An Investigation of Drilling Success in Geothermal Exploration, Development and Operation

Subir K. Sanyal and James W. Morrow

GeothermEx, Inc., Richmond, California
mw@geothermex.com

Keywords
Drilling success, drilling success rate, drilling risk, learning curve

ABSTRACT

This paper presents a statistical investigation of drilling success in the exploration, development and operation phases of a geothermal power project. Drilling "success rate" is shown to be an awkward concept; it is argued that drilling success is better represented by the average cost per MW capacity secured from a drilling program. The case histories of the Kamojang field in Indonesia and a project at The Geysers field in California are used to illustrate some of the concepts. More than 80 exploration, development and make-up wells have been drilled and commercial power has been produced in the Kamojang field over the last three decades. Fifteen wells were drilled initially at the above-referenced project at The Geysers field, which has been providing commercial geothermal power for three decades now. It is shown that the average drilling success rate improves as more wells are drilled due both to its inherent statistical nature, which becomes better defined with an increasing sample size, as well as due to the "learning curve" effect. For the two case histories presented, the learning curve effect was found to be relatively minor compared to the statistical effect. It is concluded that there is little basis on which to estimate the drilling success rate in exploration, and drilling success rate ranges from 60% to 100%, and typically 70% to 90%, in the development phase, and greater than 90% in the operation phase.

Background

Drilling success is a prominent area of risk in any geothermal project, but forecasting the level of this risk in any specific project is generally a matter of speculation or an educated guess based on empirical data from similar projects. However, the existence of a statistically significant empirical database from substantially similar projects would be generally uncommon. This leads to various myths about what level of drilling risk to expect in a new project, particularly in a specific stage of the project, such as, exploration, development or operation. This risk is often represented as the drilling success rate, that is, what fraction of the wells drilled are successful in any given phase of the project or over the whole project life. However, what is meant by a successful well is often not explicitly stated, which reduces the statistical dependability of a stated drilling success rate. If a drilled well fails to produce, it is obviously an unsuccessful well, a classic "dry hole." But a well that cannot self-flow can often be flowed at a commercial flow rate by the use of a downhole pump. A well cannot be considered successful if the well can neither self-flow nor can be pumped because the well has too low a productivity index or internal diameter of the production casing is too narrow to accommodate a pump or the fluid temperature is higher than the temperature limit of the pump. Although not a dry hole per se, a well that produces water too cool for commercial use would also be an unsuccessful well.

Even if a well can self flow or can be pumped, what is the threshold of well success in terms of flow rate or power capacity? This is often not explicitly specified when reporting a well success. A well capacity of at least 2 or 3 MW is often considered successful, but whether it is gross MW or net MW (after deducting the parasitic power used for pumping) maybe left out of an announcement on well success. Then, there is the basic question of commerciality. A 2 or 3 MW (net) well would be commercial if it is a relatively shallow well costing on the order of a million dollars but may be non-commercial if the well were deep, costing several million dollars. Therefore, we believe "drilling success rate" is an awkward concept; power capacity achieved per dollar spent in drilling is a better measure.

To complicate matters further, the economic success of a well of a certain net power capacity for a certain drilling cost would also depend on the power price for the project. A one MW capacity per million dollar drilling cost is a success story when the power price is 10¢/kW.hour but presents a grim prospect at a 6¢/kW.hour power price. Therefore, even expressing drilling success rate in MW per unit drilling cost does not entirely eliminate the problem.

Notwithstanding the above limitations in defining the drilling success rate, this paper attempts a statistical investigation of this parameter based on statistical theory as well as case histories of some commercial projects.

Why are Some Wells Unsuccessful?

In geothermal fields, a “dry hole” is a rarity; all geothermal wells flow to some extent. However, a geothermal well may be deemed unsuccessful for one or more reasons discussed earlier, for example:

(a) it encounters unexpected mechanical problems during drilling, and is partly filled or bridged by drill cutting and/or casing collapse;

(b) it has an inadequate temperature;

(c) it has too low a static pressure;

(d) it encounters a reservoir that is too “tight” (that is, the productivity index is low); and

(e) it has unacceptable chemical problems (such as, gassy, corrosive or scaling-prone fluids).

This paper considers a well as unsuccessful if it fails to show a power capacity above an assumed threshold level whichever combination of the above causes may have caused that.

Statistical Nature of Drilling Success

If of n wells drilled, r are successful, then from the classical principle of binomial probability distribution, the probability (þ) is given by:

$$þ = \frac{n!}{r!(n-r)!}(S)^r(1-S)^{n-r},$$

where each well has a discrete binary probability S of being successful. Assuming a binomial probability distribution, one can estimate the most likely average success rate in drilling a given number of wells drilled; Figure 1 shows such probability distributions assuming an even chance of success (50%) for any individual well. This figure shows that as more wells are drilled, the probability distribution develops a stronger central tendency around a 50% probability of success (as for an individual well). In any practical drilling program, only a finite number of wells are drilled; therefore the actual average success rate would be different from 50%, which is the most probable value. For example, Figure 1 shows that for a 30 well drilling program with an even chance of success for an individual well, the average success rate could be as low as 25% to as high as 75%, the most likely still being 50%.

Therefore, as more wells are drilled, the average success rate typically increases due to the inherent statistical nature of drilling success. Additionally, as more wells are drilled the developer improves his skill and knowledge of the project. This “learning curve” effect could also contribute to the average drilling success rate as more wells are drilled. There is no straight forward way to separate the purely statistical effect from the learning curve effect on the success rate in a given drilling program.

Case History of the Kammojang Field

Figure 2 presents the average drilling success rate versus number of wells drilled over two decades at the Kamojang field

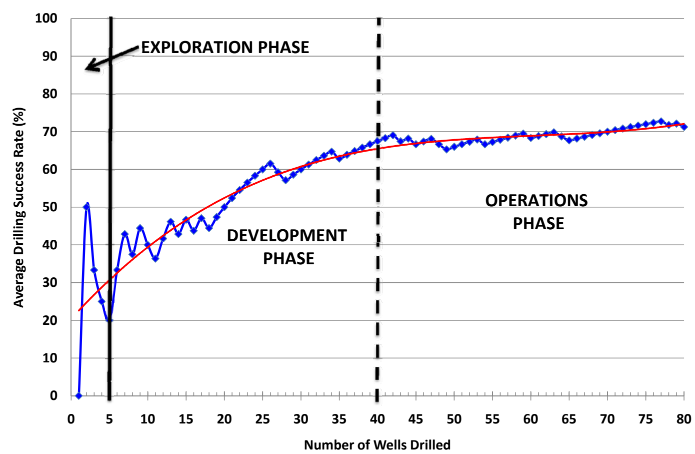

Figure 2. Average Drilling Success Rate vs. Number of Wells Drilled at Kamojang Field, Indonesia.

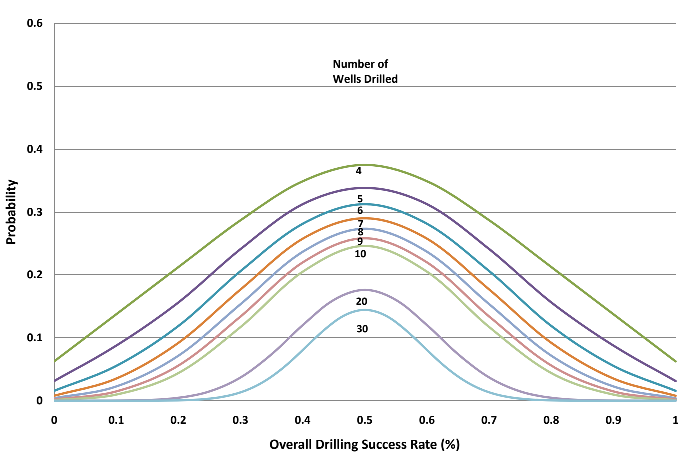

Figure 1. Probability versus Overall Drilling Success Rate (50% chance of success with an individual well).

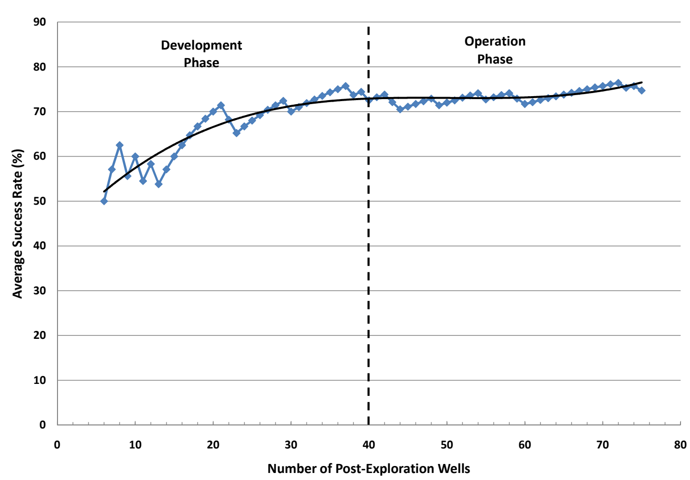

Figure 3. Success Rate in Development Drilling at Kamojang.

in Indonesia, a successful well being one with a capacity of at least 3 MW (net). Drilling success rate in Figure 2 increased with the number of wells drilled until at least 40 wells were drilled, of which the first 5 were exploration wells, the next 35 were development wells and the last 40 were drilled in the operational phase of the project. The average success rate in drilling development wells (that is, post-exploration wells) stabilized at about 75% (Figure 3).

Figure 4 shows the average MW capacity achieved per well, considering all wells drilled as well as considering only the successful wells, versus the number of wells drilled at Kamojang. Again, the average capacity of all wells drilled and of only the successful wells both increased as more wells were drilled and eventually stabilized, at 4.75 MW for all wells drilled over the entire project life and 6.6 MW for the successful wells only. The ratio of 4.75/6.4 is 0.743 which is nearly the same as the level at which the average drilling success rate stabilized (Figure 3); this confirms the internal consistency of this database. It should be noted that after 20 wells were drilled the capacity per well became nearly constant, implying little lingering learning curve effect. Figure 5 is a plot of the cumulative well capacity (MW) achieved versus the number of wells drilled, with red circles indicating unsuccessful wells. Considering that of the 5 exploration wells drilled, only one was successful (Figure 5), the success rate in exploration drilling was only 20%. Of the 35 development wells drilled, 9 were unsuccessful and 26 were successful (Figure 5); this gives a development drilling success rate of 74.3%, as also seen from Figure 3. The linearity of the data trend implies a minimal learning curve effect in that it indicates a steady average well capacity of 5 MW for wells throughout the development and operation stage. This conclusion supersedes Sanyal et al (2011)'s earlier speculation about the learning curve effect on drilling success at the Kamojang field.

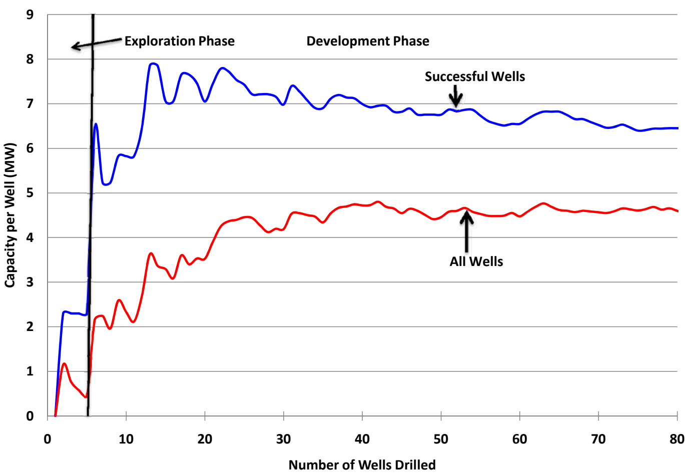

Figure 4. Average MW per Well vs. Number of Wells Drilled in Kamojang Field, Indonesia.

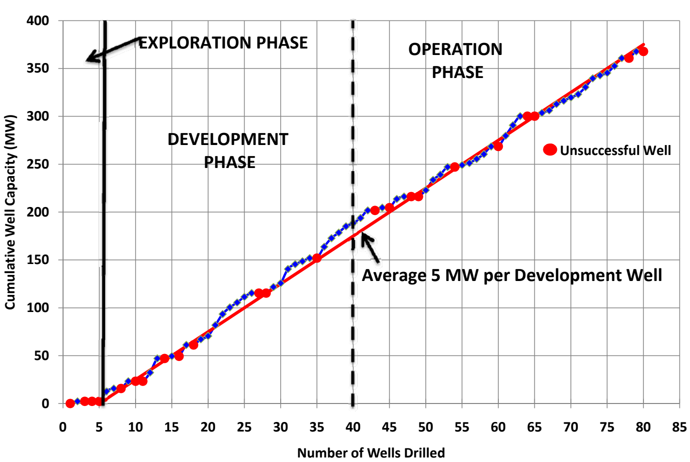

Figure 5. Cumulative Well Capacity versus Number of Development Wells Drilled, Kamojang Field, Indonesia.

Case History of a Project at The Geysers Field

Figure 6 shows the average drilling success rate for this project, assuming at least 3 MW capacity for a successful well, versus the number of exploration and development wells drilled. The first exploration well for this project was successful, giving a 100% success rate in exploratory drilling. But the second well was unsuccessful, reducing the average success rate to 50%. However, the well was not completed but re-drilled; upon redrilling (considered as the third well in Figure 6) this well was successful. Therefore, the drilling success rate in exploration effectively increased to 66.7%, and field development started in earnest at this point. Thirteen more wells, all successful, were drilled in the development phase with the overall average success rate increasing gradually from 66.7% to 93.0% as more and more wells were drilled.

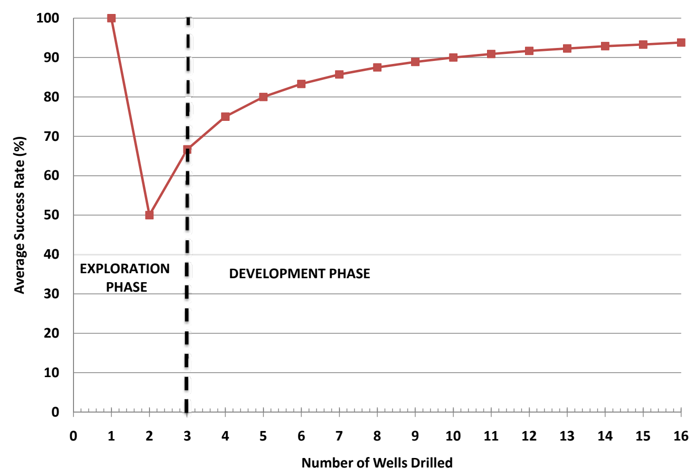

Figure 6. Case History of a Project at The Geysers Field, California Success Rate.

Figure 7, overleaf, shows a plot of the cumulative well capacity achieved in this project versus number of wells completed; in this figure only "completed" wells were included, ignoring the second well, which was not completed but re-drilled. Figure 7 shows that the average capacity per completed well was 8.5 MW for the first 8 completed wells, but jumped to 11.8 MW for the subsequent wells. This cause of this increase is unknown, but appears to be due to some sort of a change in drilling strategy, and a corresponding jump in the learning curve.

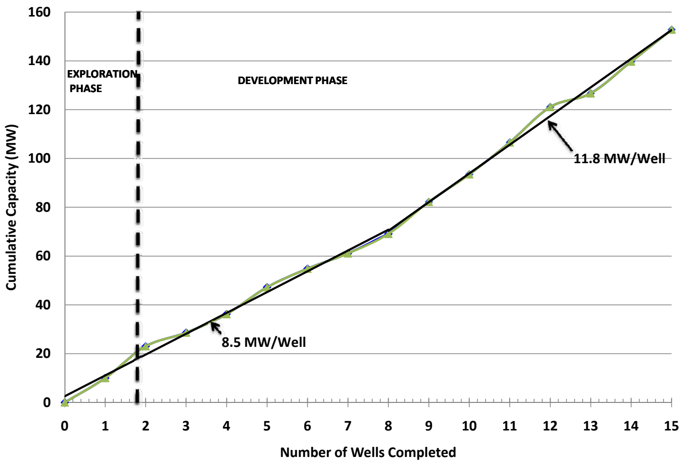

Figure 7. Cumulative Power Capacity of a Project at The Geysers Field, California.

The Learning Curve Effect in Drilling Success

One would expect a positive learning curve effect in drilling success as more wells are drilled. But it is difficult to separate the impact of this effect on the average drilling success rate relative to the purely statistical effect due to achieving a larger sample size as more wells are drilled. Figure 8 shows a theoretical curve illustrating the impact of the learning curve on a 5-well drilling program. The dashed curve in Figure 8 shows the probability of drilling various numbers of successful wells in a 5-well drilling program assuming an even chance of success for any individual well. This figure shows that both 2 or 3 successful wells out of 5 wells drilled have the same likelihood of 31.25%. Let us arbitrarily assume that the first well has a 50% chance of success but due to the learning curve effect, this chance rises to 55% for the second well, 60% for the third well, 65% for the fourth well and 70% for the fifth well. With these assumptions, the solid curve in Figure 8 shows the calculated probability of drilling various numbers of successful wells. It is clear from Figure 8 that the learning curve effect increases the probability of drilling 3 successful wells from 31.25% to 35%, a rather modest improvement. Figure 9 compares the cumulative probability of drilling a minimum number of successful wells in a 5-well program assuming a 50% chance of success for an individual well (red, solid curve) and assuming the learning curve effect to be as described before (dashed blue curve). Figure 9 indicates that the maximum impact of the learning curve effect is seen in the cumulative probability of getting at least 3 successful wells out of 5 increasing from 50% to 70%; this is a significant impact but not a major one.

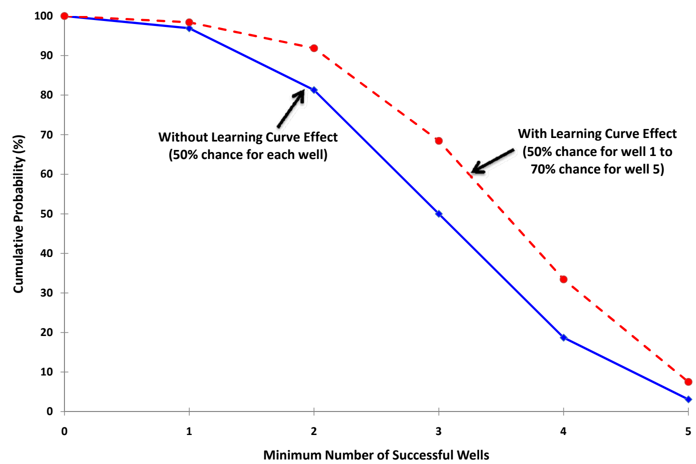

Figure 9. The Effect of Learning Curve on a Five-Well Drilling Program.

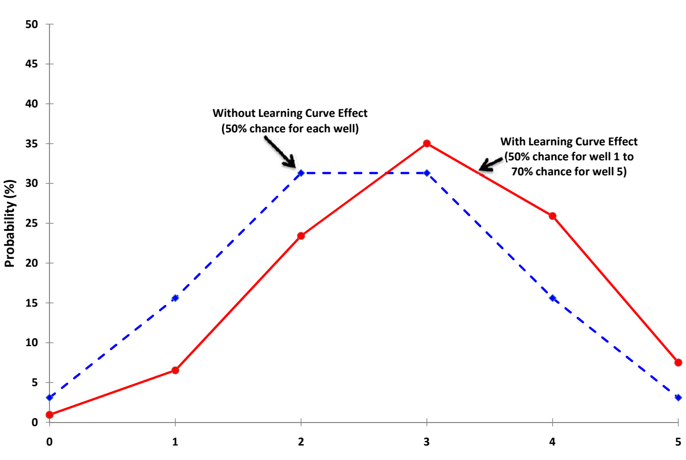

Figure 8. The Effect of Learning Curve on a Five-Well Drilling Program.

Let us now assess to what extent the learning curve effect had affected the drilling results at Kamojang. If the learning curve effect were strong, one would expect an increasing well capacity as more wells are drilled; however, Figure 5 indicates this is not the case at Kamojang. This conclusion is verified in Figure 10. The solid curve (blue) in Figure 10 shows the probability of no drilling success as a function of the number of wells in the drilling program for a 75% chance of success in drilling an individual well (equivalent to the stabilized rate seen in Figure 3 for Kamojang). On Figure 10 is also shown, by the dashed curve, the percent of drilling success achieved at Kamojang for various assumed numbers of wells in a sample. The data for this (red dashed) curve are tallied from Figure 5 for various sample sizes of consecutive sets of wells drilled. In Figure 10 we also show the probability of no

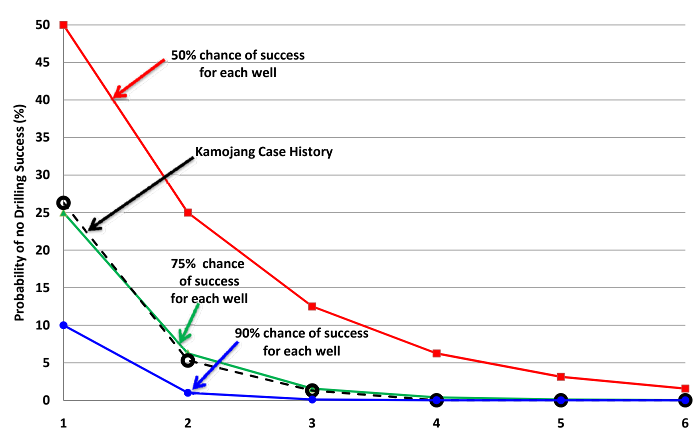

Figure 10. Probability of No Success versus Number of Wells in the Drilling Program.

drilling success as a function of the number of wells drilled for an even chance of success in drilling an individual well. Figure 10 shows a good match between the calculated probabilities and those experienced at Kamojang 75% discrete probability of success in drilling an individual well. Therefore, we conclude that at Kamojang any impact of the learning curve effect has been minor compared to the statistical impact of a larger sample size of wells with a fixed 75% probability of success for any individual well. In other words, the probability of success in drilling any individual well did not increase significantly at Kamojang as more wells were drilled.

Drilling Success Rates in the Various Stages of a Project

For Kamojang and The Geysers project, the drilling success rates initially fluctuated sharply as more and more wells were drilled (Figures 2 and 6). This fluctuation reflects the problem of making conclusions from small sample sizes of wells drilled in the exploration phase. Figure 1 implies that because only a few wells are drilled in the exploration phase of a project it is impossible to reasonably characterize the drilling success rate. Given the basic uncertainty in defining what constitutes a successful well and the small number of wells drilled, there is no reasonable basis to assess the success rate in exploratory drilling.

The case histories shown indicate that the drilling success rate stabilized during the development phase. This has also been our experience in other commercial geothermal projects. At Kamojang and at The Geysers project, the success rate in the development drilling phase stabilized at 75% and 100%, respectively. Based on the results of development drilling in many commercial projects we find the success rate to be in the 60% to 100% range, and typically 70% to 90%. For example, at The Geysers field, where about one thousand wells have been drilled, we have observed that roughly two-thirds of the development wells drilled have been successful, and upon redrilling, about half of the unsuccessful wells were rendered successful. Therefore, the overall success rate in development drilling at The Geysers has been about (⅔ + ½ (⅓)), that is, 83.4%. Sanyal et al (1989) assumed a success rate of 80% to 95% with equal probability in assessing the economics of power generation at The Geysers.

In the numerous operating projects we have been involved in, drilling success rate in the operation phase (generally for make-up well drilling) has been higher than 90%. Drilling in the operation phase at The Geysers also has generally been higher than 90%.

Conclusions

1. Drilling “success rate” is an awkward concept; it is better represented by the average cost per MW capacity secured from a drilling program.
2. There is little basis for forecasting drilling success rate in the exploration stage
3. Average success rate in a drilling program increases with the number of wells drilled due to the effect of an increasingly larger statistical sample size and the learning curve effect; the learning curve effect appears to have a relatively minor impact on drilling success for the two cases cited.
4. Drilling success rate in the development stage is expected to be in the 60% to 100% range, and more typically 70% to 90%.
5. Drilling success rate in the operational phase is expected to be higher than 90%.

References

Sanyal, S.K., R.C. Henneberger and P.J. Brown, 1989. Economic Analysis of Steam Production at The Geysers Geothermal Field, California, Trans. Geothermal Resources Council, vol. 13, pp. 423-430, October, 1989.

Sanyal, S.K., J.W. Morrow, M.S. Jayawardena, N. Berrah, S.F. Li and Suryadarma, 2011. Geothermal Risk in Indonesia – A Statistical Inquiry, Proc. Thirty-Sixth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 31 – February 2, 2011, SGP – TR-191.