably verifiable production data. A histogram of this data shows a peak at 3 to 5 MW, and a median of 7 MW.

This study further considered individually 60 geothermal fields from 14 countries to assess the drilling success rate on a field-by-field basis and the possible presence of any learning curve effect on geothermal drilling. The chosen fields represent a total installed plant capacity of about 70% of the current worldwide installed capacity (11,000 MW). Drilling success rate in each field fluctuates widely in the exploration phase, the fluctuation subsides as more and more wells are drilled and eventually stabilizes in the late development or operational stage. Verifiable production data were available from 52 of these 60 fields. In these 52 individual geothermal fields the success rate in drilling varies from 33% to 100% with a prevalent range of 60% to 80% and a median of 68%. Twelve of these fields with the longest history were studied in further detail; the average success rate estimated from the detailed study of 1,112 wells from these dozen fields is 71%.

This study did not detect a continuous learning curve effect on drilling success rate in most fields. However, some sort of a discrete learning curve

effect appears to generally improve, and occasionally reduce, the average well capacity in a few obvious steps as more and more wells are drilled in a field. In general, any positive learning curve effect on drilling success appears to be masked by the larger statistical uncertainty for a relatively small sample size, the number of wells drilled in a geothermal field being statistically small compared to a petroleum field.

In many fields there is a continuous and positive learning curve effect on the drilling rate (that is, meters drilled per hour). The continuous learning curve effect on drilling rate and the discrete changes in average well capacity as more wells are drilled can obviously affect the overall economics of drilling, that is, the MW capacity achieved per unit drilling cost.

### **INTRODUCTION**

We believe at least 4,000 geothermal wells have been drilled to date in the world. This number should be large enough to represent a statistically representative sample from which both the success rate in drilling production wells as well as the impact of any learning curve effect on drilling results should be possible to assess. In reality, this turns out to be a frustrating effort because of the virtual impossibility of gathering and verifying the needed data on such a large number of wells from many countries, geological provinces and the diverse owners of those data. The main problem is the proprietary nature of well data from most sites.

GeothermEx has amassed over the last four decades technical data from nearly two-thirds of the existing wells worldwide in its assessment of more than 60 geothermal fields in the world; most of these data are confidential and cannot be released. Nevertheless, the statistical results from worldwide drilling activities can still be considered from this confidential database by specifically not identifying the individual wells and fields, except for a few fields where the data are

available from public archives or sources and could be released. Thus the confidentiality of the data could be protected even as statistical inferences were attempted from the database. This paper presents the results of such an investigation of the technical data from 2,528 wells from 52 fields in 14 countries conducted over the last few years.

Although well data from many other fields were also retrievable from the GeothermEx archives, a reasonably complete or consistent data set was unavailable from all wells within each of these additional fields; these wells, therefore, could not be included in this statistical analysis.

### **LIMITATIONS OF THE DATABASE**

The study encountered many difficulties in assembling and verifying the production capacity data from wells. For some wells, a single MW value was reported in the archives, without specifying the power plant technology assumed (flash, binary, or hybrid), or what the flowing wellhead pressure during the test was, or whether the well was pumped or self-flowed, or sometimes even whether the MW value represented a gross or net value. One the other hand, for many wells detailed deliverability test records (flow rate and enthalpy versus flowing wellhead pressure) were available, along with the pump-setting depth and other relevant data on the well and pump (if the well was pumped). Obviously, the latter data types were preferable and used as far as possible. For most wells no data on the content of the non-condensable gases was available; the gas content was assumed nil for those wells. Another problem with such a hybrid database was the lack of uniformity or consistency of the parameters reported from the various wells. In many fields the number of wells drilled to date was deemed too few for a statistical study; we found only 12 fields containing at least two dozen wells each along with verifiable production data. In spite of these limitations enough verifiable data were retrieved from 2,528 wells from which a useful statistical study could be attempted. This study considered only conventional diameter wells drilled for production; slim holes and wells drilled specifically for exploration or injection or any unusual purpose were ignored.

### **POWER CAPACITY OF SUCCESSFUL WELLS**

There is no consensus in the geothermal industry as to what MW capacity level qualifies a well as successful; however, we often consider a 3 MW level the minimum required from a commercial well. Using this arbitrary definition, we were able to retrieve and verify the relevant database on 869 successful wells. Figure 1 presents a histogram of the

MW capacities of these 869 wells; this figure shows a crudely log normal distribution with a peak at 3 to 5 MW. Figure 2 is a plot of cumulative probability from Figure 1 versus MW capacity on a log scale; this figure indicates a median capacity of 7 MW. However, given the wide diversity of fields considered in the above plots, it was considered worthwhile to further analyze the well data on a field-by-field basis. Secondly, it would be worthwhile investigating the extent to which the “learning curve” effect affects the drilling success; this is addressed next.

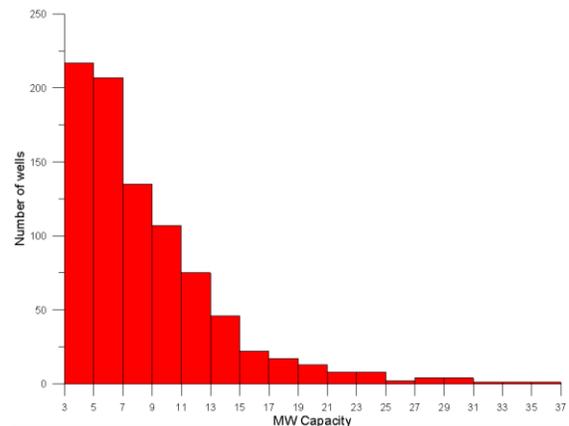


Figure 1: Histogram of Capacities of Productive Wells (3 MW or Higher) Worldwide (869 wells)

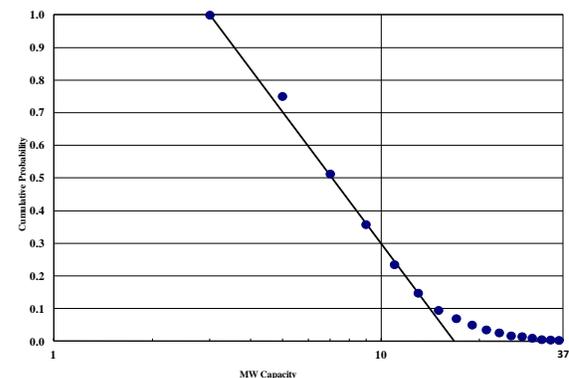


Figure 2: Cumulative probability vs. Capacities of Productive Wells (3 MW or Higher) Worldwide

### **THE LEARNING CURVE EFFECT**

Any task is expected to get faster or easier to conduct with practice. The learning curve concept in the management science literature uses a plot of a dependent variable, such as the time to complete a task against an independent variable (usually time) to represent the issue. (Adler and Clark 1991) Typically the learning curve follows the “Power Law of Practice” or an exponential trend. Since drilling is the most expensive and fundamental task in developing a geothermal field it is worthwhile looking into any

positive impact the learning curve effect may have on it. As regards the dependent variable in such an exercise one could consider the average MW capacity of wells or the drilling rate (meters per hour) and the independent variable could be the cumulative number of wells drilled; these issues are considered next for both the fields with a constant average well capacity and those with the average well capacity changing as more and more wells are drilled.

**FIELDS WITH CONSTANT AVERAGE WELL CAPACITY**

Figure 3 presents the cumulative MW capacity achieved versus the number of wells drilled in a specific field, namely, the Kamojang steam field in Indonesia (Sanyal et al, 2000; Suryadarma et al, 2010; Sanyal et al, 2011; Sanyal and Morrow, 2011). Figure 3 shows the statistics separately for both all wells drilled (red curve) and only the successful wells (blue curve), defined here as wells of at least 3 MW capacity. The ratio of the cumulative MW values from the red curve in Figure 3 to those from the blue curve should represent the average success rate in drilling in this field as a function of the number of wells drilled. Figure 4 shows the trend of drilling success rate thus estimated from Figure 3 as a function of the cumulative number of wells drilled (Sanyal and Morrow, 2011); this figure shows that in the exploration phase of drilling, the success rate fluctuated widely as more wells were drilled, the fluctuations declined steadily through the development phase and eventually stabilized in the operational phase at a level over 70%. Figure 5 presents the cumulative MW capacity following the exploration phase versus the number of wells drilled in this field; the red data points on this figure, and the next eleven figures following this one (Figure 6 through 16), represent unsuccessful wells. The data on Figure 5 can be readily fitted with a linear trend of about 4.9 MW average capacity per well with a very high correlation coefficient ( $R^2$ ) of 99.7%.

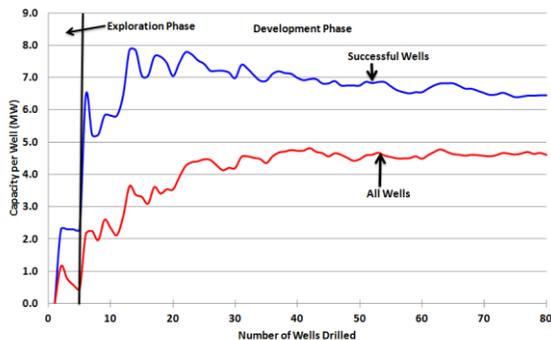


Figure 3: Average MW per Well vs. Number of Wells Drilled in the Kamojang Field, Indonesia

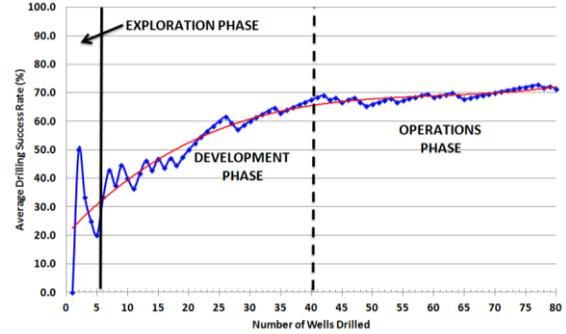


Figure 4: Average Drilling Success Rate vs. Number of Wells Drilled in the Kamojang Field, Indonesia

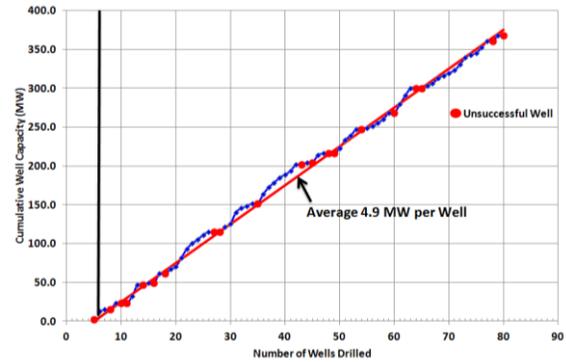


Figure 5: Cumulative Well Capacity versus Number of Development Wells Drilled, the Kamojang Field, Indonesia

The fact that there is a single consistent slope of the data trend in Figure 5 implies that this field apparently did not exhibit a significant and continuous learning curve effect in drilling as regards well productivity; had there been such an effect, the average MW capacity and success rate would have increased, or declined, as more and more wells were drilled. Therefore, as argued in Sanyal and Morrow (2011), the increasing drilling success rate versus the number of wells drilled (Figure 4) is not due to a continuous learning curve effect but rather due to the impact of a progressively larger sample size on statistics. We examine below if this observation holds true for the other fields studied here.

Figure 6 presents the cumulative MW capacity versus the number of the production wells drilled at The Geysers steam field in California, which has the largest number of wells drilled (more than 700 production, injection, exploration and special purpose wells) in any single geothermal field in the world. Figure 6 is similar to the case at Kamojang in that the production wells have shown a consistent average MW capacity (7.7MW) per well until about 315 wells were drilled, after which the MW capacity per well declined because of reservoir pressure depletion

(Sanyal and Eney, 2011). We conclude that there is little apparent impact of a learning curve effect on average MW capacity of wells in this field. However, our study shows that most fields do not show such a constant average MW capacity per well unaffected by drilling, and instead, a discrete learning curve effect appears to cause changes in the average MW capacity per well in a few (typically two) obvious and distinct steps as more wells are drilled in a field.

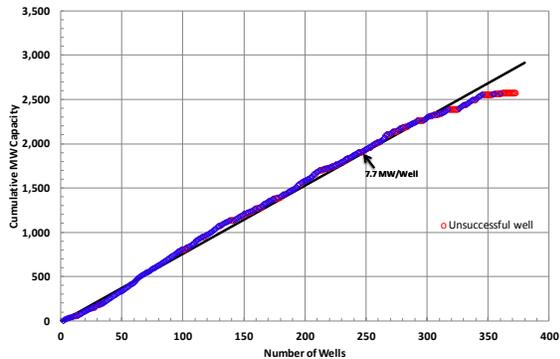


Figure 6: Cumulative Megawatt Capacity versus Number of Wells Drilled in the Geysers Steam Field

### **FIELDS WITH CHANGING AVERAGE WELL CAPACITY**

For most fields studied the drilling history represents a few episodes of constant average MW per well. Figure 7 and 8 show the cumulate MW versus the number of wells drilled in two high-temperature fields. In both figures, a constant average MW per well was achieved for the first 14 or 15 wells; thereafter, average MW per well increased abruptly. In figure 7, beyond the 135<sup>th</sup> well, the average MW per well stopped increasing, as a series of unsuccessful wells were drilled, due presumably to reservoir pressure depletion. In Figure 8, the average MW capacity per well increased from 4.6 to 8.1 MW between the 28<sup>th</sup> and the 74<sup>th</sup> well, after which it reverted to 4.6 MW until a total of 90 wells were drilled. Figures 9 through 11 show three more examples of abrupt increases in average well capacity in low-temperature and high-temperature fields.

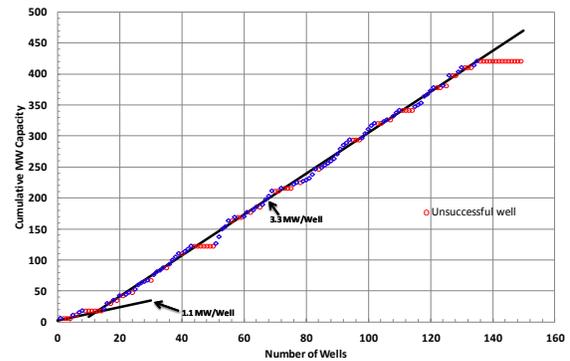


Figure 7: Cumulative Megawatt Capacity versus Number of Wells Drilled in a High-Temperature Field

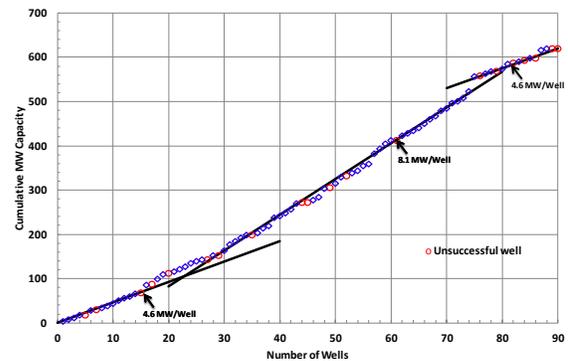


Figure 8: Cumulative Megawatt Capacity versus Number of Wells Drilled at a High-temperature Field

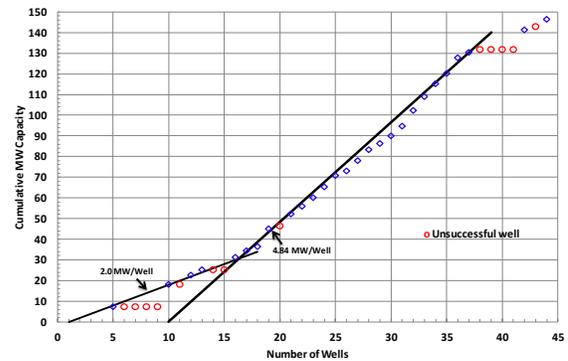


Figure 9: Cumulative Megawatt Capacity versus Number of Wells Drilled in a High-temperature Field

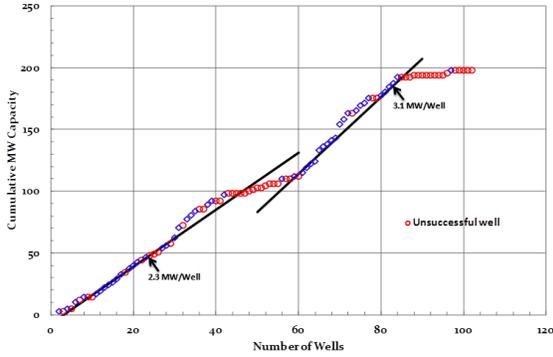


Figure 10: Cumulative Megawatt Capacity versus Number of Wells Drilled in a High-temperature Field

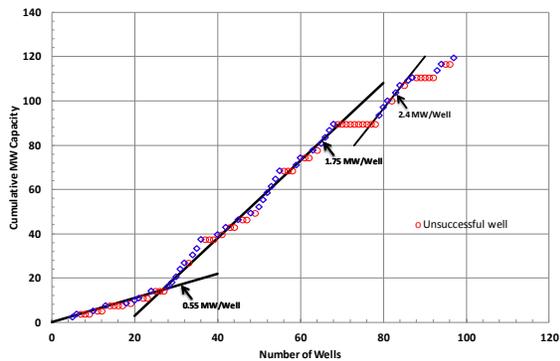


Figure 11: Cumulative Megawatt Capacity versus Number of Wells Drilled in a Low-temperature Field

However, in some fields the average MW per well declined, rather than increased, in a few discrete steps as shown in Figures 12 and 13, which show the cumulative MW capacity achieved versus the number of wells drilled in two high-temperature fields. Figure 12 also shows a relatively uncommon example of 100% drilling success in a 25-well drilling history.

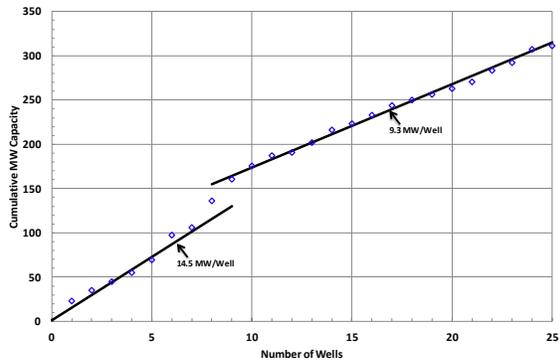


Figure 12: Cumulative Megawatt Capacity versus Number of Wells Drilled in a High-temperature Field

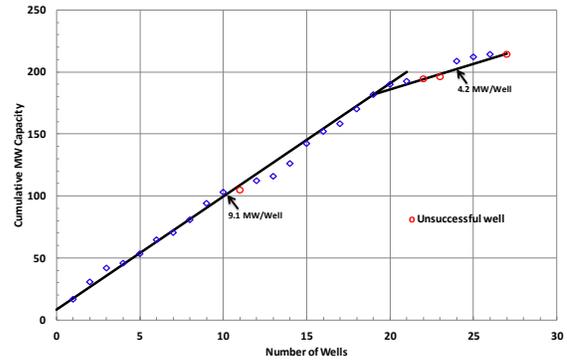


Figure 13: Cumulative Megawatt Capacity versus Number of Wells Drilled in a High-temperature Field

Figures 14 through 16 show less common examples of several rather arbitrary increases and decreases in average well capacity as drilling continued. Figure 16 also shows the unusual example of the average MW capacity plummeting, resulting in an episode of a paltry 18% drilling success rate, between the 10<sup>th</sup> and 34<sup>th</sup> wells before recovering robustly.

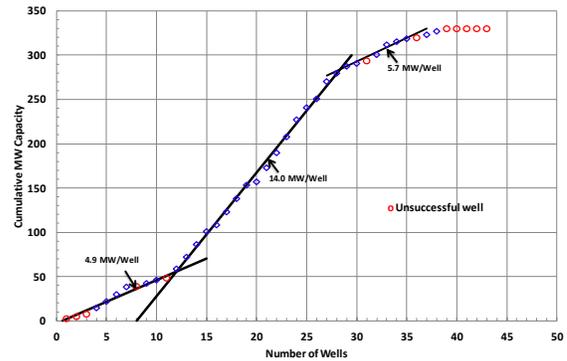


Figure 14: Cumulative Megawatt Capacity versus Number of Wells Drilled in a High-temperature Field

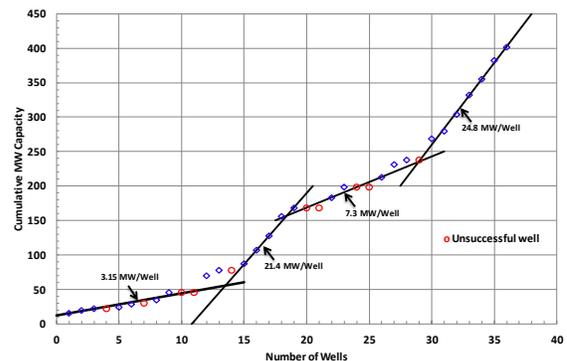


Figure 15: Cumulative Megawatt Capacity versus Number of Wells Drilled in a High-temperature Field

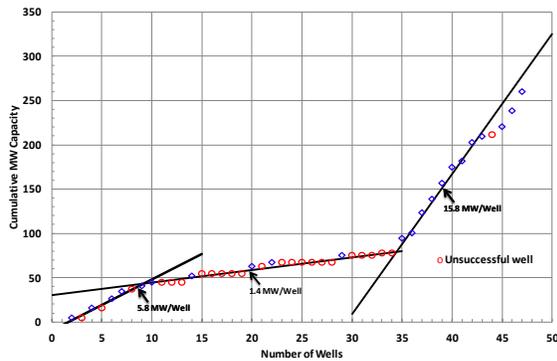


Figure 16: Cumulative Megawatt Capacity versus Number of Wells Drilled in a High-temperature Field

It is tempting to speculate on the circumstances that might give rise to the “step” changes in average well capacity as seen in ten of the 12 fields studied in detail (Figures 7 through 16) but not at Kamojang (Figure 5) or The Geysers (Figure 6). At both the latter fields, there exist relatively large numbers of wells in pure steam reservoirs. The large number of existing wells in these two reservoirs provide good controls on reservoir definition, and a steam reservoir intrinsically has more homogeneity in reservoir pressure and enthalpy than does a liquid reservoir. Therefore, it is not surprising that a constant average MW capacity per well exists in these two fields.

The rather unpredictable step changes in average well capacity in the 19 liquid-dominated fields could be due to the changes in the conceptual model of the field that affects well siting and or design. The conceptual model may concern purely geological constraints of where the fractures are or the distribution of the enthalpy of the fluids in the reservoir. A well shows higher MW capacity when it intersects open fractures and/or high-enthalpy zones.

The changes in the conceptual model of a field appear to be sparked by episodes of low drilling success. For example, Figure 16 is an example of a sharp decrease in average well capacity between the 10<sup>th</sup> well and the 34<sup>th</sup> well, when the capacity sharply declined from 5.8 to 1.4 MW per well and the drilling success rate plummeted to 18% (20 dry holes out of 24); following this episode the overall capacity jumped sharply. This clear episode of drilling failure motivated the developer to re-order the drilling strategy based on a revised conceptual model of the field. In several other fields the drilling of a series of unsuccessful wells (Figures 9, 10, 11 and 15) appears to have triggered an improved drilling strategy that resulted in improvements in average MW capacity.

In a number of fields with relatively long histories, unsuccessful wells appear to dominate drilling results in the operation phase (Figures 6, 7, 9, 10 and 14); we believe this is caused by reservoir pressure depletion upon prolonged operation.

### DRILLING SUCCESS RATE

Figure 17 presents the computed drilling success rate versus number of wells drilled for each of the 12 individual geothermal fields described above. This figure shows that drilling success rate fluctuates widely in the exploration phase, in the course which the first 3 to 5 wells are typically drilled. Beyond this phase the fluctuation in success rate subsides as more and more wells are drilled. Figure 17 shows that the drilling success rate eventually stabilized in the 45% to 100% range in these 12 fields, after about 40 wells were drilled.

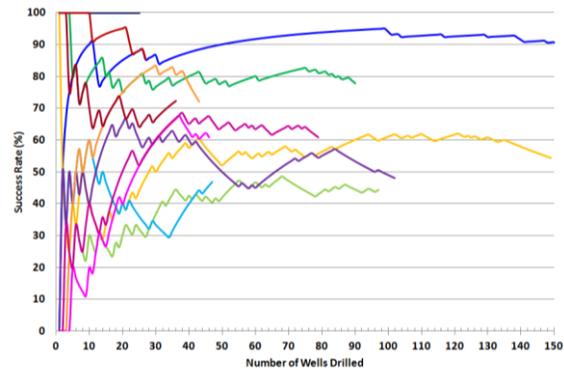


Figure 17: Average Drilling Success Rate in 12 Fields Worldwide

Drilling success rate in the 52 fields for which the data were verifiable were as follows:

Success Rate	No. of Fields
33% - 40%	4
41% - 50%	5
51% - 60%	9
61% - 70%	11
71% - 80%	10
81% - 90%	8
91% - 100%	5

The above table represents a normal distribution with a mean of about 68%. Figure 18 is a plot of the cumulative number of fields versus drilling success rate estimated in these 52 fields; this figure shows that the median drilling success rate is approximately 68%. The average MW capacity of all the 1,112 wells in these 12 fields amount to 71%.

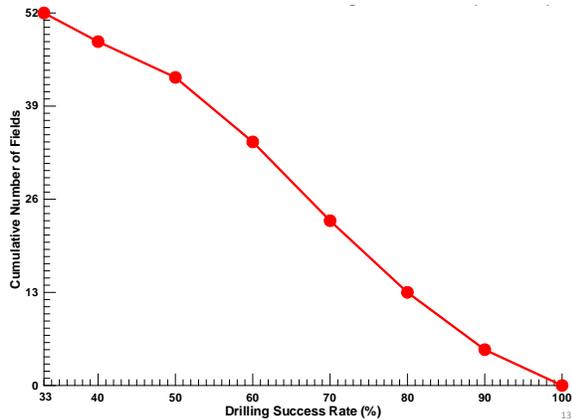


Figure 18: Cumulative of Number of Fields vs. Drilling Success Rate (52 Fields)

### WHERE THE LEARNING CURVE EFFECT EXISTS

We have shown that there appears to be no continuous learning curve effect on drilling success rate. However, in many fields we have seen that a continuous learning curve effect appears to impact positively the average drilling rate (meters drilled per day) so that the rate increases as more wells are drilled and eventually stabilizes after a relatively large number of wells. For example, Figure 19 presents the average drilling rate achieved versus the number of wells drilled at the Kamojang field; the rate stabilizes at a peak value of 20 m/day after some 45 wells were drilled. The rate versus number of wells data on Figure 19 can be re-plotted as a linear log-log plot confirming a classical learning curve effect trend.

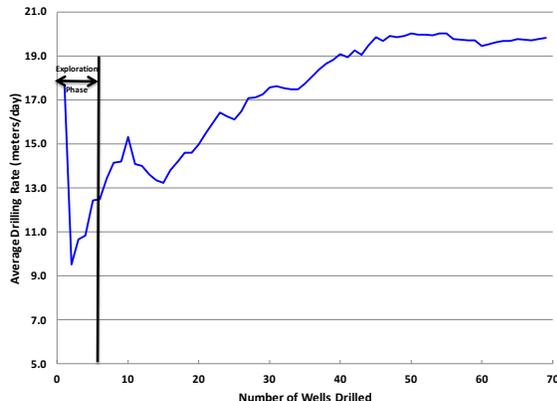


Figure 19: Average Drilling Rate vs. Number of Wells Drilled in the Kamojang Field, Indonesia

This learning curve effect improves the drilling rate, and as such, the economics of drilling because drilling time is the major component of drilling cost. Figure 19 shows that the drilling rate approximately doubled from about 10m/day in the exploration phase to about 20m/day after 45 wells were drilled; therefore, the drilling cost per well in the

development phase of this project was nearly halved through the learning curve effect.

### CONCLUSIONS

- The production capacity of 869 successful geothermal wells (defined here as wells of 3 MW or higher capacity) studied show a peak at 3 to 5 MW with a median value of 7 MW.
- Drilling success rate fluctuates widely in the exploration phase; the fluctuations gradually lessen in the development phase and eventually stabilize after a relatively large number of wells have been drilled.
- Based on the results from 52 individual geothermal fields with verifiable data, both the average and median success rates are about 68%. The average success rate estimated from detailed studies of 1,112 wells from the 12 fields studied in detail is 71%.
- The success rate in geothermal drilling varies from about 33% to 100% with a prevalent range of 60% to 80% and most likely as well as median values in the 68% to 71% range.
- This study did not detect in any field a continuous learning curve effect on drilling success rate. However, some sort of a learning curve effect appears to generally improve, and occasionally reduce, the average well capacity in a few obvious and discrete steps as more and more wells are drilled; no obvious reason could be found to explain these changes.
- A continuous learning curve effect on drilling success, if any, appears to be masked by the large statistical uncertainty for a relatively small sample size because of the limited number of wells drilled in a geothermal field.
- In most fields there is a continuous and positive learning curve effect on the drilling rate as more wells are drilled.
- The continuous positive learning curve effect on drilling rate and the discrete changes in average well capacity can strongly affect the overall economics of drilling, that is, the MW capacity achieved per unit drilling cost.

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