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Best Practices to Achieve Optimal Geothermal Drilling Performance in A Cost-Effective Manner: Case Study of the Fastest Geothermal Well Drilling in Java and Sumatra

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ABSTRACT - Indonesia, recognized for possessing substantial geothermal energy potential, is working towards harnessing the resource to achieve numerous objectives. Among the primary challenges encountered is the considerable expense of geothermal drilling. One of the most significant obstacles to achieving this objective is the high drilling cost, which constitutes 35-40% of the total cost of geothermal energy development. The drilling cost is mainly affected by the time needed to drill one well because the faster the time, the lower the cost. Therefore, this research analyzed drilling activities, identified the fastest and most effective methods for optimal geothermal drilling performance, and reduced costs. The research also determined the factors that contributed to the sustained status of Well X as the fastest well drilled in the past decade. The methodology comprised literature review, data collection through adequate background on well and geothermal field, and data analysis. The result showed that the fastest drilling operation of a geothermal well in Indonesia in 2012 occured in West Java (Well X) for only 9.9 days with 1736.5 meters (mMD). Meanwhile, in 2021, Well Y in Sumatra spent 21.74 days to reach a depth of 2200 mMD. The use of a single-run and clean-out Bottom Hole Assembly (BHA) throughout the entire section affected the drilling duration and significantly reduced the inner side cleaning time, respectively. The cost of Well Y drilling, achieved using the best performance of two wells, reduced drilling costs by 19.2%.

Keywords: drilling efficiency, geothermal drilling, drilling practice, m/days.

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INTRODUCTION

Clean energy is needed to achieve net zero emissions in the energy industry. Geothermal energy, which is one of the important renewable sources due to its abundant and clean nature, requires considerable investment expecially in drilling. According to the annual report of the Energy Sector Management Assistance Program (ESMAP, 2012), drilling accounts for 35 to 40% of the total geothermal energy development cost. Therefore, improving drilling efficiency is crucial to reduce the overall costs of geothermal energy and make it more economically sustainable.

Drilling cost is mainly influenced by the duration required to complete a single well, with shorter operating times resulting in reduced expenses. It usually takes 32 to 60 days to drill one geothermal well with a total depth (TD) of 2000 to 2500 meters (Thorhallsson and Sveinbjornsson, 2014). The average cost required to drill a geothermal well is approximately five million dollars (Hartono, 2023).

The swiftest geothermal well drilling operation in Indonesia occurred in 2012, termed Well X, specifically situated in West Java. It was successfully completed in relatively 9.9 days, reaching a depth of 1736.5 (mMD). Presently, no geothermal well drilling effort has surpassed the exceptional performance achieved in the case of Well X. Following the Well X project, another rapid geothermal well drilling operation which occurred in North Sumatra was identified as Well Y. This project required 21.74 days to reach a depth of 2200 meters below mean sea level (mMD) and was successfully completed in 2021. Therefore, this research aimed to determine the fastest and most effective methods for achieving optimal geothermal drilling performance and cost reduction while also investigating the reasons behind the continued status of Well X as the fastest well drilled in the past decade. It aimed not only to conduct a comparative analysis of the drilling performances of Wells X and Y but also to identify opportunities for enhancing the drilling process of Well Y, with a focus on evaluating its cost efficiency. The improvement process is centered on the integration of Cycle Time Factors (CTFs), a set of interconnected variables. Therefore, the objective of this research is to enhance drilling efficiency without compromising other important factors. The main outcome of this research is a series of recommendations aimed at achieving optimal geothermal drilling performance.

METHODOLOGY

The research adopted a comprehensive methodology comprising a literature review, data collection, and drilling activities analysis. The main objective is to determine the fastest and most effective approaches for achieving optimal geothermal drilling performance and reducing associated costs. The detailed flow chart outlining this process is shown in Figure 1.

RESULT AND DISCUSSION

Series of Drilling Activities

Drilling operations comprise several common activities, whether in oil and gas or geothermal drilling. These include spudding in the initial phase before drilling operations start, drilling ahead, the main activity of boring holes in the intended target, tripping the bit, and replacement of a dull drill bit. Others are running casing, insertion of casing into the borehole to prevent formation collapse, and leak off test, conducted to determine the fracture pressure of the formation just beneath the initial casing shoe by applying pressure. The entire drilling cycle is repeated until the well reaches its Total Depth (TD) (Schlumberger, 2011).

Geothermal Field Formation

Geothermal reservoirs typically contain rocks like granite, granodiorite, quartzite, greywacke, basalt, rhyolite, and volcanic tuff. These formations present distinct challenges compared to sedimentary structures in most oil and gas reservoirs. Geothermal formations are often characterized by hardness (with a compressive strength of 240+ MPa), high temperatures (ranging from 160 to 300+°C at production intervals), abrasiveness (specifically when quartz content is greater than 50%), extensive fracturing, and under-pressured. Its fluids are often corrosive, and some formations have high or total dissolved solids, with brine in the Imperial Valley exceeding 250,000 ppm. These challenging conditions render drilling operations in geothermal fields more demanding and lead to lower penetration rates and reduced bit life (Macini & Mesini, 1994). Furthermore, corrosion issues are a frequent concern in geothermal fields (Unocal Geothermal Div, 1989). Circulation loss is often a severe problem, and the elevated temperatures further intensify these challenges (Finger and Blankenship, 2010). The X geothermal field is located near the Sunda Volcanic Arc in West Java province. Encircled by mountains with elevations ranging from 950 to 1,500 meters above sea level, this geothermal site is situated approximately 60 kilometers from Jakarta, the capital city of Indonesia. The X geothermal system is mostly liquid and possesses a fracture-controlled reservoir characterized by moderate to high temperatures ranging from 464°F to 600°F. It contains benign fluids with moderate to low non-condensable gas. This geothermal reservoir is associated with recent volcanic activities and intrusions in the highlands region, situated east and west of the Cianten caldera and X mountain. The Y geothermal field is located in northern Sumatra and is characterized by a young andesitic stratovolcano. It reaches an elevation of 2,145 meters, with a 600 meters wide summit crater containing a lake. A smaller parasitic crater on the upper SE flank also houses a small crater lake. The craters and a series of smaller explosion pits line up along a NW – SE line. The volcano possesses an extensive and robust hydrothermal system that has attracted geothermal exploration and production.

Geothermal systems generally contain dissolved or free carbon dioxide (CO_2) and hydrogen sulfide (H_2S) gas, both of which can lead to corrosion problems. The presence of H_2S gas limits the use of materials in drilling equipment and casings, requiring the utilization of steel with lower strength to prevent sulfide stress cracking (NACE International, 2003). corrosion-resistant alloys, and other alloys for service in equipment used in oil and natural gas production and natural gas treatment plants in H2S-containing environments, whose failure could pose a risk to the health and safety of the public and personnel or to the environment. It can be applied to help to avoid costly corrosion damage to the equipment itself.\"--NACE International Web site. pt. 1. General principles for selection of cracking-resistant materials -- pt. 2. Cracking-resistant carbon and low alloy steels, and the use of cast irons -- pt. 3. Cracking-resistant CRAs (corrosion-resistant alloys

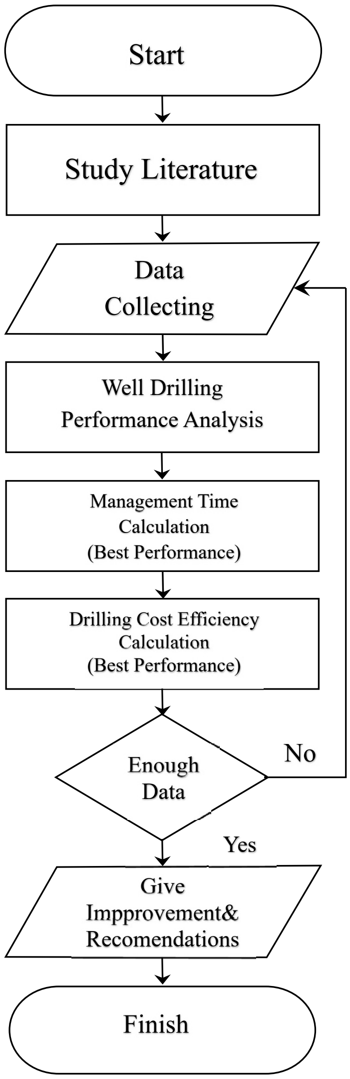

Figure 1
Research flowchart

Figure 2
Drilling component cycle time (Mensa-Wilmot, Cotanda, and Pazziuagan, 2023)

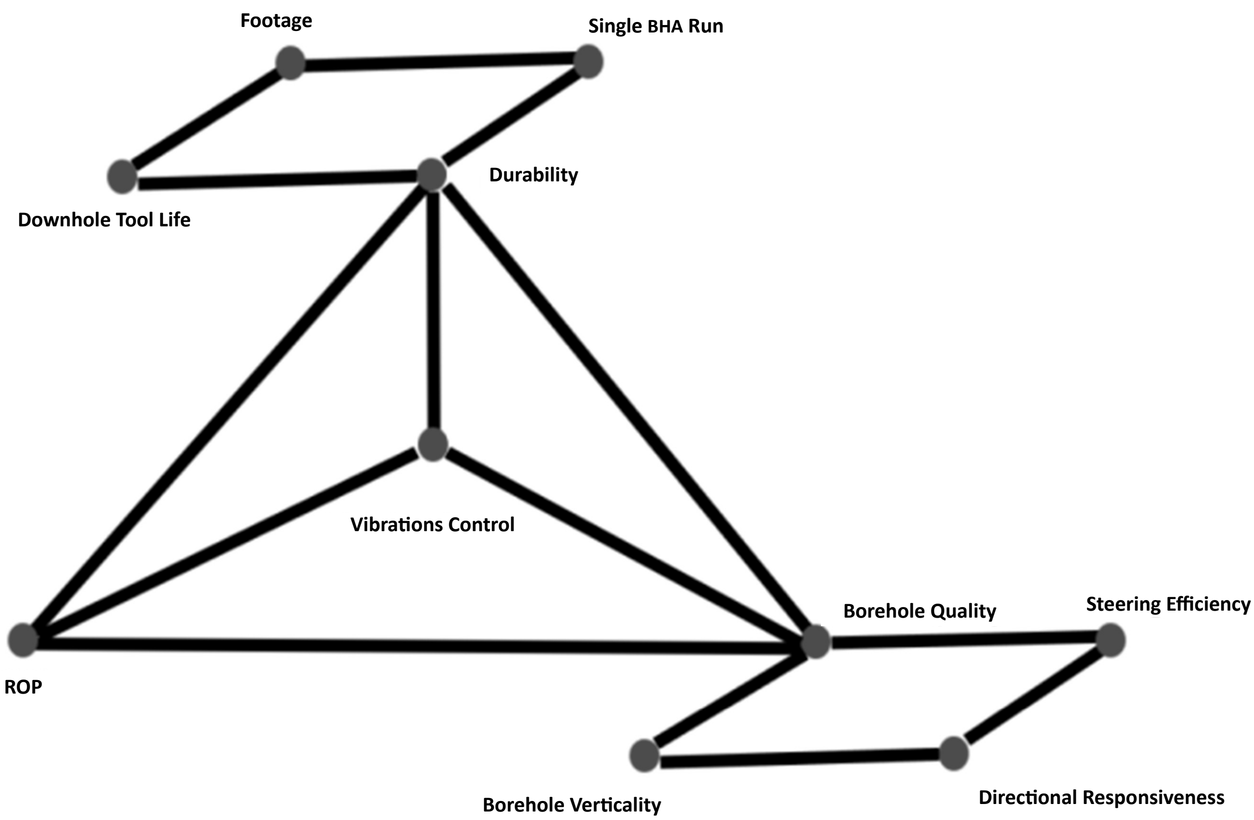

Figure 3
Cycle Time Factors (CTFs) (Mensa-Wilmot, Cotanda, and Pazziuagan, 2023)

Drilling efficiency

Drilling efficiency is consistently interconnected with critical parameters such as Cost per foot (CPF), mechanical specific energy (MSE), and feet per day (FPD), all of which significantly rely on Rate of Penetration (ROP) (Graham. R., Mensa W., 2010). Prior drilling campaigns showed that enhancing the drilling efficiency solely by maximizing ROP through increased Weight on Bit (WOB) does not yield favorable results, instead, it accelerates drill bit wear. Therefore, the path to improved drilling efficiency requires a general optimization approach that considers all factors, compared to maximizing one parameter.

Drilling cycle time

In the process of well drilling, several cyclic activities, such as Bottom Hole Assembly (BHA) Pick-up, Drill-Out, Drill Ahead, Trip-Out, Run Casing, and BHA Trips, are conducted for each section, as shown in Figure 2 (Mensa. W., Graham. R., D. Pazziuagan 2023). These activities, performed systematically, are designed to optimize drilling operations to reduce cycle time. The optimization process is expected to have a positive effect on the total drilling time and lead to a reduction in costs. However, specific factors such as Cycle Time Factors (CTFs) strongly influence the drilling cycle time.

Cycle Time Factor

As previously stated, the drilling cycle time is strongly influenced by a set of interconnected variables known as Cycle Time Factors (CTFs). These CTFs comprise several aspects, including drilled footage, downhole tool longevity, single Bottom Hole Assembly (BHA) run, durability, vibration control, Rate of Penetration (ROP), borehole quality, steering efficiency, borehole verticality, and directional responsiveness, as shown in Figure 3. Furthermore, CTFs cannot be examined in isolation, adjustments to one aspect affects others, requiring a typical approach when analyzing and modifying any factor. It should be prioritized based on the contributions to operational efficiency and project success, guiding the design and analysis of drilling systems (Graham Mensa-Wilmot, 2023). These factors will be considered for any improvements suggested in this research.

RESULT AND DISCUSSION

Well Background

Well X, situated in West Java, achieved an impressive depth of 1736 meters in an extraordinary feat, triggering an impressive drilling rate of approximately 175.4 meters per day. The outcome of this well, which was achieved in 9.9 days, made it the quickest to be ever drilled in the region. In contrast, Well Y, located in North Sumatra, reached a depth of 2200 meters, making it the fastest borewell in its region. This achievement required 21.74 days, with an average daily drilling rate of approximately 101.2 meters. In addition, the calculation of the time needed to drill these two wells includes the period from drilling the 26” hole section to the installation of the perforated liner, followed by the rig release, which does not include logging operations and well testing.

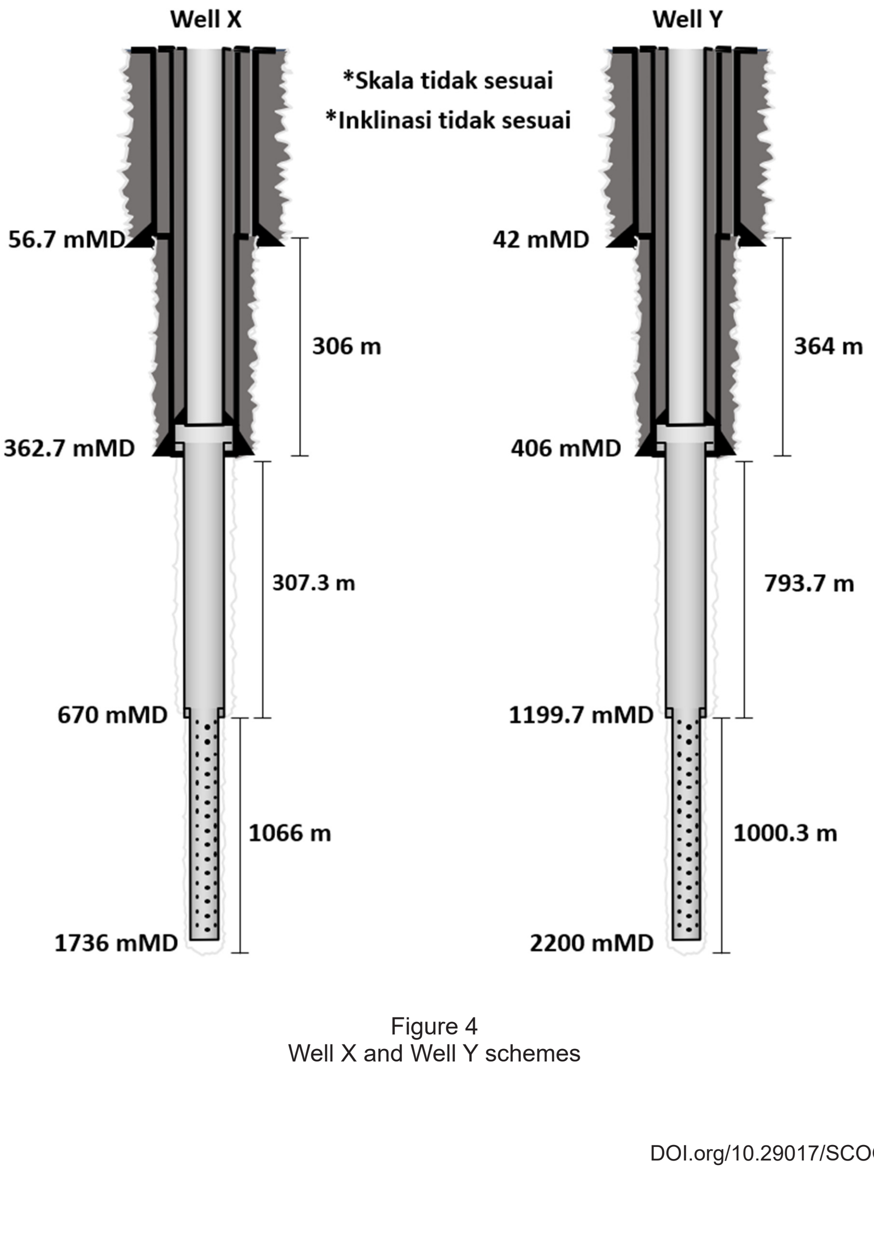

Figure 4
Well X and Well Y schemes

Drilling Operations Overview

This section provides a comprehensive discussion of the drilling operations for both wells, and aim to determine the main factors that contribute to performance.

- **Hole section drilled**

Both Wells X and Y were subjected to drilling of identical hole sections, comprising the 26”, 17-1/2”, and 12-1/4” segments. The augering method was used to install 30” conductor casings in both wells. However, the most extensive drilling depth was encountered within the 12-1/4” bore section, with Wells X and Y reaching depths of 1066 meters and 1000.3 meters, below mean sea level (mMD), respectively. This section constituted the lengthiest drilling effort among all the others, as illustrated by the depth data in Figure 4.

A performance analysis showed that Well X outperformed Y across all sections, as shown in Table 1. Specifically, in the concluding section, the 12-1/4” hole section, Well Y necessitates two Bottom Hole Assembly (BHA) runs to achieve the Total Depth (TD), consequently leading to an extended duration for the completion of this segment. This observation was further examined in the subsequent section, focusing on the assessment of potential areas for enhancement.

Table 1
Duration and ROP of each section

Hole Section	Well X		Well Y	
	Duration (hour)	ROP (m/hr)	Duration (hour)	ROP (m/hr)
26”	30.6	10	51	7.2
17-1/2”	30.1	10.2	95	7.5
12-1/4”	78.9	13.5	171	5.8

- **Equipment problem**

These two wells are exemplars of top-tier performance on the site, but equipment-related issues continue to manifest during the drilling processes. This focuses on potential avenues for improvement, particularly when these equipment challenges can be effectively addressed in the context of future geothermal drilling efforts. A comprehensive catalog of all equipment issues encountered is shown in Table 2 for reference.

Table 2
Equipment problem

Hole Section	Well X		Well Y	
	Problem	Duration (hours)	Problem	Duration (hours)
26”	Leaking wash pipe	1.25	-	-
17-1/2”	Bowl head seal damaged	1.5	Union connection washed out	5.5
12-1/4”	-	-	Flowline plugged	3.5

Based on observation of the equipment issues in both wells, it was evident that Y experienced significantly more time-consuming challenges compared to X. Addressing equipment problems in Well Y requires a duration of nine hours, while X showed a quicker response of resolving issues within 2.75 hours.

- **Hole problem**

During the drilling of these two wells, several challenges related to borehole integrity, as shown in Table 3. As a result, the improvement of these borehole-related issues has significant value in guiding future drilling efforts.

The drilling of the 12-1/4” hole sections showed a higher frequency of operational challenges than other segments. Specifically, in Well X, this was characterized by elevated torque leading to pipe stall and a simultaneous well kick event, occurring within the depth range of 1232.3 to 1241.45 meters below mean sea level (mMD). In the case of Well Y, the challenges manifested as tight spots during Bottom Hole Assembly (BHA) trips at a depth of 1375 mMD, in addition to erratic torque fluctuations observed within intervals of 1960 to 1979 mMD. These insights focused on critical operational aspects that require thorough consideration in geothermal drilling activities.

- **Bit selection & performance**

The calculation of cost per foot for all drill bits used in drilling Wells X and Y is the same rig rental cost of $ 27,615 / day. The CPF drill bit value used in Well X tends to be smaller, indicating that the drilling operations showed better performance compared to Y.

Table 3
Hole problem

Hole Section	Well X			Well Y		
	Problem	Depth (mMD)	Duration (hours)	Problem	Depth (mMD)	Duration (hours)
26”	Tight hole	315	0.5	Pipe stalled	53	0.5
17-1/2”	-	-	-	Pipe stalled	1140	0.5
12-1/4”	Pipe stalled & Well kick	1232-1241	0.75	Tight spot	1375	0.5
				Erratic torque	1960-1979	0.5

Table 4
Drilling bit cost per foot

Well	Bit Type	Size	Bit Cost	Drill Time (hr)	Trip Time (hr)	Interval (m)	Cost per Foot
X	Roller Cone	26”	$ 39,900	24.3	7	306	$ 2,955.06
	Roller Cone	17-1/2”	$ 26,250	24.5	10.65	307.3	$ 3,244.12
	Roller Cone	12-1/4”	$ 17,850	70	15.45	1066	$ 2,230.35
Y	Roller Cone	26”	$ 39,900	48	4	364	$ 4,054.62
	Hybrid	17-1/2”	$ 92,715	99.1	21.05	793.7	$ 4,297.16
	Roller Cone	12-1/4”	$ 17,850	43.5	26	364.3	$ 5,317.30
	PDC	12-1/4”	$ 62,843	81	17.5	636	$ 4,375.66

Well Performance Comparison

The performance metrics for each activity in Wells X and Y drilling are measured in hours. Furthermore, the duration of non-depth dependent activities are independent of the borehole depth. Conversely, the data is expressed as hours per meter (hour/meter) for depth-dependent drilling activities, indicating that the duration increases as the borehole deepens. Furthermore, for depth-dependent drilling activities that are bound inward (depth-dependent activity), the data is measured in hours/meters, indicating that the deeper a borehole, the longer the duration.

Drilling Operation Time Calculation (Best Performance)

The total drilling operation time needed to determine the best performance was obtained by calculating and comparing the performance of each activity in the X and Y wells. The duration of each activity is calculated by multiplying its performance in hr/m by the depth of the section where the activity is conducted. The total duration of drilling operations required to drill a well identical to Well Y, with the best performance, is 12.38 days. The duration of the Well Y drilling operation with the best performance is relatively shorter than its actual drilling operations, which is 21.74 days, as shown in Table 10. This reduction is significant, amounting to a 43% decrease from the actual duration of Well Y drilling operations.

Drilling Cost Efficiency

After determining the duration of Well Y drilling using the best performance data from both wells, drilling cost efficiency can be calculated. This is because the faster the duration of drilling operations, the more affordable the costs.

Table 5
Drilling performance comparison (Well X Vs Well Y)

Hole Section	Activity	Well X	Well Y	Performance Gap (Well Y - Well X)	Units
26”	1. Drilling 26"	0.10	0.14	**0.040**	hr/m
26”	2. Running Casing 20"	0.025	0.025	0.000	hr/m
26”	3. Cementing 20"	11	40	29.000	Hr
26”	4. N/U and test BOPE and flowlines.	5	7	2.000	Hr
26”	5. M/U 17-1/2" BHA, shallow test MWD and RIH to TOC	0.014	0.035	0.021	hr/m
17-1/2”	6. Drilling 17-1/2"	0.098	0.134	0.036	hr/m
17-1/2”	7. Running Casing 13-3/8"	0.008	0.011	0.003	hr/m
17-1/2”	8. Cementing 13-3/8" Liner	10.5	19.5	9.000	Hr
17-1/2”	9. M/U hole opener. RIH and redress tieback receptacle. POOH	0.024	0.064	**0.040**	hr/m
17-1/2”	10. N/D BOP. Final cut 20" casing	5.5	5.5	0.000	Hr
17-1/2”	11. Running 13-3/8" Tieback	0.02	0.02	0.000	hr/m
17-1/2”	12. Cementing 13-3/8" Tieback	9.5	20.5	11.000	Hr
12-1/4”	13. Drilling 12-1/4"	0.074	0.171	**0.097**	hr/m
12-1/4”	14. POOH and L/D 12-1/4" BHA	0.004	0.003	-0.001	hr/m
12-1/4”	15. Running 10-3/4" Perforated Liner	0.007	0.01	0.003	hr/m
12-1/4”	16. N/D BOP. Shut in well and release the rig.	3.5	0.5	-3.000	Hr

- **Components of drilling costs**

Before calculating the total drilling cost, the initial step is identifying the components to be included in the calculation and researching its reference costs in the market or based on company transactions. The subsequent discussion will focus on the calculation of drilling costs, considering the following components. Drilling costs are divided into two main categories, namely tangible and intangible. Tangible costs have a physical form and are generally purchased by company operators such as casings, wellheads, liners, etc. In contrast, intangible costs are expenses without a physical form related to leasing tools or equipment used for drilling operations.

- **Calculation of actual drilling costs3**

Based on the tangible and intangible cost components discussed earlier, the actual drilling cost is calculated by multiplying the rate/day of intangible costs by the operating day and, similarly, multiplying the stand-by rate/day of intangible costs by the stand-by period. These values are then added to the tangible costs. In this cost calculation, each component is also adjusted by multiplying it by an inflation factor of 1.05. The total cost of drilling Well Y, with a duration of 21.74 days, is $2,664,313.63.

- **Cost calculation drilling improved**

After calculating the improved duration of Well Y drilling operations using the best performance data from both wells (X and Y), the estimated cost with a reduced duration of 12.38 days can be determined using the same method applied in the calculation of the actual Well Y drilling cost. In addition, the total estimated cost amounted to $2,152,843.73.

Based on Table 12, the total cost required to drill Well Y, with the best performance of both wells, is $2,152,843.73. This amount is significantly reduced when compared to the actual cost of drilling Well Y, which was $2,664,313.63. The cost reduction of 19.2% resulted in substantial savings in drilling costs.

- **Break Even Point (BEP)**

Break Even Point (BEP) represents the stage at which the total capital invested in a project is recovered from the generated income, essentially showing the timeframe for a return on investment.

It is important to calculate the BEP for every investment, including activities like drilling geothermal wells. BEP calculation aims to determine the duration needed for the invested capital in drilling a geothermal well to be recouped through the production and sale of electricity generated from the facility. It can be calculated using the following formula.

$$\text{Break Even Point (Day)} = \frac{\text{Drilling Cost}}{\text{Electricity Price} * \text{Generated Electricity} * 24} \quad (1)$$

Break Even Point calculation:

- Electricity Price ($/kWh): 0.07 – 0.13 $ /kWh
- Generated Electricity (kWh): 500 kWh

The Break-Even Point (BEP) for Well Y, in both its actual and improved scenarios, was calculated using the data on electricity price and generated electricity mentioned earlier.

BEP Well Y Actual (0.07 $/kWh):

$$= \frac{\$\ 2{,}664{,}313.63}{\$\ 0{,}07 * 500 * 24} = 3171{,}8 \text{ day or } 8.69 \text{ year}$$

BEP Well Y Actual (0.13 $/kWh):

$$= \frac{\$\ 2{,}664{,}313.63}{\$\ 0{,}13 * 500 * 24} = 1707{,}9 \text{ day or } 4.68 \text{ year}$$

BEP Well Y Improved (0.07 $/kWh):

$$= \frac{\$\ 2{,}152{,}843.73}{\$\ 0{,}07 * 500 * 24} = 2563 \text{ day or } 7.02 \text{ year}$$

BEP Well Y Improved (0.13 $/kWh):

$$= \frac{\$\ 2{,}152{,}843.73}{\$\ 0{,}13 * 500 * 24} = 1380 \text{ day or } 3.78 \text{ year}$$

The value of BEP varies based on the selling price of electricity used. The improved Well Y experienced a BEP decrease of 19.2% when compared to its actual condition.

F. Improvement Recommendations

The main focus of this research is to determine areas for improvement and outline strategies to attain optimal geothermal drilling performance, thereby reducing the duration of drilling operations. The most effective method is to replicate the drilling practices applied in Well X, adjusting it to be in line with the well prognosis for future operations. Therefore, this research provides recommendations for drilling practices to achieve the best performance through a thorough analysis of Wells X and Y.

- **Single run BHA**

To enhance drilling efficiency and achieve the total depth (TD) section with a single Bottom Hole Assembly (BHA) series, it was recommended to adopt high-performance drill bits like Kymera. As shown in Table 4.4, kymera is the best performing drill bit in Well Y drilling, with the highest ROP of 16.7 m/hr. Additionally, it covers the longest distance of approximately 793.7 meters while maintaining a relatively low Krev of 285, which is 49% of Krev limit), even after usage. Despite the relatively higher cost associated with Kymera bits, the potential savings from drilling a section using only one BHA series tend to justify the investment.

- **Single clean-out BHA**

To enhance future drilling operations, it was recommended to design Bottom Hole Assembly (BHA) clean-outs with bits and a variety of hole opener sizes. This design facilitates the execution of cleaning-out activities using a single clean-out series BHA, resulting in direct time and cost savings. When designing this single clean-out BHA, careful consideration should be given to the selection of drill bit and hole opener sizes, as well as the strategic placement of hole openers within the clean-out series. The hole opener should not be placed too close to the drill bit, due to its ability to hinder the effective cleaning of cement inside the liner. This process pose potential risks to the tie-back receptacle, thereby compromising the integrity of the liner used. Proper attention to the spacing between hole openers is also crucial, assuming the placement is too far apart, optimal cement cleaning above the tie-back receptacle may be compromised.

- **Effective application of wiper trips**

The minimal use of wiper trips in both wells has played a significant role in its establishment as the fastest in all locations. Specifically, Well X applied only two wiper trips during drilling, in contrast to Y, which incorporated six conducted twice per section.

- **Technical limit understanding and optimal drilling parameter application**

Among the two fastest wells, the drilling efficiency of X outperformed Y, and was influenced by three parameters, namely WOB, ROP, and RPM. Well X applied higher drilling parameters, leading to exceptional performance compared to Y.

CONCLUSION

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- In conclusion, the use of single-run Bottom Hole Assembly (BHA), designed for drilling an entire section, had a great impact on the duration of the drilling operation.
- The use of BHA use also played a critical role in reducing the time needed to clean the inner side. As a result, the tie-back receptacle was recommended for this purpose.
- The effective application of trip wipers played a significant role in minimizing trip-outs. Consequently, it was recommended to refrain from unnecessary trip-ins in related situations.
- Understanding the technical limits of each piece of equipment and applying relative optimal drilling parameters was recommended.
- The cost efficiency of drilling Well Y was significantly improved by using the best performance characteristics from both wells, leading to a substantial reduction of 19.2% in drilling costs.

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GLOSSARY OF TERM

Symbol	Definition
BHA	Bottom Hole Assembly
BEP	Break Even Point
CPF	Cost per Foot
CTFs	Cycle Time Factors
ESMAP	Energy Sector Management Assistance Program
FPD	Feet per Day
MSE	Mechanical Specific Energy
ROP	Rate of Penetration
TDS	Total Dissolved Solids
WOB	Weight on Bit

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