The Rate of Success of Geothermal Wells Drilled in Nevada

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ABSTRACT

Numerous assertions have been made regarding the success rates of geothermal well drilling, with difficulties obtaining early-stage financing often attributed to the relatively low drilling success rate. Typically, data intended to evaluate this issue have not been collected in a consistent manner, and "success" depends upon whether one considers exploration, confirmation or production wells. Exploration and confirmation wells in particular are difficult to quantify relative to a success rate, as their purpose is largely data/information gathering. Well permitting records are reported by state agencies and well production is reported monthly (in NV), so one can only determine in retrospect which of the permitted wells actually led to geothermal production and power generation. This paper compiles and evaluates geothermal well records submitted to the Nevada Division of Minerals, and estimates success rates in Nevada from the 1970s and 1980s exploration efforts through construction of the current power plants. The number of wells drilled (all wells including exploration) per MW of production ranges from 0.65 at Dixie Valley to approximately 33.1 at San Emidio. The number of wells drilled per MW of production at eight sites (excluding San Emidio) is 3.1 ± 1.8. The average number of feet drilled per MW of production at the nine sites investigated was 6,644 ± 3,781 ft (including all exploration wells), ranging from 3,528 ft at Bradys to 14,555 ft at San Emidio. If only production, injection, and observation wells required for development are considered, the average ft/MW is 2,093 ± 878 ft, ranging from 1,414 at Bradys to 3,655 at Soda Lake. Production well success rates (percent of those use as production that were drilled for production), following successful exploration and confirmation efforts range from 60-66% at the nine power producing sites investigated in Nevada.

Introduction

This paper compiles and evaluates geothermal well records submitted to the Nevada Division of Minerals in order to estimate success rates of geothermal wells drilled in Nevada. These data are currently being compiled for inclusion into the National Geothermal Data System (NGDS), and are available from early-stage exploration in the 1970s and 1980s through construction of the power plants. Permitted wells data are used to calculate total and average well depths by producing area. It is common to hear comments related to the "success rate" of geothermal wells in the context of overall development costs and financing, with numbers on the order of 50-75% commonly used to estimate the success rate (typically in reference to production wells). These types of assertions are often in the context that individual production wells cost $3-5 million, with the implication that even unsuccessful wells may cost a developer up to $5 million. Such risk-benefit scenarios may be difficult to present to investors, certainly if the first two or three wells drilled in a new area fall into this category. However, aside from a study by GeothermEx (2004), this author is not aware of a study of such specific information, in large part because the types of data needed to evaluate success rates are often held proprietary by the power plant owners and operators. However, a fairly comprehensive report by Hance (2005) indicates that the first wildcat well has a 25% success rate, whereas confirmation drilling successes approach 60%, and development wells successes average 70-80%. In this paper we attempt to determine the success rate of geothermal well drilling in Nevada using publicly-available data, and present this data in the context of how many wells are actually used for production and injection in a commercial operation.

All drilled wells are included in this analysis because, although many wells are not used in production, all drilled wells help define an individual resource, which in turn should increase success rates for future production and injection wells. These well data are available from the Nevada Division of Minerals (DOM) for nine currently producing power plant areas (that may include one or more commercial units each) in Nevada us-

ing available data through 2010 (e.g., more than nine areas are producing, but the more recently constructed power plants do not yet have sufficient data for evaluation). These data are currently being compiled and quality checked for inclusion into the National Geothermal Data System (NGDS) to be made publicly and freely available through several user interfaces.

Method

The Nevada Division of Minerals (DOM) maintains files of geothermal wells permitted by the state, including domestic, exploration (geothermal gradient, test wells), observation, industrial injection and production wells. Their records indicate whether a permit expired prior to well drilling, and thus, a large number of permitted, undrilled sites can be removed from any counts of wells drilled. The DOM also maintains records on monthly well production and injection volumes by well (from 2002 onward), which indicates if permitted wells were actually drilled and put into production. Prior to 2002, records are not available to determine which of the permitted wells were used for production and injection. However, it can reasonably be assumed that any wells producing in 2002 were likely in production since the commissioning (or shortly thereafter) of the original power plant (plus or minus one or two wells) because there was a lull in geothermal exploration and expansion activities from the late 1990s into 2005. Two periods of time are evaluated for each producing power plant: pre-commissioning (including all wells permitted for exploration up to and including plant construction), and post-commissioning (including wells drilled to better define and expand the resource). Each set of data for the individual power producing operations (Steamboat being considered as one area/operation) is evaluated to determine how many wells were drilled in comparison to how many were actually used in commercial production and injection. Note that well depths for more recent wells in the DOM-maintained database are only the permitted depth, not the actual depth drilled, and also, that many of the older wells do not list any depths at all. Hence, any estimates of total feet drilled or the number of feet per well averages are all underestimates due to the incomplete data reported for depths of the wells.

Each area is evaluated to determine the number of wells drilled versus the number of wells actually used in geothermal power generation. In each set of tables, the well counts are arranged by the date, with two categories being formed: the dates prior to the commissioning of the first power plant at the site, and the dates after the first power plant was constructed. Within each of these two categories, the wells were subdivided as follows: D for Domestic, E for Exploration, I for Injection, O for Observation, and P for Production. In some cases the production and injection wells are lumped in the original data as Industrial or Commercial wells, in which case it is assumed those wells are production wells. It can be assumed that wells would have been labeled as injection if indeed they were because injection well permitting requires a unique form distinct from the other permitted wells. The following were categorized as exploration wells: exploration, test, stratigraphic test, thermal gradient, and geothermal wells.

Background

Figure 1 shows the locations of the operating power plants in Nevada as of mid-2012.

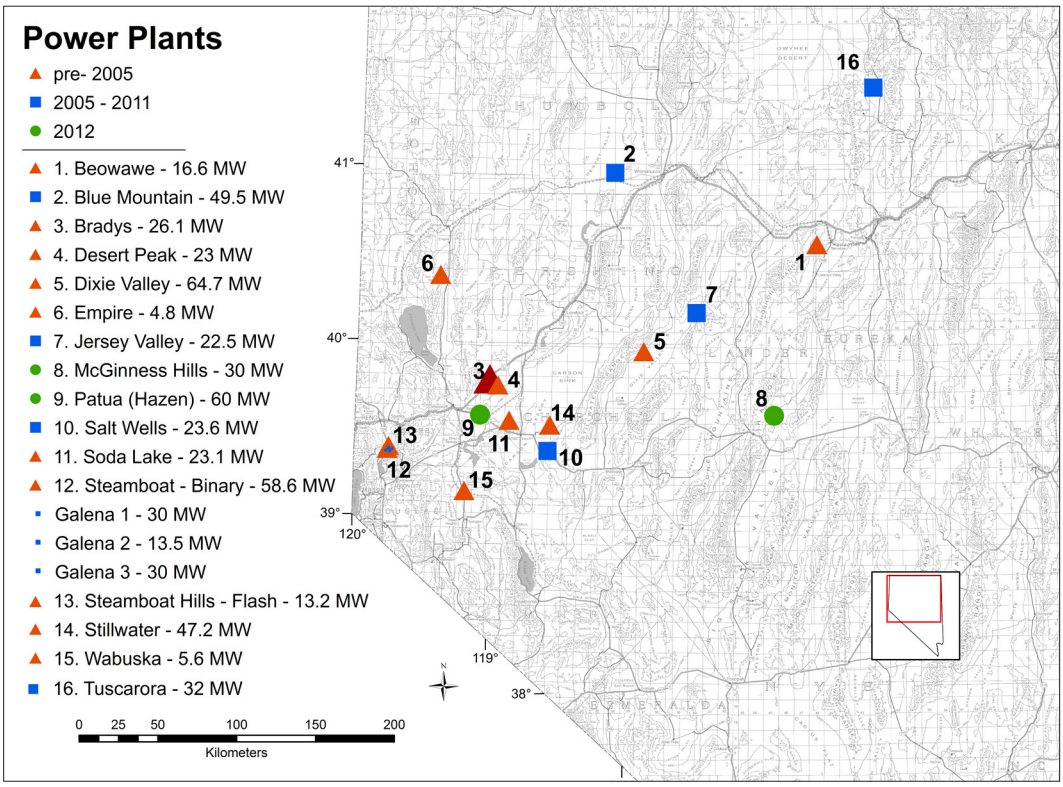

Figure 1. Location of existing and planned power plants in Nevada. Steamboat-binary consists of 6 separate power plant units that have a combined generating capacity of 137 MW. Only the three new plants constructed since 1992 are listed separately under the binary category. The MW numbers are nameplate capacities and not actual production capacities in any given year.

Current capacity and year of commissioning for the existing power plants shown in Figure 1 are listed in Table 1. Locations of these power plants are illustrated in Figure 1.

The MW numbers quoted above are nameplate capacities (typically the maxima), which are relatively elusive numbers, and often the values reported year to year by the operators vary slightly (±5 MW). Nameplate capacity is the manufacturer's rating of equipment output capacity as reported to the Nevada DOM by the plant operators (as of February, 2012) and does not necessarily

Table 1. Nevada geothermal power plants as of spring 2012.

Plant name (year on line)	Nameplate Capacity (MW)	Year Commissioned	Location	Operator
Beowawe	16.6	1985	S13,T31N,R47E	TerraGen Power, LLC
Blue Mountain*	49.5	2009	S14,T34N, R34E	Nevada Geothermal Power
Bradys	26.1	1992	S12,T22N,R26E	Ormat Nevada
Desert Peak (Decommissioned)		1985	S21,T22N,R27E	Ormat Nevada
Desert Peak II (2006)	23.0	2006		
Dixie Valley	64.7	1988	S7,T24N,R37E	TerraGen Power, LLC
Empire	4.8	1987	S21,T29N,R23E	USG Nevada LLC
Jersey Valley*	22.5	2011	S28,T27N,R40E	Ormat Nevada
Salt Wells*	23.6	2009	S36,T17N,R30E	Enel North America
Soda Lake No. 1	5.1	1987	S33,T20N,R28E	Magma Energy Corp
Soda Lake No. 2	18.0	1991	S33,T20N,R28E	
Steamboat I[1]	8.4	1986	S29,T18N,R20E	Ormat Nevada
Steamboat I-A	2.4	1986	S29,T18N,R20E	
Steamboat II	23.9	1992		
Steamboat III	23.9	1992		
Galena	30.0	2005		
Galena 2	13.5	2007		
Galena 3	30.0	2008		
Steamboat Hills (1988, formerly Yankee Caithness)	13.2	1988	S5,6,T17N,R20E	
Total MW at Steamboat			**136.9**	
Stillwater (1989) isolated from the grid; shut down		1989	S1,T19N,R30E	Enel Stillwater
Stillwater 2	47.2	2009	S6,T19N,R31E	
Tuscarora*	32.0	2012	S2, T41N, R52E	Ormat Nevada
Wabuska	5.6	1984	S15,16,T15N,R25E	Homestretch Geothermal
Total	**475.6**			

[1] Ormat decommissioned the Steamboat I plant.
* These sites are not included in the data evaluation below because insufficient data are available

reflect the capability of the currently developed resource. These nameplate capacities are estimates, and several different values can be found in the literature. Generator nameplate capacity actually refers to how big the actual generator is but not the turbines or the actual capacity of the power plant. There are no public documents breaking down nameplate capacity of the turbines or gross power so these numbers may not adequately reflect actual generation (Dan Fleischmann, pers. comm., Ormat, June 2010).

A brief description of the new power plants constructed between 1992 and 2011, and the relationship between the number of permits and drilled wells can be found in Shevenell and Zehner (2011). Earlier descriptions are found Garside et al. (2002) and in the annual Nevada Mineral Industry reports (http://www.nbmg.unr.edu/dox/mi/XX.pdf, where XX are the last two digits of the individual year from this annual report series, which was first published in 1979 for 1978 information).

Results

General Summary

An overall summary of results from all sites is provided, followed by a comparison of site observations. Most of the currently producing power plant areas do not have permitted domestic wells, except for 28 permitted wells at Steamboat, two at Soda Lake, and three at Stillwater. Beowawe, Bradys, Desert Peak, Dixie Valley, San Emidio, and Wabuska all had no domestic wells permitted, and hence this well type is not discussed further in this paper. Note that the most recently commissioned plants (Jersey Valley, Salt Wells and Blue Mountain, Tuscarora) have a paucity of depth and production (use) data because they were recently commissioned, and records had not been updated as of May 2012, so that depth and industrial use data are not available for these newer wells, and hence, post-commissioning depth and use totals are not reported here. Data compilation is generally only complete through 2010 at the other sites, and observations and statistics are presented below for the data set from approximately the 1940s (in a small number of cases) through 2010 at the plants commissioned between 1984 (Wabuska) and 2008 (Galena 3 at Steamboat). Because Steamboat has several different power plants, which often use wells interchangeably among them (either continuously or sporadically), the Steamboat area is considered in total, and not by individual power plant unit.

Well Use – All Wells

First, the intended use of the industrial geothermal wells is investigated. A well drilled for the purpose of injection may ultimately be used as a production well, and as vice-versa, as well as other combinations of intended versus actual use. Table 2 summarizes the well permitted use versus the actual use of the well, focusing only on wells that are actually used in a geothermal power production operation.

Clearly, not all wells drilled are used for industrial (P or I) purposes, and some wells drilled for other purposes (E and O) ultimately become industrial development wells (P and I). A total number of 143 wells have been in use as either P (80 wells) or I (61 wells) at the nine power plant areas investigated. One well (0.7%) initially permitted and intended as a P well was ultimately categorized as an E well, and one well (0.7%) initially intended as an injection well was used as an observation well. Fifty-six percent of the wells drilled to be industrial wells were used as production wells, and 43% of the industrial operation wells were used as injection wells.

One well permitted as an exploration well was used as a production well (at Steamboat), and seven wells permitted as exploration wells were used as an injection wells (Beowawe and Brady, Table 2). Hence, a relatively small percentage of all wells used (per wells used) were converted from exploration to industrial (5.7%), and a smaller percentage (3%) of the total wells drilled as exploration wells (265 wells) were ultimately used in the power generation operation. Hence, the number of wells permitted as exploration wells that are ultimately used in the power generation

Table 2. Wells used as industrial (injection or production; I or P) at each site. No other types of use are included.

	Drilled as	Number Drilled as	used as E	P	O	I
Beowawe	E	1				1
	P	3		3		
	O	1				1
	I					
Bradys	E	6				6
	P	5		5		
	O	2		1		1
	I	5		1		4
Desert Peak	E					
	P	7	1	6		
	O					
	I	2				2
Dixie Valley	E					
	P	18		12		6
	O					
	I	5				5
San Emidio	E					
	P	5		2		3
	O	5		3		2
	I	2				2
Soda Lake	E					
	P	3		3		
	O	2		2		
	I	5		2	1	2
Steamboat	E	1		1		
	P	28		22		6
	O	3		1		2
	I	7		2		5
Stillwater	E					
	P	13		10		3
	O	1				1
	I	11		2		9
Wabuska	E					
	P	2		2		
	O					
	I					
Total wells		**143**	**1**	**80**	**1**	**61**

operations is minimal, although the information gained from these exploration wells to properly locate the future industrial wells is significant, but difficult to quantify.

Eighty-nine percent of the industrial wells used at the nine sites were originally permitted as industrial wells (either P, I or O). Of the wells intended to be production wells, 59% were ultimately used as industrial wells. Of the wells intended to be injection wells, 26.6% were ultimately used as industrial wells (Table 2). All of the wells listed in Table 2 as observation wells were converted to industrial production or injection wells after completion. Nevertheless, one of the statistics provided below includes a category of all industrial wells drilled to include P+I+O, because the number converted from observation to industrial is significant (10% of the wells noted in Table 2 that became P or I wells were initially drilled as observation wells). Most (89%) of the observation wells drilled are not reflected in Table 2 and were not converted to industrial wells after completion (see Tables 3 and 4). This would necessarily result in smaller calculated success rates because many of the O wells were never intended for industrial use. Hence, statistics using P+I+O will result in minimum success rates.

Number of Wells – All Wells, All Years

The tabulation and discussion of success rates is presented by producing power plant area summarized in total to provide a data-based estimate of drilling "success rate," or the number/percentage of wells drilled to ultimately result in an operating power plant. Not all wells were drilled by the ultimate operator, and many exploration wells were drilled in the 1970s and 1980s by previous companies, who then abandoned the prospects, so statistics presented are not a reflection of the current operator's success rate. As noted, the permitted and drilled wells are tabulated by the category in which they were originally permitted, but the ultimate use may have differed from the permitted category. For instance, at San Emidio, the following injection wells were drilled as follows (with the permitted categories in parentheses): 45-21 (I), 42-21 (P), 43-21 (O), 35-21 (I), 51-16 (O), and 53-21 (P). All six of these were noted in at least one annual production report as having been injection wells even though not all of them were originally intended for that use. Similarly, 65C-16 (O), 75B-16 (O) and 75-16 (O) were reported as producing in annual production statistics (the other two production wells from San Emidio were originally drilled to be production wells). In the case of San Emidio, three of the 24 permitted observation wells became production wells, and two observation wells became injection wells. Hence, the success rate is calculated using just the number of wells actually used in operations by category (I or P), and by industrial wells in total (P + I + O) (as well as in reference to P+I) as the use of the well may have ultimately differed from the original permitted category.

Table 3 shows a summary of all wells drilled in an area (all years), whereas Table 4 lists the same information as Table 3, but

Table 3. Total numbers of wells (all years) by geothermal area.

	Year On-line	Total MW	Permit # Wells	Expired	Total Drilled	P&A	Total P + I + O	Total P + I	Total P	Ind Use	P Use	Feet Drilled
Beowawe	1985	16.6	64	1	63	3	8	6	5	5	3	79,965
Bradys	1992	26.1	83	24	59	8	37	21	13	18	7	117,676
Desert Peak	1985	23	31	1	30	1	13	12	11	9	6	83,632
Dixie Valley	1988	64.7	98	31	67	7	56	37	24	23	12	318,369
San Emidio	1987	4.8	113	16	97	9	38	12	8	12	5	53,250
Soda Lake	1987	22.1	68	6	62	9	32	22	16	10	7	98,630
Steamboat	1986	137	162	30	132	21	57	49	41	39	26	107,414
Stillwater	1989	47.2	63	11	52	6	40	35	21	25	12	97,891
Wabuska	1984	5.6	10	0	10	4	7	5	2	2	2	8,063
Average:		38.6	77	13	64	8	32	22	16	16	9	107,210
Std Dev:		41.6	45	13	35	6	19	15	12	12	7	85,804
Sum			**692**	**120**	**572**	**68**	**288**	**199**	**141**	**143**	**80**	**964,890**

only for wells drilled up to and including the year of commissioning of the individual power plants.

Using data presented in Table 3, several observations can be made. More wells are permitted (692) than drilled (572) and used (Figure 2), as expected, with a significant amount of those drilled being plugged and abandoned (68, or 10% of those drilled). A relatively large number (120, or 17.3%) of permits were allowed to expire before wells were drilled, particularly at Bradys, Dixie Valley and Steamboat. The average number of wells drilled for any purpose at the sites is 64 wells, with the average being biased high due to the large number of wells at Steamboat and Dixie Valley, which produce the most power in megawatts (MW) in Nevada. The average number of wells used for industrial purposes (P+I) is 23, again with the average being biased toward the higher number at Steamboat and San Emidio (although many are shallow exploration wells). Note that Dixie Valley encompasses a large area that has experienced considerable geothermal exploration and drilling. The focus of the preceding (and following) comments is on the area directly around the current power plant and excludes some of the outlying areas that have been categorized by the permit applicants as "Dixie Valley." The minimum number of feet drilled in Nevada for geothermal purposes is approximately 965,000 feet as of 2010 (e.g., some of the wells have no reported depths).

Number of Wells – Only Those Wells up to and Including the Year of Commissioning

These same types of data are evaluated while only including wells drilled up to and including the year of commissioning of the power plant. Table 4 lists the results of this compilation whereas

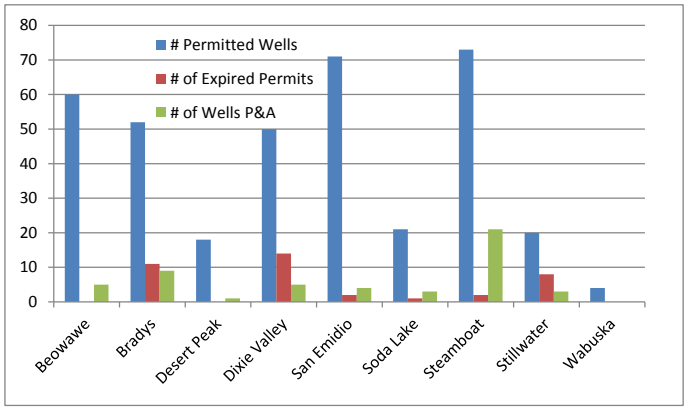

Figure 3. Number of wells permitted, expired permits, and wells plugged and abandoned by power plant area up to and including the year of plant commissioning.

Table 4. Total numbers of wells by geothermal area. Only wells drilled up to and including the year of first commissioned plant at that area are included, with wells drilled following that year excluded.

	Year On-line	Total MW	Permitted	Expired	Total Drilled	P&A	Total P + I + O	Total P + I w/depth	Total P	Ind Use	P Use	Feet Drilled
Beowawe	1985	13.9	60	0	60	5	5	3	2	4	2	64,757
Bradys	1992	28.7	52	11	41	9	22	12	11	7	4	72,663
Desert Peak	1985	9.5	18	0	18	1	5	4	3	5	3	61,210
Dixie Valley	1988	55.7	50	14	36	5	25	17	10	13	7	194,819
San Emidio	1987	2.1	71	2	69	4	10	5	3	5	1	30,339
Soda Lake	1987	3.5	21	1	20	3	2	2	1	2	1	32,147
Steamboat	1986	16.5	73	2	71	21	20	15	13	7	4	57,392
Stillwater	1989	6.8	20	8	12	3	5	5	4	5	1	45,410
Wabuska	1984	0.4	4	0	4	0	1	1	1	1	1	3,743
Average:		15.2	41	4	37	6	11	7	5	5	3	62,498
Std Dev:		17.5	26	5	25	6	9	6	5	3	2	54,019
Sum	**--**	**137.1**	**369**	**38**	**331**	**51**	**95**	**64**	**48**	**49**	**24**	**562,480**

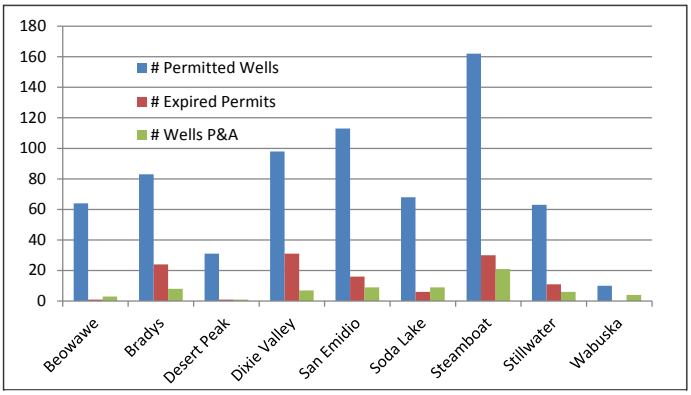

Figure 2. Numbers of permitted, expired permits. and wells plugged and abandoned at each of the producing power plants in Nevada (all years with data).

Figure 3 plots the various categories of wells. Using the data presented in Table 4, several observations can be made. A much smaller number of permits were allowed to expire before wells were drilled than in the case of all wells (compare Figures 2 and 3). The average number of wells drilled for any purpose at the sites is 37 wells, with the average biased high due to the large number of wells at Steamboat and Beowawe, as well as at San Emidio, which by the number of wells appears to be the least successful operating plant in Nevada (more wells, fewer megawatts). The average number of wells used for industrial purposes (P+I) is 7, again with the average being biased toward the two higher producers (Dixie Valley and Steamboat, and to a lesser extent, Bradys). The average number of feet drilled per area is 62,498 ft (Table 4), compared to 107,210 ft for all years (Table 3), with the largest by far being recorded at Dixie Valley (194,819 ft, Table 4), which is the deepest resource currently being developed in Nevada.

Table 5 lists the total number of wells drilled available for analysis along with the number of those wells lacking depth data, and the percentage which lack the depth data. Clearly, the post-commissioning well data set is less complete than the pre-commissioning data set, lacking an average of 32.6% of the depths for the reported wells, with some sites missing up to 50% of the depths from drilled wells (Soda Lake, Stillwater). When all years are considered, the proportion is slightly better at 15.7%

Table 5. Number of wells drilled (permitted but not expired) that did not have depths reported and percent missing from each area.

	Pre-Commissioning		Post-Commissioning		Percent	Percent	Percent
	Total # Wells	Wells w/o Depth	Total # Wells	Wells w/o Depth	Pre-comm	Post-comm	All years
Beowawe	60	0	3	1	0.00%	33.33%	1.59%
Bradys	41	1	18	1	2.44%	5.56%	3.39%
Desert Peak	18	1	11	5	5.56%	45.45%	20.69%
Dixie Valley	36	0	31	15	0.00%	48.39%	22.39%
Empire	69	0	28	10	0.00%	35.71%	10.31%
Soda Lake	20	0	42	21	0.00%	50.00%	33.87%
Steamboat	71	1	61	15	1.41%	24.59%	12.12%
Stillwater	12	0	34	17	0.00%	50.00%	36.96%
Wabuska	4	0	6	0	0.00%	0.00%	0.00%
Total	**331**	**3**	**234**	**85**			
Average	**36.8**	**0.3**	**26.0**	**9.4**	**1.04%**	**32.56%**	**15.70%**

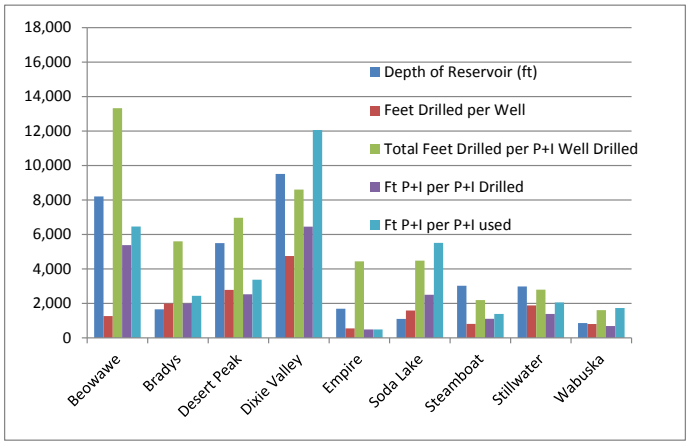

Figure 4a. Feet drilled per well (all wells drilled), feet per P+I wells, and depth to reservoir for nine areas in Nevada with producing power plants. This plot does not account for the missing depth values from the data sets noted in Table 5.

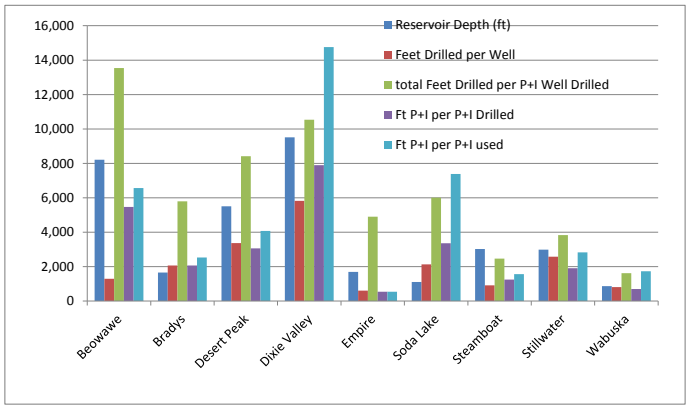

Figure 4b. Feet drilled per well (all wells drilled), feet per P+I wells, and depth to reservoir for nine areas in Nevada with producing power plants. These totals account for the missing depth values from the data sets according to Table 5, last column (e.g., multiplying Beowawe values in Figure 4a by 1.059, Bradys by 1.0339, etc.).

of the wells missing depth data. However, success rates based on total feet drilled are best evaluated using the pre-commissioning data as it has a more complete data set, albeit, smaller.

Number of Feet – Wells Drilled From All Years

The number of feet per well by area is presented in Figure 4 (a & b) in comparison to the depth of the reservoir under production. Because of the relatively large number of non-industrial, shallower wells drilled at each site (e.g., E + O), many of the areas have an average depth per well (maroon) less than the depth of the reservoir. However, when only industrial wells drilled (P+I - not all used, green) are considered, several sites have an average well depth greater than the reservoir because not all wells are used that were drilled: Beowawe, Bradys, Desert Peak, San Emidio (Empire). The average feet per well drilled (all areas) is relatively small (average 1,827 ft), but the feet per well used (when all depths available are considered) is relatively large (average 3,946 ft). When the significantly deeper resource at Dixie Valley is omitted, the average well depth (all wells) is 1,462 ft when the depth of all wells drilled (used or not) are considered, and the average depth of wells drilled for either P or I that are used in power generation operations (P+I) is 2,932 ft.

The percentage adjustments noted in Table 5 and reflected in Figure 4b do not directly account for the depth differences because the types of wells lacking depth information varies between sites (and different well types tend to have different depths). However, the percentage adjustments provide a first approximation of accounting for the sporadic lack of depth data, although a large percentage of the wells with missing depth data (42%) were production wells, all in the post-commissioning period. Nevertheless, the general patterns within the areas remain nearly the same, as do the patterns between the areas. For instance, Dixie Valley still has the highest depth values in all categories relative to the other areas (comparing Figures 4a and 4b), and Beowawe shows the highest feet drilled per P+I drilled of all the areas, even though all of the depths were available for that area, and all the other areas had an upward adjustment to the sum of the available depths by the factors noted in Table 5.

Total feet per all wells drilled and feet per only the industrial wells used are also included in Figure 5. The average feet drilled per industrial wells used (purple) is relatively large (7,852 ft) because it includes wells drilled by not used. The total feet per all wells drilled (orange) is relatively low because many wells (E+O) in addition to production wells have been drilled at all sites, yet these wells tend to be shallower. The feet (all available depths) per P+I drilled is larger (green), with the feet per industrial well being used (purple) the largest, reflecting that many more wells are drilled than used, and somewhat more P+I wells are drilled than used, each resulting in more feet per well than when all wells are divided into the total feet (orange). Beowawe has the most feet drilled for each of the industrial categories (Figure 5), but it has a relatively small number (6) of drilled P+I wells (Table 3).

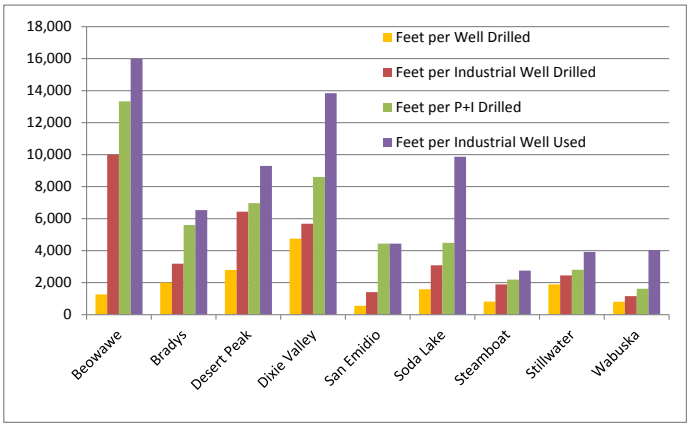

Figure 5. Feet per well drilled and used by producing areas in Nevada using the total number of feet drilled from all wells, divided by the categories noted in the legend. Note that the first two categories in the legend are also plotted in Figure 4a.

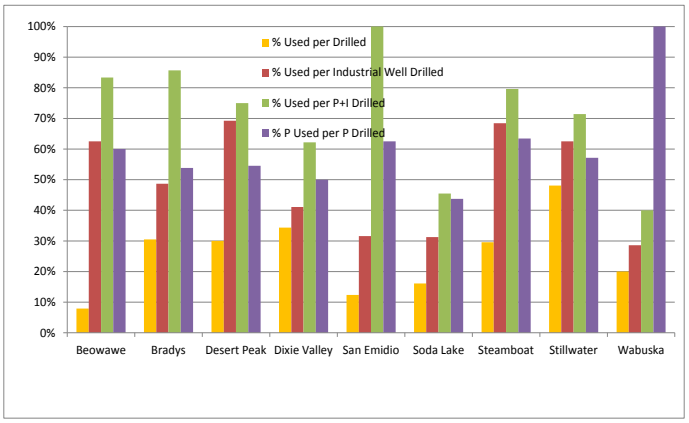

Figure 6. Percentages of wells used (combinations of P+I or P) in power generation per category drilled by power plant area in Nevada.

Success — All Wells

The percentage of wells used (P or P+I) per well drilled by category is evaluated in Table 6 and Figure 6. The average total percentage of wells used (P+I) per total wells drilled (E+I+P+O) is 25.4%. The percent of wells used in operations in comparison to the total number of wells drilled for industrial purposes (including O) is 49.3%, whereas the average percent of wells used per P+I drilled is 71.4%. The average percent of production wells used per production well drilled is 60.6%. The percent of successful production wells is the greatest at Wabuska (100%; next is Steamboat at 63.4%), indicating wells drilled in that area, though few, were the most successful, likely because Wabuska, in particular, has the shallowest reservoir resulting in fewer complications in successful well completion.

Table 6. Percentage of "successful" wells drilled by category for all years with data.

	% Used per drilled	% Used per Industrial Drilled	% Used per P + I Drilled	% P Used per P Drilled
Beowawe	7.94%	62.50%	83.33%	60.00%
Bradys	30.51%	48.65%	85.71%	53.85%
Desert Peak	30.00%	69.23%	75.00%	54.55%
Dixie Valley	34.33%	41.07%	62.16%	50.00%
San Emidio	12.37%	31.58%	100.00%	62.50%
Soda Lake	16.13%	31.25%	45.45%	43.75%
Steamboat	29.55%	68.42%	79.59%	63.41%
Stillwater	48.08%	62.50%	71.43%	57.14%
Wabuska	20.00%	28.57%	40.00%	100.00%
Average:	**25.43%**	**49.31%**	**71.41%**	**60.58%**

Number of Feet — Wells Drilled from Years up to and Including Year of Commissioning

Only wells drilled up to and including the year of first commissioning are included (excluding new plants at Blue Mountain, Jersey Valley, Salt Wells and Tuscarora), with wells drilled following that year excluded in the following discussion. Only approximately 0.6% of the wells in this group did not have a reported depth, and hence, only one analysis of the information is presented, as this small percentage is considered to be insignificant in the overall trends and observations.

The number of feet per well by area is presented in Figure 7 in comparison to the depth of the reservoir under production (blue), P+I feet divided by the number of P+I drilled (purple), and the feet P+I drilled divided by the number of P+I wells used (royal blue). Because of the relatively large number of non-industrial, shallower wells drilled at each site (e.g., E + O), many of the areas have an average depth per well less than the depth of the reservoir (maroon). When all drilled well depths are considered, Dixie Valley has the greatest number of feet per well drilled (5,412 ft) and San Emidio (Empire) the least (440 ft; maroon). However, when only the number of industrial wells drilled (not all used) are considered (green bars) in comparison to the total depth drilled by all wells, most areas (except Dixie Valley) have an average well depth greater than the reservoir because not all wells are used that were drilled, and the feet drilled includes all wells, not just those drilled for P+I purposes. Figure 7 shows the feet drilled per P+I (not the sum of all wells *drilled* as in previous cases) divided by the P+I wells drilled (purple), and the P+I wells *used* (royal blue). These categories are less in all cases than the total feet per P+I drilled as expected (green), whereas the feet per P+I used varies, with some being higher (e.g., Bradys, Dixie Valley, Steamboat) and some being lower (e.g., Beowawe, Desert Peak, Stillwater) than the feet per P+I drilled. This is because the P+I used sometimes includes wells that were not initially drilled for those purposes, and hence the number of feet used in the calculations does not account for these additional wells, resulting in a lower feet per P+I well used.

When the significantly deeper resource at Dixie Valley is omitted, the average well depth (all wells) is 1,728 ft, and the average depth of all wells drilled divided by those that were drilled and are used in power generation operations is similar to the value without omitting Dixie Valley at 10,271 ft when the depth of all wells drilled (used or not; orange) are considered. Hence, omitting Dixie Valley makes little impact on the calculated average depths needed to be drilled in total to obtain useful industrial wells.

Total feet per all wells drilled and feet per only the industrial wells used are also included in Figure 8. The feet drilled per industrial wells used (purple) are relatively large (average of

10,774 ft) because they include wells drilled but not used. The total feet per all wells drilled (orange) is relatively low because many wells (E+O) in addition to production wells have been drilled at all sites, yet these wells tend to be shallower. Beowawe has the most feet drilled when considering depths of all wells attributed only to P+I wells drilled (green, Figure 8), but it has a relatively small number of drilled P+I wells (Table 4).

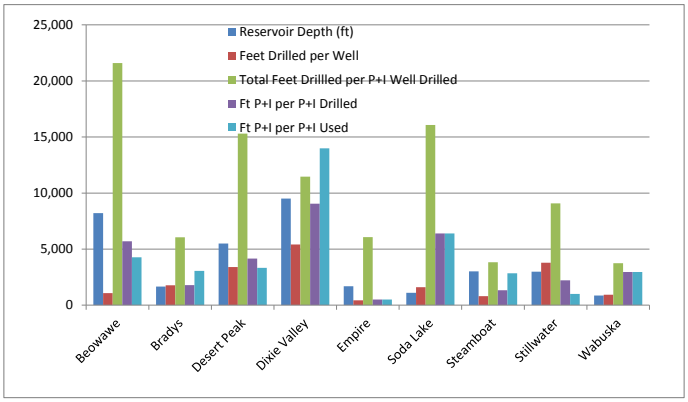

Figure 7. Feet drilled per well (all wells drilled), feet per P+I wells, and depth to reservoir for nine areas in Nevada with producing power plants.

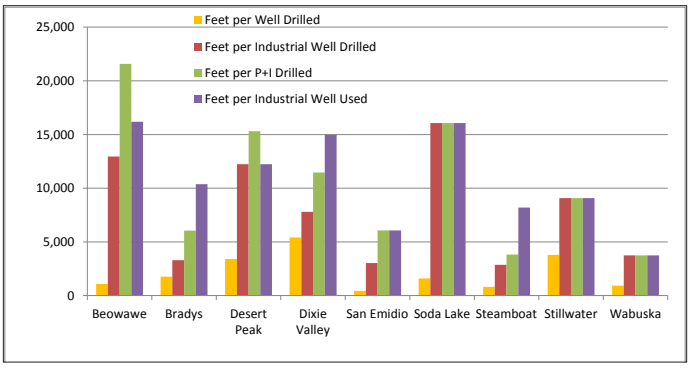

Figure 8. Feet per well drilled and used by producing areas in Nevada.

Success – Pre Commissioning Wells

The percent of wells used for industrial purposes by category is presented in Table 7 and Figure 10. The percent of wells used per total wells drilled in all categories is low at 6.7 to 28.3% because E+O are included (orange). However, if only P+I wells drilled are used in the comparison, the percent success rate is much higher, ranging from 30.4 to over 100% (Table 7), with Beowawe, Desert Peak, San Emidio , Soda Lake, and Wabuska all being ≥100%. Two areas have >100% well usage (green; Beowawe and Desert Peak) when considering only the P+I wells noted as having been drilled, because some of the other wells (O+E) were converted to P or I used wells following having been drilled. The percent of wells used for production in comparison to the total wells noted as having been drilled for production is 100% in four cases (purple): Beowawe, Desert Peak, Soda Lake and Wabuska. the remaining five areas show relatively low success rates of production wells drilled to be ultimately used as production wells (12.5 to 36.4%, Stillwater and Bradys, respectively).

Table 7. The percentage of "successful" wells drilled by category for wells up to and including the year of operation.

	% Used per drilled	% Used per Industrial Drilled	% Used per P + I Drilled	% P Used per P Drilled
Beowawe	6.7%	80.0%	133.3%	100.0%
Bradys	17.1%	31.8%	58.3%	36.4%
Desert Peak	27.8%	100.0%	125.0%	100.0%
Dixie Valley	36.1%	52.0%	76.5%	70.0%
San Emidio	7.2%	50.0%	100.0%	33.3%
Soda Lake	10.0%	100.0%	100.0%	100.0%
Steamboat	9.9%	35.0%	46.7%	30.8%
Stillwater	41.7%	100.0%	100.0%	25.0%
Wabuska	25.0%	100.0%	100.0%	100.0%
Average	**20.2%**	**72.1%**	**93.3%**	**66.2%**

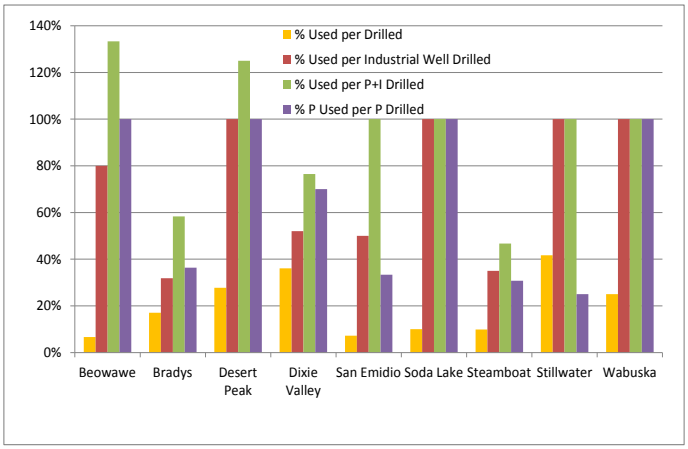

Figure 9. Percentages of wells used (combinations of P+I or P) in power generation per category drilled by power plant area in Nevada.

Discussion

So, what is the "success rate" of geothermal wells drilled in Nevada? Clearly, the raw data can be presented, viewed, and interpreted in a number of different ways. Because not all wells are ultimately used for their originally intended purpose, the success rate is not an absolute. For instance, a small percentage, one of the 55 exploration wells and one of the two observation wells, ultimately became injection wells at Beowawe. Two of the 24 observation wells became injection wells at San Emidio.

The Steamboat area has had a considerable amount of exploration, evaluation, assessment and expansion with the first power plant coming online in 1986, with several expansions occurring over the next 2.5 decades resulting in eight units with production capacities of approximately 137 MW from two areas of the resource (a higher temperature source near the upflow, which produces power from a flash plant, and a lower temperature resource in the outflow of the resource, which contains the majority of the binary power plant units). Each area was drilled by different exploration and development companies over time, so no consistency in development philosophies can be expected. This variability in company attitudes over time could be a factor in the high variability of success rate statistics presented earlier. Some areas had extensive exploration drilling in the 1970s and

1980s (e.g., Chevron at San Emidio), resulting in a large number of wells per MW. However, the cost of these wells was not borne by the present operators, and the low indicated success rate cannot be attributed to current (post-1985) developer activities. Dixie Valley is the most successful when gauging success as the smallest number of wells per MW of production capacity, which is somewhat surprising given it is the deepest reservoir and should be more difficult to locate productive zones.

The summary of drilled and used wells shows several things. Three-hundred and sixty-nine drilling permits of all types were issued before the first power plant commissioning, and 323 permits were issued after the first commissioning of power plants (with years varying by power plant, and many wells permitted that were never drilled). The wells drilled after initial commissioning at many of the areas have a relatively high percentage of wells without reported depths. The percentage of wells drilled without depths reported are far greater in the post-commissioning wells than in the earlier wells, with percentages up to 50% (Soda Lake and Stillwater) being recorded in the post-commissioning period (Table 5). A data set using depth data over the post-commissioning time interval will therefore minimize total depths drilled and maximize the number of MW per foot drilled. Hence the better data set, although for a shorter period of time and smaller, is the pre-commissioning information because it has the most complete depth data. Only Beowawe and Bradys have a sufficiently complete record of depths for all years to make realistic conclusions regarding feet drilled for the entire data set (e.g., missing 1.59 and 3.39% of the depths, respectively).

Up to the commissioning of the first power plant unit, 100% of the wells drilled for either P or I uses were used as P or I wells at San Emidio, Soda Lake, Stillwater, and Wabuska (Table 7). Over 100% of the P+I drilled were used as P+I at Beowawe and Desert Peak because of conversion of E or O wells to P+I after drilling. At Bradys, Dixie Valley, and Steamboat, 53.8%, 76.5%, 46.7% of wells drilled and intended for a P or I purpose in power plant operations were actually used for production or injection.

Although Wabuska is the smallest plant in operation in Nevada (Table 1), it was the first one built (in 1984), and utilizes the lowest temperature resource currently producing power in the state (107°C). The data presented for Wabuska are anomalous in that all permitted wells were drilled, all drilled wells have a reported depth, and all production wells drilled were used as production wells (100% success rate). Also note that used geothermal fluid has been discharged to the surface such that injection wells were not used. The total number of wells drilled and the total number permitted are the same at Wabuska, 10. There have been two production wells drilled and produced, with the total number of industrial (production and injection) being five, although the injection wells are not being used as noted. In this case, in this small, shallow resource, the success rate of drilling production wells intended for production is 100%. However, only 50% of the wells drilled were for production or injection wells, indicating that 50% of the wells drilled were for exploration and resource definition. Of the total 8,063 feet drilled, 3,460 of the feet were drilled in commercial industrial wells. Hence, 50% of all wells drilled at Wabuska were categorized as industrial wells, with 43% of the feet drilled. The success rate at this area is, therefore, anomalously high relative to other areas.

Because the most complete data relative to feet drilled is in the dataset up to the time of the individual plant commissioning, only these data are used for the final analysis of success rates evaluated as a function of depth and number of wells drilled at each site. Table 8 lists the plants with year on-line, MW in a year produced and calculated statistics on the number of wells per MW for different scenarios. Most of the noted MW-year values were obtained from the Nevada Mineral Industry Report for 1991 (http://www.nbmg.unr.edu/dox/mi/91.pdf) to obtain information after initial commissioning but before any expansions. The data from this report series report gross MW-hrs, which was used in Table, divided by the hours per year. The MW-yr value for Bradys was obtained from the same report series for 1993, one year after commissioning (as usually numbers are low in the first year after initiation of production). The value from Soda Lake was obtained from the MW capacity reported in 1987, before expansion occurred in 1991.

Table 8. Statistics showing the number of wells per MW under production at the nine power plants at the time of commissioning under various scenarios.

	Year On-line	MW/yr	# Wells per MW	# P+I+O per MW	# P+I per MW	# P per MW	# P used per MW
Beowawe	1985	13.9	4.3	0.36	0.22	0.14	0.14
Bradys	1992	28.7	1.4	0.77	0.42	0.38	0.14
Desert Peak	1985	9.5	1.9	0.53	0.42	0.32	0.32
Dixie Valley	1988	55.7	0.6	0.45	0.31	0.18	0.13
San Emidio	1987	2.1	33.1	4.80	2.40	1.44	0.48
Soda Lake	1987	3.5	5.7	0.57	0.57	0.29	0.29
Steamboat	1986	16.5	4.3	1.21	0.91	0.79	0.24
Stillwater	1989	6.8	1.8	0.73	0.73	0.59	0.15
Wabuska	1984	0.4	9.4	2.34	2.34	2.34	2.34
		15.2	**6.9**	**1.31**	**0.92**	**0.72**	**0.47**
		17.5	**10.2**	**1.44**	**0.85**	**0.73**	**0.71**

The number of wells per MW includes exploration wells, needed for resource location and definition prior to drilling of development wells, whereas the P+I+O generally reflects confirmation of the resource, and the number of P or P+I wells generally reflects the number of wells needed in operations (i.e., not including the larger number of wells required to conduct the exploration and resource confirmation stages of project development).

The summary in Table 8 shows a large range in total number of wells drilled per MW from 0.65 at Dixie Valley to 33.1 at San Emidio, with the number averaging 6.9 total wells per MW. The large range is in part due to the extremely large number of shallow (typically <500 ft) exploration wells drilled by Chevron at San Emidio in the late 1970's (58). No additional exploration wells were drilled once the site was revisited for development in the late 1980's. The large number for Wabuska is somewhat misleading as this had a very low capacity of only 0.43 MW as of commissioning in 1984. Omitting these outliers, a reasonable expectation of number of wells needed to be drilled (including exploration, confirmation and production) is 2.9 wells per MW. Noting the other statistics, Bradys, Desert Peak, Dixie Valley and Stillwater are the most successful sites having drilled the fewest number of wells of all types to obtain their respective MW under

production (0.65 to 1.9 Wells/MW). Based on a summary the data, it can be expected that future development would require 0.9 wells per MW to result in a successful production operation (i.e., approximately 1 pumping or injection well per MW of production). Even if 100% of the drilled production wells were to be successful (last column Table 8), a developer could expect to drill 0.5 production wells per MW of produced electricity, with costs obviously increasing with depth of the resource. However, obviously, the goal is to drill multiple-MW wells.

Table 9 lists the summary statistics relative to feet having been drilled per MW produced. This table lists summary statistics, beginning with the feet per MW using all well types drilled to all depths, which ranges from approximately 2,500 ft/MW at Bradys to 14,555 ft/MW at San Emidio. In this analysis, San Emidio, Soda Lake and Wabuska are all outliers in that they all show the number of feet drilled per MW >8,000 ft, whereas the other sites were developed by drilling <7,000 ft per MW. The total feet drilled per MW at the sites averages 6,644 ft, but only 4,500 ft removing the three outliers. Omitting the exploration wells from the analysis, expected feet drilled per MW (P+I+O per MW) are far less at 2,093 ft for all industrial wells, and 1,219 ft/MW for all production wells drilled (whether used or not, e.g., whether successful or not). Soda Lake still shows as an outlier with the highest number of feet per MW drilled for all categories, even though the resource at Dixie Valley is much deeper. Note that "successful" wells are multiple-MW wells, making the feet drilled per MW relatively low relative to the depth of the reservoirs, explaining the relatively low depths/MW at Dixie Valley.

Table 9. Summary statistics relating feet drilled per MW for sites in Nevada up to and including the year of commissioning.

	Year On-line	MW/yr	Total Feet per MW	Feet P+I+O per MW	Feet P+I per MW	Feet P per MW
Beowawe	1985	13.9	4663	1588	1231	804
Bradys	1992	28.7	2528	1414	746	638
Desert Peak	1985	9.5	6464	2777	1759	1422
Dixie Valley	1988	55.7	3497	3179	2761	1689
San Emidio	1987	2.1	14555	1777	1213	683
Soda Lake	1987	3.5	9185	3655	3655	2425
Steamboat	1986	16.5	3475	1645	1205	944
Stillwater	1989	6.8	6671	1630	1630	1201
Wabuska	1984	0.4	8760	1170	1170	1170
Ave		**15.2**	**6644**	**2093**	**1708**	**1219**
Stdev		**17.5**	**3781**	**878**	**925**	**569**

Summary

A relatively small percentage (3%) of the 265 exploration wells were converted to industrial (P+I) wells, resulting in 5.6% of all industrial wells having initially been drilled as E wells. A larger percentage (10.2%) of the observation wells (88) drilled were converted to P or I categories after drilling, with 9.8% of the industrial wells having been drilled as O. Hence, the number of wells permitted as exploration wells that ultimately are used in power generation operations is minimal at the nine Nevada plants investigated. Ultimately, 143 of the wells drilled were used in production operations, of which 80 were production wells, and 61 were injection wells.

Beowawe has the most feet drilled for each of the 3 industrial categories (Figure 6), but it has a relatively small number of drilled P+I wells (Table 5).

Using all wells, all years, the average total percentage of wells used (P+I) per total wells drilled (E+I+P+O) is 25.4% (Table 6, with a high of 48.1% at Stillwater, and a low of 7.9% at Beowawe). The percent of wells used in operations in comparison to the total number of wells drilled for industrial purposes (P+I+O) is 49.3%, whereas the average percent of wells used per P+I drilled is 71.4%. The average percent of production wells used per production well drilled is 60.6%. The percent of successful production wells is the greatest at Wabuska (100%; next is Steamboat at 63.4%), indicating wells drilled in that area, though few, were the most successful, likely because Wabuska, in particular, has the shallowest reservoir, resulting in fewer complications in successful well completion. Similarly, the Steamboat system is also relatively shallow relative to other areas in Nevada.

When only the pre-commissioning wells are used in this type of analysis (Table 7), 20.2% of all wells drilled were used in production operations, 72.1% of the wells drilled for industrial purposes were used, and 93.3% of the wells drilled for either P or I uses were ultimately used as industrial production or injection wells. This high success rate is likely attributable to having sufficient exploration and confirmation wells to properly site the industrial wells. The percentage of production wells drilled that were used as production wells was 66.2%.

Based on the presented data and analysis, it can be expected/summarized that, for Nevada:

- Few (3%) exploration wells are converted to production or injection wells
- A relatively large percentage (10.2%) of observation wells were converted to production or injection wells
- Approximately 20% of all the wells drilled will likely be used in production operations
- Many of the remaining 80% are typically to be shallower exploration wells
- Production and injection wells combined had an 72.1% success rate when success is measured by use (within the range of 70-80% found by Hance, 2005)
- Production wells had a success rate of approximately 60-66% when success is measured by use
- Average depths needed to be drilled per field to obtain a successful production operation was approximately 62,000 feet total using only the more complete pre-commissioning data (often combining many small diameter exploration wells with some large diameter production wells)
- Average feet drilled per MW of production at all nine sites (pre-commissioning) was 6,644 ± 3,781, ranging from 2,528 (Beowawe) to 14,555 (San Emidio).
- Excluding exploration wells, the average feet needed to be drilled per MW is 2,093 ± 878 feet
- The number of wells per MW (excluding exploration wells) is 1.3 ± 1.4

- The number of pumping wells per MW that need to be drilled averages 0.7 ± 0.7.

Note that not all wells were drilled by the current operators, and many exploration wells were drilled in the 1970s and 1980s by previous companies, who then abandoned the prospects. Therefore, presented statistics are not a reflection of the current operators' success rates.

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