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An Updated Statistic Evaluation of Drilling Performance, Drilling Cost and Well Capacity of Geothermal Fields in Indonesia

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ABSTRACT

Geothermal electricity price is greatly affected by essential constituents, predominantly exploration and development costs. Both exploration and development drilling costs in Indonesia are accountable for nearly 51% of power generation project investment. Consequently, the effectiveness of resource planning when followed by successful drilling operation executions, will result in a commercial well that will provide sufficient steam supply for the duration of the projects lifetime.

This paper presents statistical evaluation of drilling performance, which is conducted by using geothermal drilling unit cost (cost/meter) criteria. This study investigates drilling cost comparisons with reference to 203 drilling activities, which were conducted from 2011 to 2019 using statistical methods. Geothermal wells in Indonesia are mostly drilled to depths ranging from 1200 to 2800m, which represent a wide range of various reservoir depths. The results indicate that drilling cost in Indonesia ranges from 2000 to 3900 USD/m with mean average of 3499 USD/m, which is somewhat higher than other geothermal leading countries. Drilling performances exhibit a gradual "learning curve" from the exploration to operation phase. We also evaluate the effect of influencing factors affecting drilling cost in Indonesia such as drilling depths, geological setting, operational challenges, contractual scheme, and other global factors such as oil price trends.

This study also offers subsurface geothermal information in Indonesia obtained from drilling activities and is presented in a table that contains the maximum depth of drilling, range of reservoir depth, reservoir temperature, and well capacity. By considering information on well productivity, we estimate that drilling cost per MW capacity distribution of productive wells in Indonesia is in the range of 0.4 to 1.5 MUSD per MW.

1. INTRODUCTION

Tectonically, Indonesia is in an area that supports the formation of a geothermal system. Based on distribution data published by the Geological Agency, in 2019, Indonesia had abundant geothermal resources of 23965.5 MW. However, at the end of 2019 the utilization of geothermal power generation was around 2130.7 MW, which only accounted for 8.9% of the total available resources (MEMR, 2019). The geothermal industry in Indonesia believes that one of the main obstacles that inhibits geothermal development in Indonesia is upstream risk, which is considered high. Sanyal (2011) identifies that upstream risk is significantly affected by resource availability, well costs, and well productivity.

According to published data by the Directorate General NREEC (2020) based off 4 different geothermal project scales, which range from 10 to 120 MW in Indonesia and were implemented between 2016-2019, the cost of exploration drilling wells contributed 11 to 32% of the total project cost, whereas development drilling contributed from 25 to 40% of the total project cost. Consequently, it can be concluded that the total cost of geothermal drilling in Indonesia contributes up to 51% of the total cost of geothermal projects (Figure 1). As a comparison, several studies show that geothermal drilling is responsible for more than 50% of project cost for geothermal projects worldwide (Lukawski et al 2014; Blankeship et al 2005). Furthermore, Gehringer and Loksha (2012) explain that according to investment cost breakdown of geothermal power developments in Iceland, exploration and development drilling accounts for up to 34% of total project cost, while an indicative cost analysis in a typical 50 MW green field project estimates that 45% of investment costs are contributed by drilling.

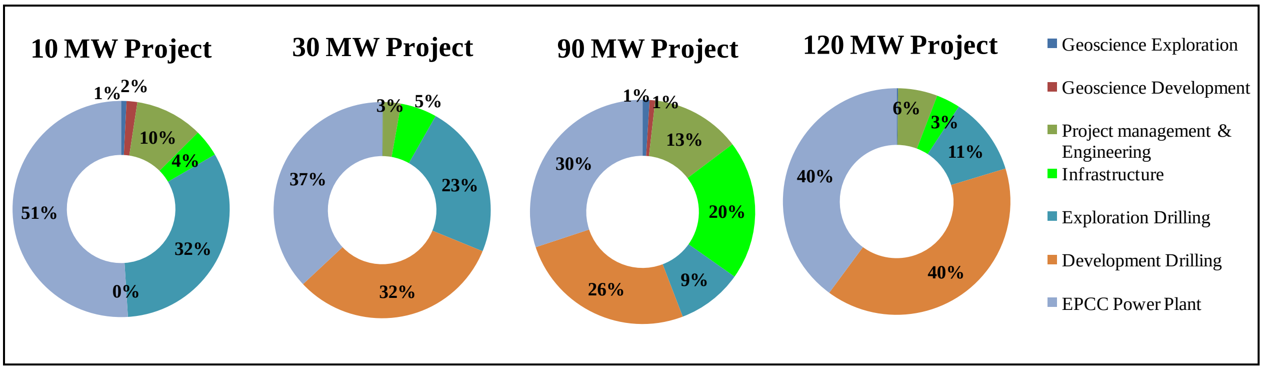

Figure 1: Investment cost distributions of 4 geothermal projects in Indonesia during 2016 to 2019 (modified from Directorate General of NREEC, 2020)

This study is driven by the demand to provide geothermal drilling data. This is because the realization of geothermal drilling costs has rarely been published due to the nature of confidentiality data, so it is considered difficult to inform drilling cost data that encompass a reasonable level of statistical confidence. It is expected that the result from this research can be used in preparing the economic costs model of geothermal projects and support decision makings in the implementation of geothermal projects, and support accelerating geothermal development in Indonesia. Directorate of Geothermal, Ministry and Mineral Resources (MEMR) has obligations in planning and supervising geothermal activities by geothermal developers. MEMR carried out this observation with aims to encourage geothermal developers to drill efficiently, and the intention to increase the economic value of geothermal projects and stimulate competitiveness with power generators using fossil fuels, and other renewable energies.

2. GEOTHERMAL DRILLING ACTIVITY IN INDONESIA

Geothermal drilling in Indonesia has been carried out significantly in several prospects since the 1970s, where exploration drilling was carried out in the Kamojang, Dieng, and Darajat fields (Hochstein and Sudarman, 2008). Drilling activities continued intensively from the 1980s to the late 1990s, this was related to exploration activities and to fulfill steam supply in supporting the generation capacity in Kamojang, Salak, Darajat, and Sibayak fields, which commercially operated within that period for a total installed capacity of 778 MW by the end of 2000. The drilling activity was partially curtailed in the early 2000s period due to a Governmental decision to postpone state-owned enterprise, private, and government-related projects, caused by monetary and fiscal situation through enactment of Presidential Decree Number 39 of 1997. Drilling activities continued afterwards from 2002 to date. There are at least 766 wells which were drilled until 2019 to confirm the existence of geothermal reservoirs and recover sufficient brine and steam to support geothermal power generation in Indonesia. Geothermal drilling activities in Indonesia up until 2019 are shown in Figure 2.

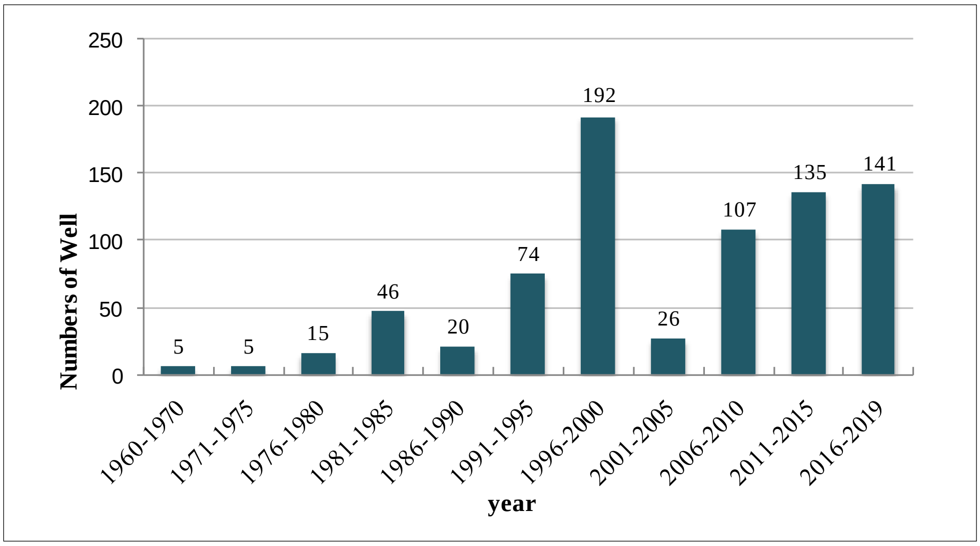

Figure 2: Geothermal drilling activity in Indonesia from 1970s to 2019

As many as 409 wells were drilled from 2002 to 2019. This significant gradual increase in the second period was mainly due to an increasing number of Power Purchase Agreement, which were signed by geothermal power producer PT PLN (Persero) as electricity offtake in Indonesia.

3. TYPICAL WELL DESIGN

Ashadi and Hartono (2020) explain that geothermal well drilling is commonly carried out at a fairly low pressure, ranging from 600 to 1300 psi, with reservoir temperatures generally ranging from 200 to 300°C. Geothermal systems are often linked with major fracture zones and volatile gases in the form of CO_2 and H_2S, which come from magmatic sources. Therefore, it is expected potential for steam kick and fluid losses, both partial and total, to be encountered during drilling activities. For that reason, a technically suitable well design is needed to enable contingency plans to be carried out if drilling problems are experienced within the upper section of the wells. Furthermore, if the drilling activities are able to discover expected steam according to drilling targets, then the well will be used during the operation lifetime. This requires a detailed drilling plan in which a well design with resilient integrity is requisite, and aims to withstand constant elevated temperatures and excessive pressures changes during the operational lifetime of the well.

Generally, well design used in geothermal wells is different during the exploration stage and at the development stage. During the exploration stage, standard hole well is predominantly used, and slim hole is widely acceptable as alternative well design to confirm geothermal system. However, large or big hole options during exploration are also adopted by geothermal developers, which have high confidence in existing geothermal resources. This approach enables a successful exploration well to be converted directly to a production well to support production. At the development and operational stages, geothermal developers regularly use big hole wells to gather geothermal fluids for production.

Based on data obtained from 60 geothermal wells in Indonesia across 11 fields in Sumatra, Java, and Sulawesi, it is concluded that 83% of geothermal wells were drilled using the big hole configuration. Typical geothermal well designs in Indonesia are described in Figure 3. Ashadi and Hartono (2020) emphasize that big hole well is more preferable to be used because it requires less amounts of surface casing, allows deeper drilling operations, involves more production hole sections to cover unforeseen events, allows larger down hole tools that have a better temperature resistance, and provides a greater number of well outputs. According to a report provided by Sveinbjornsson and Thorhallsson (2014), big hole wells provide 30-40% greater output compared to standard wells.

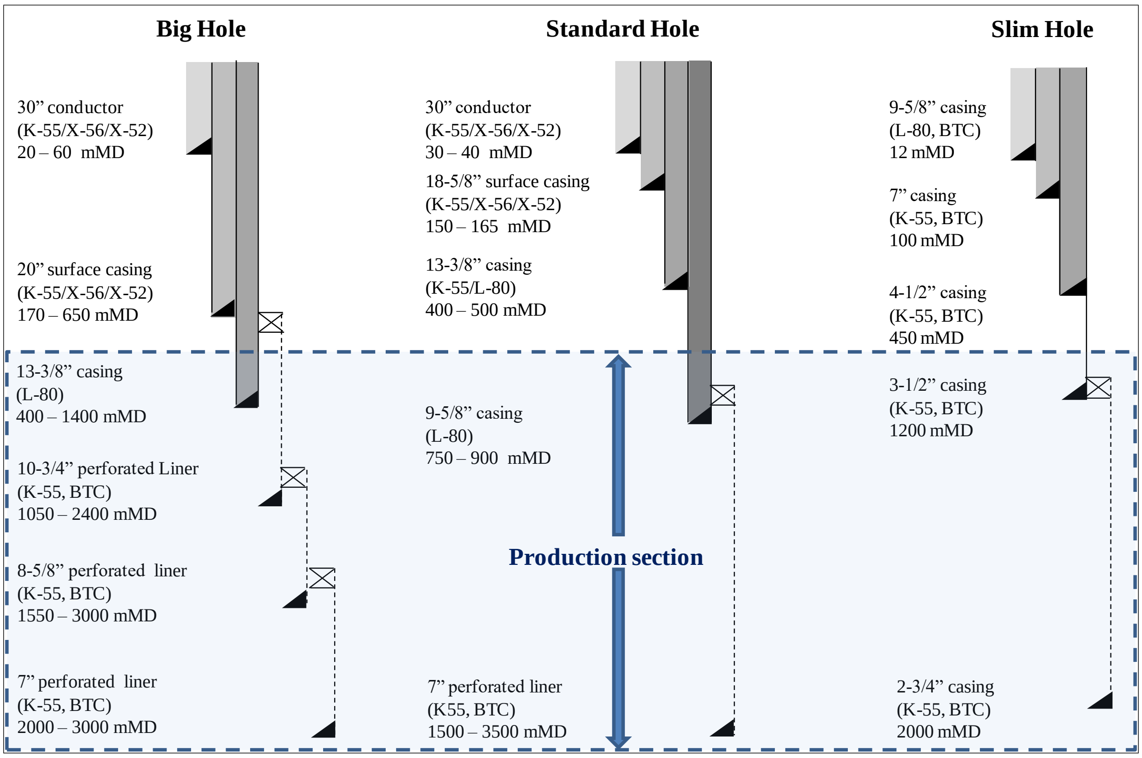

Figure 3: Typical well design and interval depth of 60 geothermal wells in Indonesia (modified from Isa et al 2017, Purwanto et al, 2018 and Ashadi and Hartono, 2020).

Slim hole drilling can be encouraged to lessen risk of failure and improve probability of exploration success. This approach can be useful for a geothermal company that has high resource uncertainty with investment cost limitation. The use of slim hole drilling is also preferable in minimising land use while acquiring physical subsurface information through conventional coring. However, deep slim hole drilling needs longer drilling time due to technical difficulties encountered during drilling, which is mainly caused by lack of deep slim hole drilling knowledge, unsuitable well design, and multiple hole problems which eventually lead to cost overruns.

Pasikki (personal communication, December, 2020) suggested that aims to minimize potentially high, upfront, capital expenditures associated with civil works as an alternative exploration program utilizing slim-hole wells for the initial geothermal exploration should be considered. Slim-hole drilling needs only minimal civil works necessary to place the truck mounted rigs. However, the biggest question is whether slim-hole will be able to sustain flow and produce representative reservoir fluid, which is important information for field development. Slim-hole is definitely more difficult to flow than the standard-hole, especially in the liquid reservoir, and therefore the slim-hole is not typically used on the commercial operation stage. Due to its limited drilling depth, slim-hole only provides minimum reservoir thickness in the range of 500 - 1000m. However, there will be abundant cores retrieved from the continuous coring of the reservoir section, providing sufficient information of rock properties, and including priorities.

4. DRILLING OPERATIONS

Drilling operations are critical in geothermal exploration and project development. During exploration, the main objective of drilling programs is to demonstrate that an explored field has a sufficient resource volume for a commercial development. To be able to support commercial development, geothermal reservoir should host high temperature, and benign fluid. The reservoir should also be permeable, so that the well drilled within the reservoir will have commercial performance. Resource capacities are assessed based on the rock properties, reservoir physics, and thermodynamics information that is gathered during the exploration program (R. Pasikki, personal communication, December, 2020).

Furthermore, in a project management context, successful drilling operations should be emphasized on gathering value of information, value of economy, maintaining incident-free operation, implemented within the specified time, and budget constraints. With aims to reduce drilling risks, a thorough analysis is required specifically to define the exploration and appraisal drilling program for a geothermal prospect. The program is detailed for each geothermal prospect. It should be based on the conceptual model and associated resource risk as indicated from previous geoscientific (geology, geochemistry and geophysical) studies. Project economics must also be considered during planning phase.

4.1 Operational challenges

Drilling associated with various risks that includes, but not limited to, commercial schemes, procurement process, technical operation, drilling hazard, output discovery, health, safety and environmental consideration, and magnitude of drilling costs. Operational risk is seen as one of the most significant factors that influences drilling success. Most challenging problems that are frequently encountered during drilling are as follows (modified from Finger and Blankenship; 2010; Vollmar et al., 2013; and Pertamina Geothermal Energy, 2018):

1. High temperature: mostly influencing tools temperature limitation, extreme thermal stress on the tubular, corrosion rate increases and degraded drilling fluid.
2. Loss circulation both partial and total. Approximately 10% of total cost of geothermal drilling is due to loss circulation combating. Loss circulation may lead to several effects such as cost increase, hydrostatic head reduction that may lead to wellbore influx, and stuck pipe due to poor cutting removal.
3. Wellbore instability which usually caused by mechanically unstable formation, swelling/ shrinking clays and differential stress that may lead to drilling obstruction.
4. Rock formation related problems such as boulders, metasedimentary rock, reactive clays, surface loss circulation, and sheeting joints.
5. Equipment failures: twist off drill pipe, burn out tools, drilling tools and down hole tools malfunction.
6. Stuck pipe, lost in hole, fishing and sidetracking.
7. Well control events such as steam kick and shallow gases which mainly CO_2 and H_2S.
8. Unplanned equipment testing.
9. Well pad construction issues.

As a way to anticipate problems that may arise during drilling, several stepwise processes should be taken into consideration prior to conducting drilling activity. Supreme Energy (2018) suggested that well delivery process entails:

1. Subsurface preparation composed of conceptual geoscientific model, subsurface engineering, and conceptual well design.
2. Pre-planning consists of detailed basis of well design and services and goods procurement.
3. Detail planning contains well authorization for expenditure (AFE), rig inspection, safety health and environmental plan, drilling operational procedure, drill well on paper, equipment certification, drilling program, drilling induction, and pre spud meeting.
4. Operation execution includes operation supervision, daily coordination meeting, drilling data and reports, and cost controlling.
5. Project closure involves action item list for project performance improvements, well performance documents, lesson learned, final well report, and AFE close out.

Lessons learned in geothermal drilling also proved to be a successful approach in mitigating unforeseen consequences for upcoming drilling campaigns. Authors analyze several lessons learned and improvements carried out by several geothermal developers in Indonesia, as described in Figure 4.

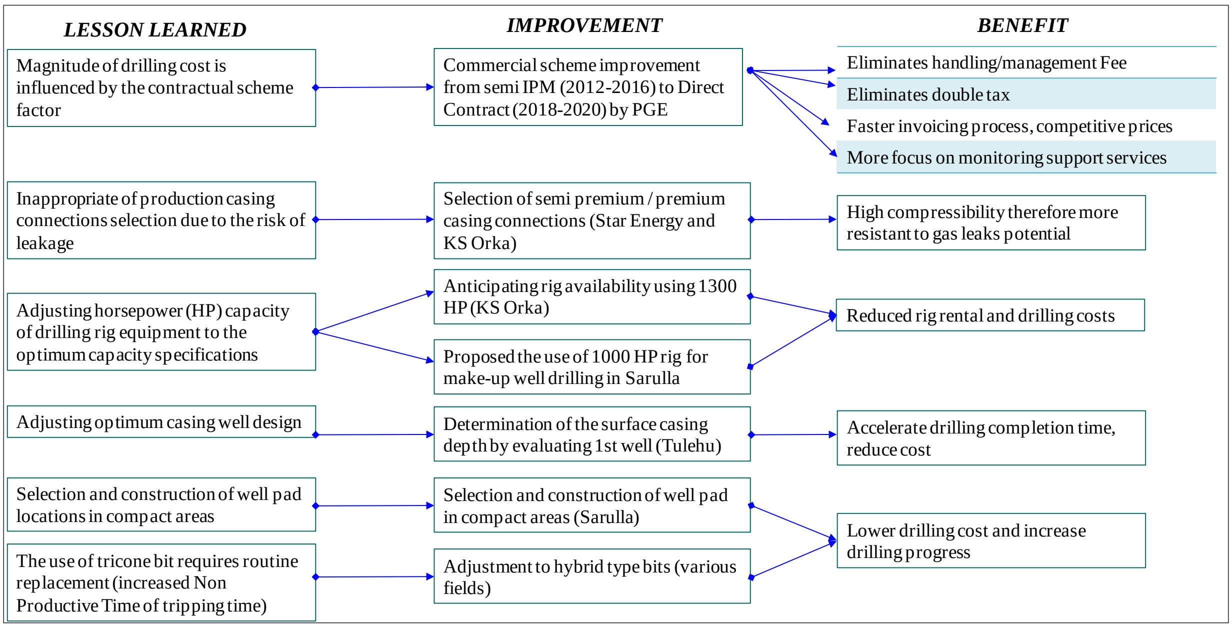

Figure 4: Lesson learned and improvement actions in geothermal drilling conducted by geothermal developers based on Author's analysis

4.2 Drilling depth

In this section, drilling depth of geothermal wells in Indonesia is presented. The depths of geothermal wells in Indonesia vary greatly and extend up to almost 3500m. Drilling depth varies depending on the target reservoir to be achieved. Based on Author's analysis, geothermal reservoirs in Indonesia are encountered in a various range of depths. Reservoir depths information can be obtained from results of geoscientific modeling, then confirmed by exploration/ test drilling. Ranges of reservoir zones in Indonesia classified by regional area are presented in Table 1.

Table 1: Reservoir depths in geothermal system in Indonesian region (updated from Purwanto et al, 2018)

Geothermal regional field	Reservoir Depth (mTVD)	Max. drilling depth (mTVD)	Maximum. Temperature (ºC)
West Java	650-2000	3200	327
Central Java	1400-2300	3477	369
East Java	1970	2000	291
Lampung	1000-2275	2394	282
Bengkulu	1600-2900	3180	300
Jambi	1800-2400	2798	281
South Sumatera	800-2850	2639	288
West Sumatera	1100-2500	2860	310
North Sumatera	1200-2100	2590	311
Naggroe Aceh	1100-1300	1300	260
North Sulawesi	920-2500	2683	358
Bali	500-1200	2687	326
East Nusa Tenggara	1900-2500	2062	255
Maluku	1300-1800	1900	230

Drilling depth varies greatly between geothermal systems in different regions. Based on Table 1, geothermal systems located in Sumatera indicate deeper reservoir depths, compared to those situated in the Java or Nusa Tenggara regions. Therefore, it can have direct correlation as a factor that controls drilling depths. We analyze drilling depths based on 675 wells in Indonesia, as seen in Figure 5. It demonstrates that geothermal wells in Indonesia range from about 800 to 3500m, and at least 81% of geothermal wells in Indonesia are drilled to range depths of 1200 to 2800m, with the deepest well depth of 3477m.

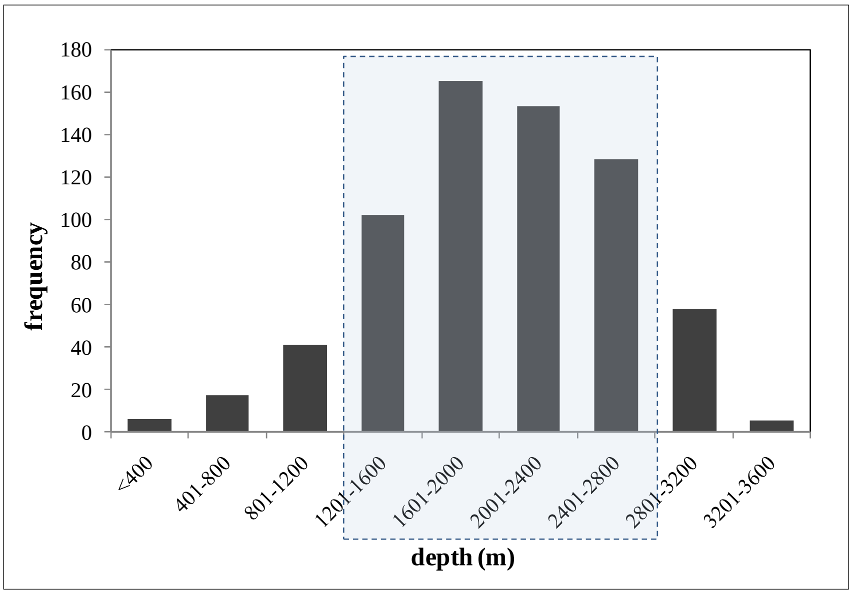

Figure 5: Geothermal well depth distribution in Indonesia

5. DRILLING COST

5.1 Total well cost

In this section, cost of drilling is evaluated as part of the well cost. Associated costs, required for geothermal wells, generally include well pad construction costs, drilling costs, well completion and testing costs, well hook up, permitting, and other supporting costs. Well costs analyzed in this study are limited to the costs required to complete the drilling of the wells, starting from the provision of drilling material to completion of drilling (Figure 6).

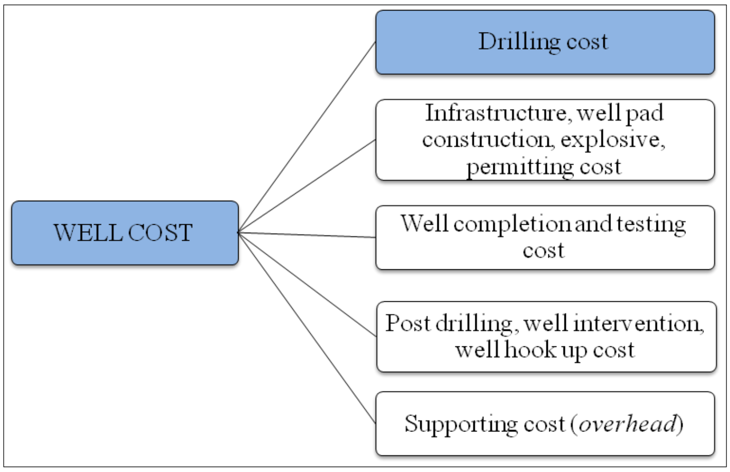

Figure 6: Typical costs associated in constructing a geothermal well

Several studies explain the correlation between drilling cost and well depth. IFC (2013) suggests that a single geothermal well may cost between 1 to 7 MUSD per well, depending on the depth and location situation. Sanyal (2011) has reported geothermal drilling cost and correlations with well productivity. According to (Sanyal 2011) depth is the main determinant of drilling cost, and typically drilling cost in any country increases exponentially with depth. Lukawski (2014) explains that geothermal wells require multiple casings intervals during drilling, which resulted in higher drilling time and cost of completions.

This study updates a previous study which conducted in 2018. As for this study, we evaluate drilling costs from 203 wells which were completed during 2011 to 2019. Several other factors that are taken into consideration in the analysis of drilling costs include normalized drilling costs, depths, contracts commercial scheme, and activity stages in geothermal projects. Therefore, the analysis carried out in this paper is able to differentiate the costs of drilling carried out at different stages of geothermal projects, namely exploration, development, and operation.

This study uses cost index for calculating cost, with time reference to enable historical cost comparison. According to Newnan et al. (2004), cost indexes are numerical values that reflect historical change of costs. Therefore, this study considers the use of annual US producer price index (US PPI) of industry data for oil and gas field machinery and equipment, published by Bureau of Labor Statistics (2019). The US PPI measures average changes in price received by domestic producers for their goods and services. This also considers that drilling cost is highly influenced by the international oil and gas market.

The result indicates that drilling cost in Indonesia varies greatly from 1.3 to 18 MUSD with a mean value at the magnitude of 7.4 MUSD per well as seen in Figure 7. The average of drilling cost decreases as project stage progresses. This indicates that geothermal developers gain insights and better understanding of subsurface conditions and optimum operational configuration in performing drilling operations, throughout the geothermal project lifecycle. Figure 8 allows drilling cost comparison to be made between each field.

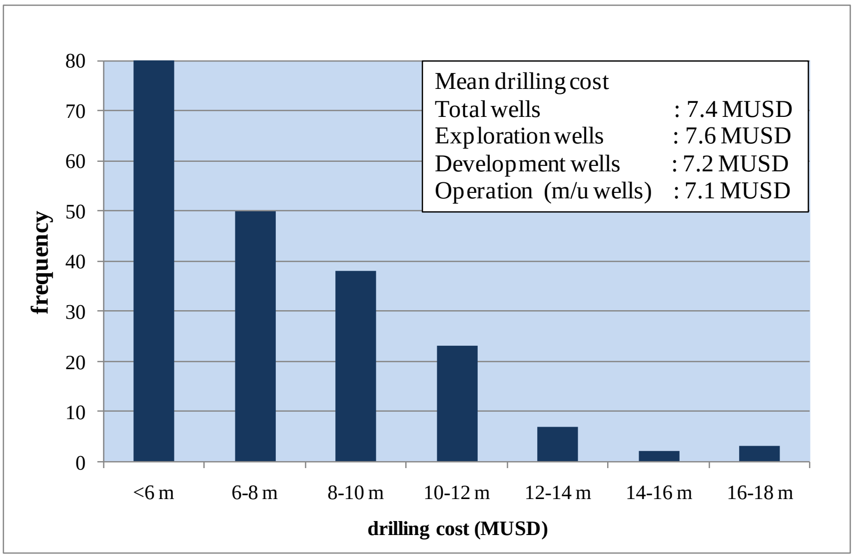

Figure 7: Frequency distribution of geothermal well cost

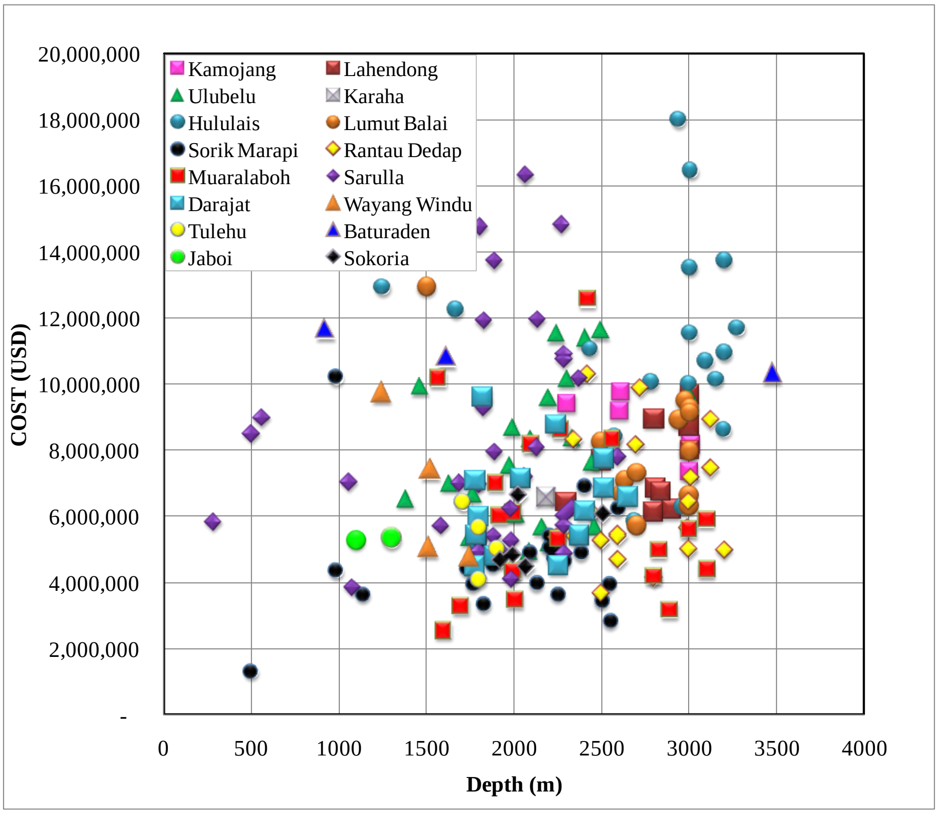

Figure 8: Drilling cost distributions of geothermal fields in Indonesia.

5.2 Geothermal drilling unit cost

In measuring drilling performance several key performance indicators are used in evaluating non-performed activities (Zuhro and Arif, 2015). One of the widely accepted criteria to measure drilling operation performance is geothermal drilling unit cost (GDUC). This normalization method enables comparisons to be carried out between fields managed by different developers by taking into account similar observation basis. The results indicate that drilling unit cost in Indonesia recently is in the magnitude of 3499 USD/m (Figure 9). The analysis also follows a similar pattern in which drilling unit cost decreases over project sequence. During the development and operation stages, drilling costs generally decreased, as geothermal developers understand the characteristics of the field and increase efficiencies when avoiding unnecessary service costs. This performance indicates the existence of a learning curve that represents the successful amount of experience implemented during cost reduction attempts.

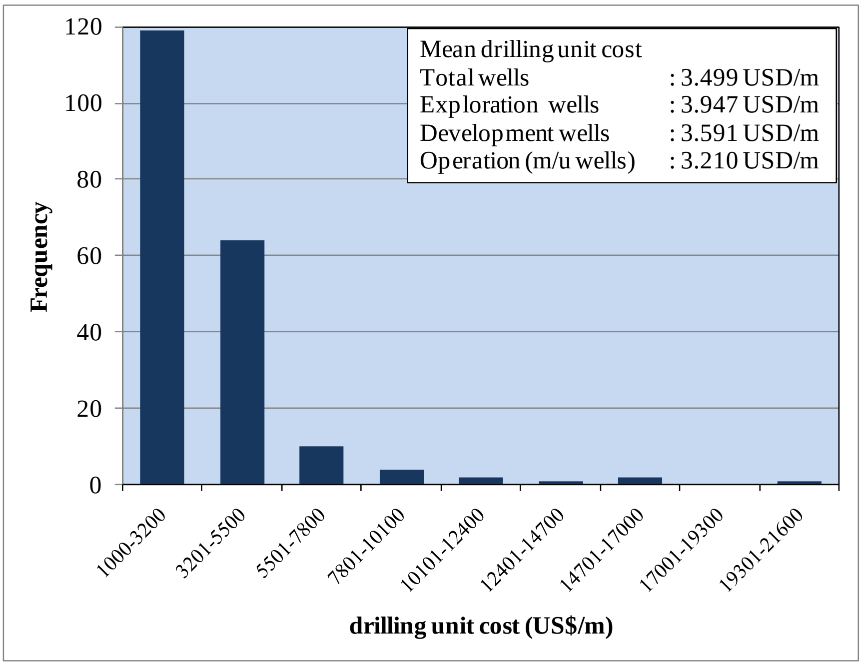

Figure 9: Drilling cost distributions of geothermal fields in Indonesia.

Based on our observation, annual drilling unit cost reduces over time. Figure 10 exhibits a downward trend particularly from 4455 USD/m in 2014 to 2944 USD/m in 2019. This is possibly caused by improvements and cost saving initiatives conducted by business entities. This condition is also due to the influence of world crude oil prices' descending trends (Figure 10). This situation forces cost components of drilling rigs to also decrease, due to the downward trend in oil price commodities and reduced frequency of drilling projects. This has resulted in a large number of rig services becoming available in the market. Additionally, with the increasing number of experts in the geothermal sector, developers can easily recruit experts and set up qualifies and a strong drilling team. This condition encourages changes in contractual schemes in managing geothermal drilling. Therefore, it stimulates commercial scheme changes from full Integrated Project Management (IPM) and semi IPM contracts, to bundled contracts or direct contracts (Figure 11). MEMR encourages drilling unit cost could be reduced further down to less than 2000 USD/m.

In Indonesia at least four drilling schemes/ contracts are needed to handle drilling operations. From the least to the greatest number of contracts handled, contractual schemes can be classified into: IPM contract, semi IPM contract, bundled contract, and direct contract. IPM type manages 1 main contract, semi IPM type handles roughly 8 contracts, bundled type deals with 13 to 20 contracts, and discrete type manages as many as 24 to 30 contracts (Isa et al, 2017; Kelley, 2018). Sorik Marapi Geothermal Power (2020) suggests that based on drilling experiences in Sorik Marapi, drilling unit cost using discrete contract is approximately 25% less expensive compared to IPM contract, whereas using discrete contract is roughly 17% less expensive compared to bundled service contract.

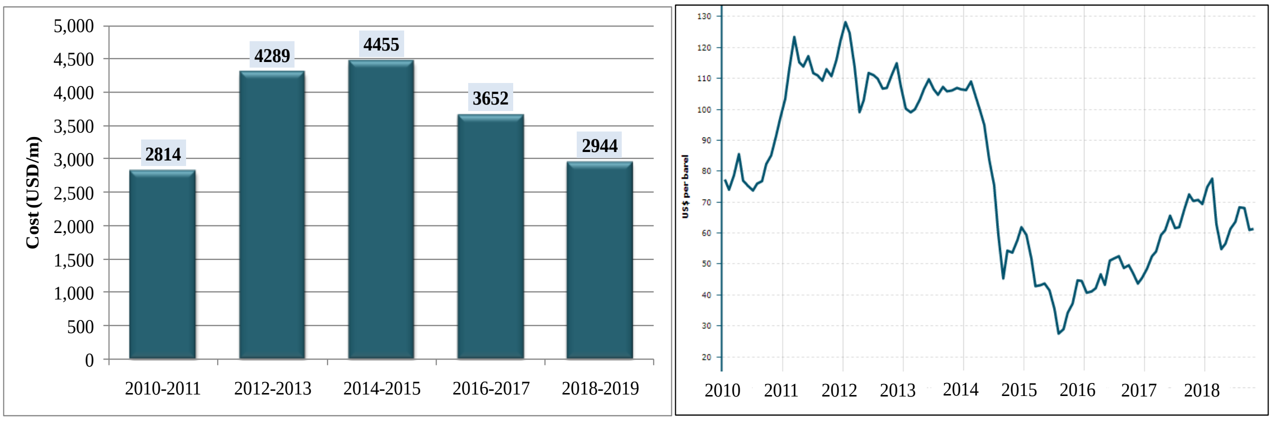

Figure 10: Drilling unit cost in 2 years interval from 2010 to 2019 (left) show good agreement with downtrend world oil price (right) which modified from Macrotrends (2020)

Fields	Geothermal drilling unit cost average of each fields in 2019 (USD/meter)		Wells	Year	Remarks
Baturaden	7,425		3	2018	IPM, Exploration, Java
Sarulla	5,495		33	2014-2017	IPM, Development, Sumatera
Wayang Windu	4,691		4	2018	Semi IPM, Make-up, Java
Jaboi	4,439	*Learning Process*	2	2017-2018	IPM, Exploration, Sabang
Hululais	4,021	← (2,888 USD/m; 10 develop; 2018)	22	2015-2018	Semi-IPM, Development, Sumatera
Ulubelu	3,851	← (2,916 USD/m; 5 Make-up; 2018)	21	2014-2016	Semi-IPM, Make-up, Sumatera
Kamojang	3,304	Contract adjustment (semi IPM → direct)	5	2015	Semi-IPM, Make-up, Java
Lumut Balai	3,178		13	2014-2018	Semi-IPM, Development, Sumatera
Karaha	3,115		2	2014	Semi-IPM, Development, Java
Darajat	3,089		11	2011 & 2019	Discrete, Make-up, Java
Tulehu	2,950	*Learning Process*	4	2017-2018	IPM, appraisal, Maluku
Muaralaboh	2,727	← (4,289 USD/m; 6 exploration wells; 2013)	13	2017-2018	Discrete, Development, Java
Lahendong	2,702		10	2015-2016	Semi-IPM, Make-up, Sulawesi
Sorik	2,648		25	2016-2019	Bundled, Development, Sumatera
Sokoria	2,536	*Learning Process*	5	2017-2018	Bundled, Development, NTT
Rantau Dedap	2,396	← (3,262 USD/m; 6 exploration wells; 2014-2015)	15	2018-2019	Discrete, Development, Sumatera

Cost (USD/m): 0, 1,000, 2,000, 3,000, 4,000, 5,000, 6,000, 7,000, 8,000

Figure 11: Contractual comparison of drilling unit cost in each field that corresponds with particular drilling campaign

5.3 Worldwide drilling unit cost comparison

Considering amounts of installed power plants, geothermal project costs involved, and numbers of geothermal wells drilled, up to date, enable comparison between Indonesia and other geothermal leading countries to be carried out. Indonesia and the Philippines exhibit more expensive drilling cost compared to other countries, with 3499 USD/m and 3600 USD/m, respectively. This is caused by high mobilization cost to remote area, mountainous-dominated geological setting, and the use of conventional contracts of daily rate.

On the other hand, drilling in Kenya and Iceland is relatively cheaper. The cost of drilling in Kenya by a developer who owned a rig with equipment is around 3.5 MUSD per well, and drilling with a rig rental is around 6.5 MUSD per well (Ngugi, 2013). Drilling costs in Iceland range from 2.5 to 4.8 MUSD per well. Palsson (2017) suggested that is because geothermal developers in Iceland use a hybrid drilling contract, which is a combination of daily rate, meterage & lump sum, which allows a well to be drilled with the cost approximately 1000 to 2000 USD/m. Drilling in Turkey is much cheaper because generally geothermal system is hosted by carbonate rocks in a relatively flat geological setting, making it easier to drill. Leading countries comparison can be observed in Table 2 and Figure 12.

Table 2: Country comparison of average drilling unit cost

Countries	Year	2019 cost US PPI corrected (MUSD)	Avg. Depth	Unit cost (USD/m)	Size of well	References
Turkey	2018	3.4	4500	752	Standard	Gul and Aslanoglu (2018)
Philippine	2019	9.0	2500	3600	Large	R. Jarque, personal communication, 2019
Kenya 1	2013	6.7	3200	2093	Large	Ngugi (2013)
Kenya 2	2013	6.2	3000	2076	Large	Kipsang (2015)
Iceland 1	2002	2.4	1500	1602	Standard	Stefánsson (2002)
Iceland 2	2012	4.9	2175	2235	Large	Thórhallson and Sveinbjörnsson (2012)
Iceland 3	2014	4.4	2235	1961	Large	Sveinbjörnson and Thórhallsson (2014)
Iceland 4	2017	4.1	2500	1638	Standard	Pálsson (2017)
New Zealand 1	2006	4.2	2600	1621	Standard	Hole (2006)
New Zealand 2	2007	5.2	2500	2506	Large	Barnett and Quinlivan (2009)
New Zealand 3	2010	3.7	2306	1610	Standard	Bush and Siega (2010)
New Zealand 4	2010	7.3	2558	2855	Large	Bush and Siega (2010)
Indonesia	2019	7.4	1200 - 2800	3499	Large	Author's analysis

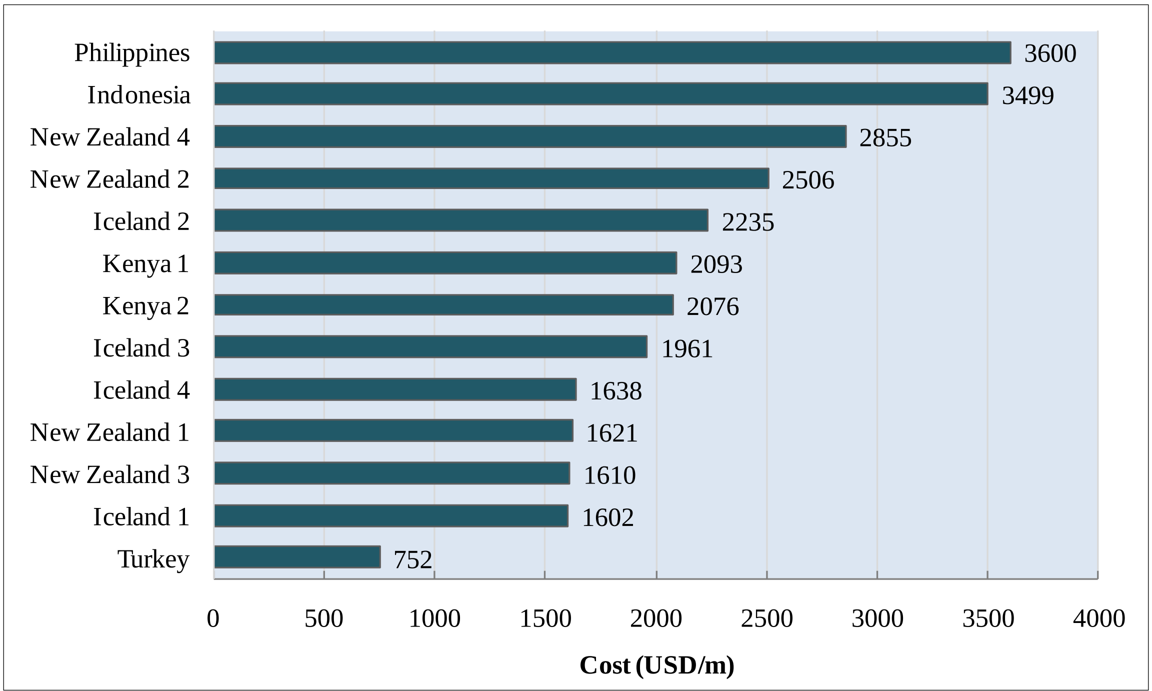

Figure 12: Country comparison of average drilling unit cost

6. WELL OUTPUT

Sanyal (2011) divides well commerciality based on its capacity and suggests that commercial wells in Indonesia range from 3 MW to 40 MW. Well capacity of less than 2 MW and sometimes 3 MW is considered non-commercial well and can function as an injection well. This study considers similar assumptions of commercial wells who have a well output larger than 2 MW. However, in some cases a well with output less than 2 MW still can be connected into the production system. Figure 13 describes well output distribution of commercial well in Indonesia.

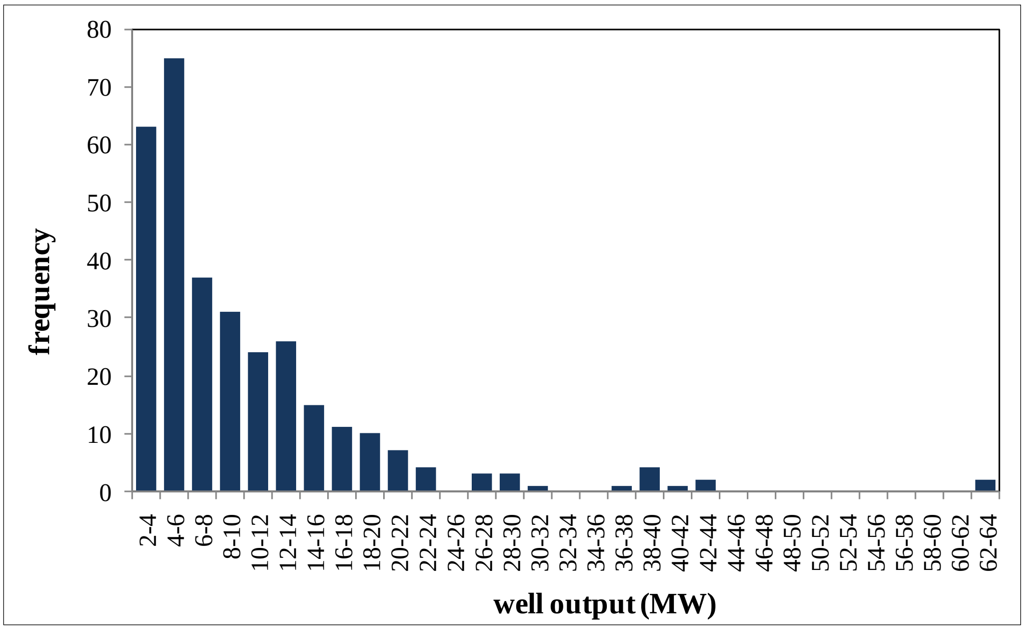

Figure 13: Distribution of commercial well output in Indonesia

For the majority of the field, power output assumption using steam is calculated using conversion ratio ranges from 7 to 8 tons/hr/MW, while in the Sarulla field it uses a conversion ratio of 7 tons/hr/ MW for steam turbine and 100 tons /hr/MW for bottoming cycle and brine technology due to brine utilization. Therefore, it will result in large well output combined. However, IFC (2013) suggests that well depth generally does not provide clear relation to well output success.

According to Sanyal (2011) drilling cost/MW well capacity in Indonesia ranges from 0.1 to nearly 2 MUSD per MW, with the most probable range of 0.3 to 0.4 MUSD per MW. According to this study geothermal drilling cost per MW well capacity evaluated from 11 fields indicate ranges of 0.4 to 1.5 MUSD per MW (Table 3).

Table 3: Geothermal drilling cost per MW in Indonesia geothermal field

Field	Depth (m)	Cost (MUSD)	Output (MW)	Avg cost (MUSD/MW)	Cost (USD/m)	Wells
Kamojang	2308-3009	8.1 – 9.7	4 – 16.8	1.05	3516	4
Lahendong-Tompaso	2300-3003	6.1 – 8.8	2 – 14.8	1.33	2646	5
Ulubelu	1979-3000	5.7 – 9.7	5 – 30	0.72	3388	8
Lumut Balai	2495-2632	6.6 – 8.2	4,3 – 7.5	1.24	2851	4
Hululais	1668-3280	8.4 – 17.9	4,8 – 15.5	1.35	4067	5
Sorik Marapi	2089-2541	3.9 – 9.9	5 – 15	0.74	3409	6
Rantau Dedap	2248-3123	3.6 – 10.2	2 – 20	1.48	2782	10
Muaralaboh	1600-3103	2.5 – 10.1	5 – 40	0.43	2362	11
Sarulla	1799-2128	4.9 – 16.2	14 – 62*	0.35	5068	10
Darajat	1775-2652	4.5 – 6.8	4 – 37	0.64	2610	8
Wayang Windu	1244-1747	4.7 – 9.7	6.7 - 18	0.67	4691	4

7. CONCLUSION AND FURTHER STUDY

The result indicates that drilling costs in Indonesia vary greatly from 1.3 to 18 MUSD, with mean value at the magnitude of 7.4 MUSD per well. Whereas drilling unit cost in Indonesia recently in the magnitude of 3499 USD/m. The average of drilling unit cost decreases as project stage progresses. This indicates that geothermal developers gain insights and better understanding of subsurface conditions and optimum operational configuration in performing drilling operations throughout the geothermal project lifecycle. Based on our analysis, annual drilling unit costs reduce over time, which later exhibits a downward trend particularly from 4455 USD/m in 2014 to 2944 USD/m in 2019. Furthermore, geothermal drilling costs when considering MW well output capacity in Indonesia suggest a range from 0.4 to 1.5 MUSD per MW.

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