PROCEEDINGS, 45th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2020
SGP-TR-216

Geothermal Drilling Cost Optimization in Indonesia: A Discussion of Various Factors

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Keywords: geothermal, drilling, rig, cementing, cost, NPT, stuck pipe, database, procurement, competencies, risks, slimhole, Indonesia

ABSTRACT

As a country that is believed to have one of the largest geothermal energy potentials in the world, Indonesia is currently in the effort of achieving the target of utilizing this potential. One of the most significant obstacles in the process of achieving this target is the high drilling cost, which has become a topic of discussion in many geothermal forums in Indonesia. Drilling activity is commonly known to have expensive cost components which can give immediate effect to the total cost of the whole geothermal project. Therefore, it is highly important to manage it from the early planning phase to the execution in order to optimize the actual cost at the end of the drilling project. One fact that makes the authors of this study confident that there is still room for improvement or optimization in geothermal drilling costs in Indonesia is the wide variation of drilling costs summarized by Government of Indonesia based on geothermal drilling operation in the period of 2011-2018.

One of the challenges in conducting this study is the difficulty of obtaining geothermal drilling data in detail from geothermal developers in Indonesia due to the absence of an integrated database system and lack of publication from Indonesian drilling engineers. While waiting for the drilling data to be gathered, the authors start a discussion to map all factors that might impact the overall drilling cost. Later, when the drilling data is available, all the factors mapped in this study can be analyzed to see the correlation strength to the total drilling cost. This study is considered as a preliminary work that summarize the brainstorming sessions among the authors on several factors impacting the geothermal drilling cost. Therefore, the short-term goals of this paper are to trigger further study with more focus on each area or factors that significantly contribute to drilling cost variation and to urge Indonesia geothermal drilling community in building an integrated drilling database system to accelerate the learning process in drilling geothermal wells.

1. INTRODUCTION

1.1 Current Geothermal Development in Indonesia

Indonesia has an abundant potential in renewable energy sources that has not been utilized in an optimal way, and one of these energy sources is geothermal energy. Indonesia is believed to have potential geothermal energy as large as 25,386 MWe (mega-watt electricity) or equal to 21% of the world's geothermal potential (EBTKE, 2020). This enormous geothermal energy potential possessed by Indonesia because it sits on the ring-of-fire that has been created by interaction between three large tectonic plates: Eurasian, Pacific, and Indian-Australian (Figure 1). The geological and tectonic setting mainly controls the distribution of the geothermal system, which clearly shows that majority of geothermal system in Indonesia, extended from Sumatra, Java, Bali, Lombok, Flores, North Sulawesi, and Halmahera are volcanos hosted.

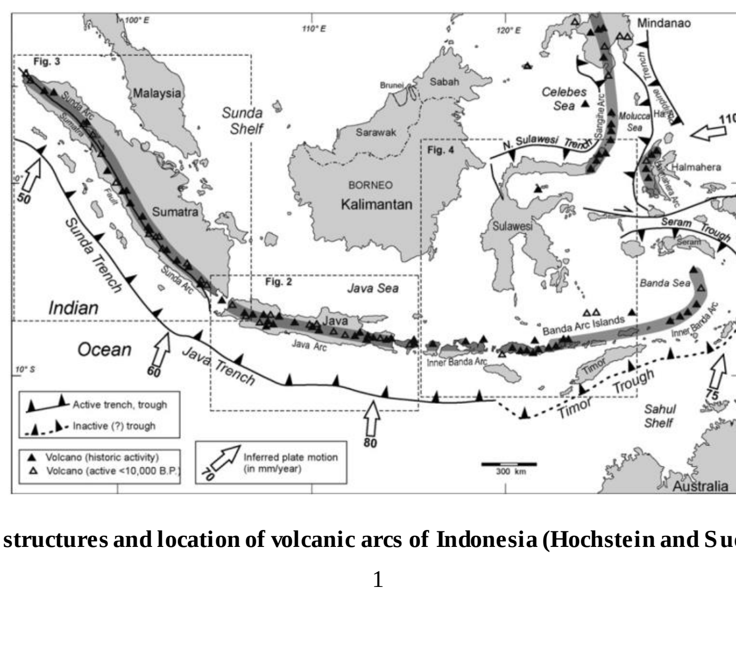

Figure 1: Plate tectonic structures and location of volcanic arcs of Indonesia (Hochstein and Sudarman, 2008; Hall, 2002)

Since geothermal system in Indonesia is commonly associated with tectonic and volcanic activities, most geothermal areas are located in the high-relief terrains. The geothermal prospects are generally identified through surface manifestations that discharge water or steam at boiling temperatures at ground level (Hochstein & Sudarman, 2015). Furthermore, Utami (2010) describes in detail the various challenges that will be faced when performing civil works in geothermal areas in Indonesia due to the unique characteristics of volcanic areas where heat, rocks and liquids interact dynamically, naturally and actively. Figure 2 shows a simple illustration of the thermal and hydrological structure of a typical geothermal field in Indonesia that lies in a steep volcanic area.

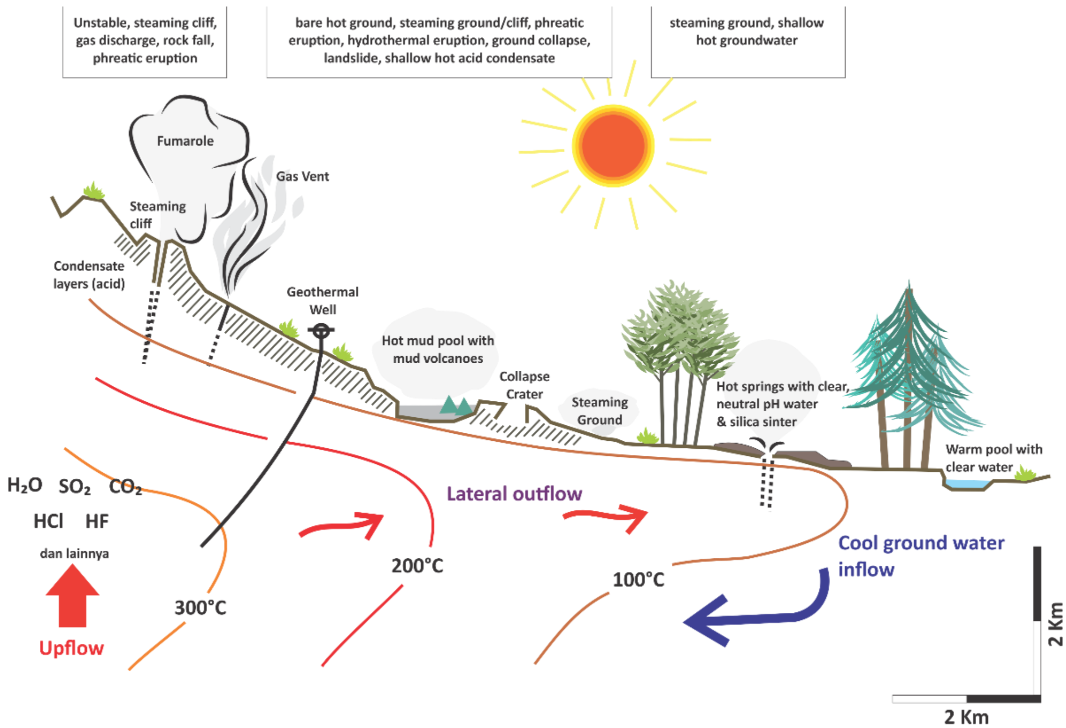

Figure 2: Illustration of typical geothermal system in Indonesia, which lies in high-relief terrain (modified from Utami, 2010)

Although Indonesia is believed to have a considerably large geothermal energy resources, it has only utilized 7.8% of its total potential, way below the Philippines 47.9%, Turkey 29.9%, Italy 28.8%, and New Zealand 27.5% (EBTKE, 2020). Figure 3 shows the increase of geothermal installed capacity in Indonesia from the year of 1983 to 2020, and the target set by the Indonesian government to develop the geothermal energy utilization by 2025.

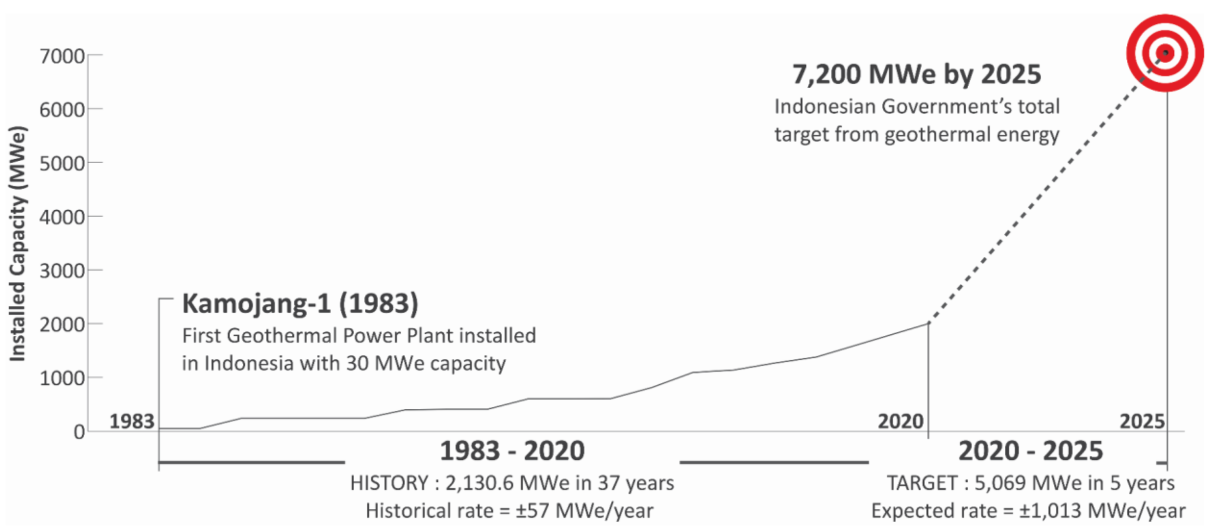

Figure 3: Indonesia geothermal installed capacity (1983-2020) and 2025 target (modified from Purba, 2018 and EBTKE, 2020)

This ambitious target on national geothermal energy utilization might bring optimism to the industry since this target indicates the level of intention the government has in developing the energy. On the other hand, this target increases the urgency to all geothermal project stakeholders to start solving and mitigating all the identified challenges lies ahead.

1.2 Major Cost Contributor in a Geothermal Project

One of the challenges that is often discussed in the geothermal community in Indonesia is the high cost of drilling activities. Worldwide, including Indonesia, shows that every geothermal project cost mainly dominated by two major components, which are power plant construction and drilling (Figure 4). In addition to that, Purwanto et al. (2018) mentioned that for a 55 MW geothermal project in Indonesia, drilling cost accounts for 58% of total project cost. Therefore, it is important for Indonesia to find ways in optimizing its drilling cost to increase the economics of the overall geothermal project.

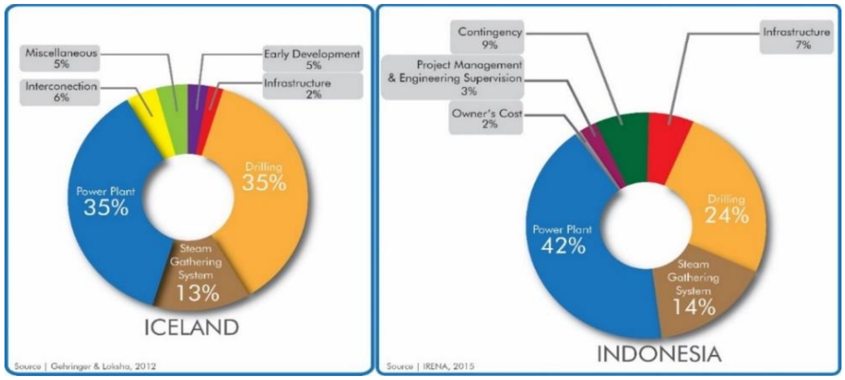

Figure 4: Cost components of a geothermal energy development project in Iceland (left) and 110 MW power plant in Indonesia (right) (modified from Gehringer and Loksha, 2012; IRENA, 2015)

Out of the two cost components, the power plant cost – though it may seem larger than the drilling cost, is considered by the authors to generate lesser variation in costs, which discussed briefly in Table 1.

Table 1: Comparison between drilling and power plant construction difficulties

Comparison	Well Construction (Drilling)	Power Plant Construction
Location	The drilling activities most likely are conducted in several different locations, in which even though they are in one area, each location has its own uniqueness, and therefore will require different planning for each well. The well or drilling location is always determined by the sub-surface target, where in Indonesia many are in hard-to-reach areas due to high-relief terrain profile.	In contrary, selecting a location to build a conventional power plant – for receiving the supply system from various wells, is conducted once the exploration phase is finish and the subsurface risk is significantly reduced. The selected location is usually stable and in a safe distance from any identified geohazards. This flexibility is the reason why costs in building a power plant is more predictable and measurable.
Risk / Uncertainties	Drilling involves sub-surface uncertainties that are difficult to be seen and predicted. The uncertainties mainly due to the rock or formation heterogeneity that forms the geothermal system below the earth.	On the other hand, power plant is built above the ground that still visible and easier to be monitored. It makes cost estimation process of power plant construction relatively easier compare to well construction.

In this study, drilling cost refers to all cost related to drilling, including tangibles (casing and wellhead) but exclude all drilling infrastructure cost such as wellpad and access road construction.

1.3 Geothermal Drilling Cost in Indonesia

1.3.1 Brief History of Geothermal Drilling in Indonesia

Geothermal activity in Indonesia has not been continuously going in a steady rate from 1920s to present time. Hochstein and Sudarman (2008) have summarized the history of geothermal exploration in Indonesia from 1970 – 2000 with sufficient level of detail. It is mentioned that geothermal drilling activities in Indonesia began in 1926 where three shallow wells (66, 123, and 128 meters deep) were drilled inside a large fumarole field in Kamojang Crater, West Java. The exploration is then followed by another shallow well drilled in the Dieng field (Sikidang Crater) in 1928 to a depth of 80 meters. After those wells, no drilling activities were made until 1972.

Based on Purwanto et al. (2018), in the period of 1970 – June 2018, there were at least 711 geothermal wells drilled in Indonesia with depth ranging from 800 – 3,500 mMD. The most active drilling period was occurred in the year of 1996 – 2000 (192 wells), 2006 – 2010 (107 wells) and 2011 – 2015 (134 wells). The authors believe that the inconsistent frequency of geothermal drilling projects in Indonesia have partly contributed to the slow learning curve within Indonesia geothermal drilling community and ultimately affect the variation of drilling cost.

1.3.2 Lack of Related Publication and Absence of Drilling Database

The authors begin this study by looking at, through literatures study, the distribution of drilling costs from various geothermal drilling projects worldwide, including Indonesia. Worldwide, the authors have been able to retrieve several published works discussing geothermal drilling cost, among them are from USA (Lukawski et al., 2016), Russia (Southon and Gorbachev, 2003), New Zealand (Hole, 2013), Saint Lucia (Bodley, 2018), Turkey (Gul and Aslanoglu, 2018), Iceland (Sveinbjornsson and Thorhallsson, 2012), The Philippines (Southon and Gorbachev, 2003) and Kenya (Kivure, 2016; Otieno, 2016; Kipsang, 2015).

While from Indonesia, the most recent study found on geothermal drilling cost was published by Purwanto et al. (2018), where they compare well costs between 121 geothermal wells that were drilled in the period of 2011 to 2018 in Indonesia. The comparison is made in the form of geothermal drilling unit cost (GDUC) expressed by US$ per meter where the drilling costs were normalized using the US Department of Labor Bureau's Producer Price Index (PPI). Another publication was by Zuhro and Arif (2015) discussed 86 wells drilled by Pertamina Geothermal Energy in the period of 2007-2014. While Sanyal et al. (2011) provided report on statistic of drilling cost per MW on 215 deep geothermal wells in Indonesia. During the time of this study, to the knowledge of the authors based on several research conducted, there are no published works are currently available specifically discussing Indonesia geothermal drilling cost and ways to optimize it other than mentioned above. Nonetheless, some useful conclusions related to geothermal drilling cost, worldwide and Indonesia, were found and are summarized in Table 2.

Table 2: Summary of conclusion drawn from several papers related to geothermal drilling cost

Authors & Year	Country	# of wells discussed	Conclusion or comments related to drilling cost reduction
Southon and Gorbachev, 2003	Russia, Philippines, Indonesia, PNG	68	This paper does not directly discuss drilling costs but rather drilling performance which refers to drilling time efficiency. The foundations for drilling wells efficiently are set down in the planning stages. The drilling rig (derrick, substructure and draw works) and pumps are key to drilling wells efficiently.
Sanyal et al., 2011	Indonesia	215	Using a correlation of drilling cost versus well depth from several countries, and the statistics on well depth and productivity in Indonesia, Sanyal et al. study estimates that the cost per MW well capacity in Indonesia is statistically less than seen in most countries, the most probable value being in the range of $300,000 to $400,000 per MW.
Sanyal et al., 2012	Worldwide	869	The continuous positive learning curve effect on drilling rate and the discrete changes in average well capacity can strongly affect the overall economics of drilling, that is, the MW capacity achieved per unit drilling cost.
Sveinbjornsson and Thorhallsson, 2012	Iceland	77	The results of this analysis of cost and effectiveness of geothermal drilling clearly indicate that the perceived high risk in this kind of drilling is less than commonly thought. The standard deviation of the total cost of a well is about 10% of the average cost. The risk lies mainly in the nature of the geological formation, problems due to loss of circulation or collapsing walls where the rig gets stuck.
Hole, 2013	New Zealand	~41	In the mid-1970s to early 1980s, the cost of drilling geothermal wells in New Zealand was in the order of NZ$1.8 to NZ$2.0 million. During the 1980s and 1990s geothermal drilling cost accounted for a little above 40% of the total development cost of a 'nominal' 50 MWe geothermal development. The sudden increase in drilling cost that commenced between 2003 and 2005 and continued to the present, has seen the drilling cost proportion rise from around 43% in 2000, to approximately 54% in 2013, with the highest around NZ$10 million. There are two categories of influences that are driving up the cost of drilling, which are (1) cost increases we have little or no control over, (2) factors that can increase drilling cost that we can control.
Zuhro and Arif, 2015	Indonesia	86	Average geothermal drilling unit cost (GDUC) during Pertamina Geothermal Energy (PGE) 2007-2014 drilling campaign is US$2,545/meter. The lowest average GDUC is US$1,420.72/meter (2007) and the highest is US$3,842/meter (2014).
Kipsang, 2015	Kenya	Not clearly mentioned	Costing of geothermal wells can be a fairly simple task if one has a clear understanding of all activities and operations involved from well planning up to when it is completed. If that is the case, it will be possible to factor all costs associated with the drilling of a geothermal well to obtain an accurate figure of the well cost.
Lukawski et al., 2016	USA	42	Well costs increase exponentially with depth as a result of the more difficult drilling environment. Uncertainty of well cost increases with depth due to increased likelihood of trouble and less predictable drilling conditions. Deep wells have more positively skewed cost probability distributions. As a result of increased trouble time, probability distributions for deep wells have long, narrow tails stretching far into the high cost region.
Kivure, 2016	Kenya	Not clearly mentioned	Drilling consumables (mud material, mud additives, lost circulation material, cement, cement additives, drilling detergent, drilling lubricants, drilling water, diesel) take the biggest portion of drilling cost where rig cost is not included. In this case the company operate its own rig.
Otieno, 2016	Kenya	9	Costs incurred due to equipment downtime should continually be analysed to plan for better maintenance, safety of the rig and the personnel. And in this era of contracted drilling it pays to have the most efficient equipment, capable staff and a properly defined way that ensures you have spares and technical support when needed.
Gul and Aslanoglu, 2018	Turkey	Not clearly mentioned	Geothermal drilling costs follow the general oil and gas industry trend, which exemplifies a total dependence to crude oil prices. This situation is likely to persist as long as the geothermal drilling sector does not build-up a strong market share of its own.
Bodley, 2018	Saint Lucia	Not clearly mentioned	This study bears strong evidence that a well elaborated project plan will assist in meeting project objectives, prevent scope creep, cost overruns and detrimental delays. The study briefly pointed out the lessons learnt from past geothermal projects which suffered from inadequate planning, giving strong justifications for ensuring high levels of effort in planning prior to the execution of the exploration drilling project.
Purwanto et.al, 2018	Indonesia	121	Statistical analysis suggests that mean geothermal drilling unit cost (GDUC) in Indonesia from 2011 to 2018 is about US$3,960/meter as a baseline. While average GDUC based on drilling contract type, from the lowest to the highest, are as follows: discrete type (US$2,930/meter), bundled type (US$3,027/meter), semi-IPM type (US$3,963/meter) and IPM type (US$5,411/meter).

The detail cost breakdown of drilling projects in Indonesia are not yet found in any paper listed in Table 2. Moreover, authors also found out that Indonesia does not yet have an integrated drilling database system that stores drilling activities records from all geothermal companies operated in Indonesia, which in turn makes it difficult for any Indonesian drilling engineers to conduct an in-depth analysis on historical drilling cost when planning the next drilling project. To optimize the drilling cost, Indonesia need to address this drilling database absence, which is considered by the authors as the crucial starting point.

1.3.3 Widespread Distribution of Drilling Cost Data in Indonesia

From 711 deep geothermal wells record from drilled in the period 1970 - 2018 successfully collected by Indonesia Directorate of Geothermal (EBTKE), not all of them can be analyzed due to data incompleteness. With the lack of available data to be analyzed, it become difficult to establish a reference / baseline of drilling cost for geothermal projects in Indonesia. Purwanto et al. (2018) has summarized 121 drilling data in Indonesia by comparing several parameters, i.e. total drilling cost, total well depth, well production output and type of drilling contract used. The data (Figure 5) shows the costs required to complete the drilling of the wells starting from the provision of drilling material to completion of drilling, which were normalized using the US Department of Labor Bureau's Producer Price Index (PPI).

The chart shows how scattered the drilling costs are in Indonesia, which ranges from 1,000 to 5,000 US $ per meter, if it is expressed in a form of Geothermal Drilling Unit Cost (GDUC). Even if we focus only on the typical Indonesia geothermal well's depth, around 1,600-2,700 meters, the distribution of drilling costs is still very wide, ranging between US $ 4-12 million per well. This wide range of variations creates difficulty for the drilling engineer to draw a clear drilling cost baseline for planning purpose. At the same time, this wide variation implies that room for improvement is available for Indonesia to optimize its geothermal drilling cost.

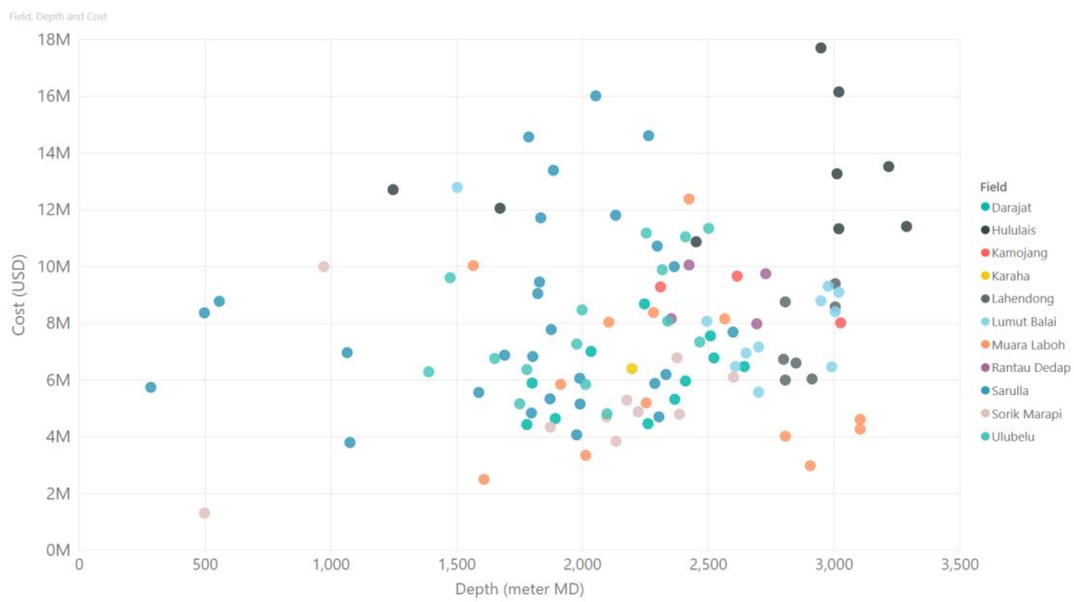

Figure 5: Scatterplot of drilling cost from several wells in Indonesia (adapted from Purwanto et al., 2018)

1.4 Discussion Objectives

The thought process of this study is shown on Figure 6. The wide variance of geothermal drilling cost in Indonesia (Figure 5) implies that there are a lot of room for improvement available. This wide variance also makes it difficult for anyone to draw any trend based on the total drilling cost alone. To understand what affecting the total drilling cost, it is important to analyze the underlying factors in the drilling activity that may affect the total drilling cost. With a proper data analysis on the geothermal drilling data in Indonesia, only then one can have a good understanding of the drilling cost in Indonesia and generate cost prediction model for future geothermal drilling in Indonesia.

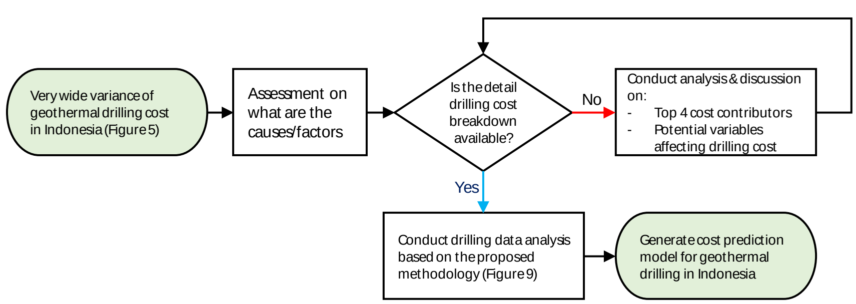

Figure 6. Thought process of the study.

However, at the time this study was conducted, the authors have very little access to geothermal drilling data in Indonesia, therefore, the intent of this study are limited to:

1. Map the factors or component that contribute to 80% of total drilling cost using available drilling data on hand.
2. Propose a simple guidance to analyze Indonesia geothermal drilling data when it is accessible.

In order to achieve these objectives, through literature studies and several brainstorming sessions, authors explore several questions as follows:

1. What are the biggest cost contributors in a geothermal drilling project?
2. What are the possible factors that may vary the drilling cost?
3. What kind of hidden cost potentially occur in each cost component?

This preliminary work does not aim to give an ultimate solution on how to optimize the geothermal drilling cost in Indonesia, but more on increasing awareness and triggering more discussion among geothermal drilling managers and drilling engineers in Indonesia on finding the best way to optimize the geothermal drilling cost.

2. GEOTHERMAL DRILLING PROJECT

Geothermal drilling project is complex since it involves multiple stakeholders, organizations, and equipment (Bodley, 2018; Gul and Aslanoglu, 2018). Inadequate project management could spin a project out of control (Discenza and Forman, 2007). Southon and Gorbachev (2003), Kipsang (2015), Bodley (2018), and Otieno (2016) clearly mentioned the paramount of planning phase and understanding of all drilling activities to control the drilling cost.

Additionally, Hole (2008) mentioned that there are two categories of influences that are driving up the cost of drilling, the one that we have little or no control over and the one that we can control. Thus, the authors use this section to discuss several aspects that play crucial roles in a geothermal drilling project to understand the wide variation of drilling cost observed in Indonesia.

2.1 Geothermal Drilling Objectives

In any geothermal project, drilling activities are performed in the exploration and development phase. The purpose of drilling activities in each of these phases is different, which can be described as follows:

1. *In the exploration phase*: the aim is to answer the question of the presences, size and viability of a conventional geothermal system in the area with drilling cost as low as possible.
2. *In the development phase*: the aim is to meet the number and size of the production and injection wells required to exploit the geothermal resources as economically and sustainably as possible.

Of course, in achieving the different objectives in these stages, drilling activities must be carried out at the most optimum cost possible. Currently in the geothermal industry in Indonesia, discussions about the best well type to be used in the exploration phase is trending. Some think that the use of big hole or standard hole in the exploration stage is more useful since these wells can later be used for production if it turns out successful in finding an economical geothermal reservoir, meaning the reservoir fluid temperature, pressure, and characteristics meet the success criteria.

On the other hand, some geothermal experts thinks that in the case of the sub-surface targets proposed still has a high level of uncertainty then the exploration drilling should be carried out using slimhole wells to minimize the drilling cost (Mackenzie et al., 2017; Adityatama et al., 2020; Purba et al., 2019). Both opinions must be comprehended in a case-by-case basis by the geothermal developers. At the end, they must ultimately be able to develop their own justified decision-tree, which will serve as a guidance in determining the most suitable well type to explore their respective geothermal prospects as part of their exploration strategy.

2.2 Geothermal Drilling Organizations

To achieve the above-mentioned drilling objectives, generally a geothermal company will involve many other companies as partners in getting various types of services, equipment or materials needed. It is very unlikely that a geothermal company in Indonesia has the capacity and ability to provide all the required drilling services independently. In general, organizations involved in a drilling project can be divided into 3 major chunks; (1) the geothermal company as the owner of the WKP (geothermal working area), (2) the drilling contractor as the provider of rig equipment, and (3) the drilling services as a provider of services and supporting equipment (Figure 7).

Figure 7 also shows that the significant number of personnel involved in a drilling project comes from various companies that most likely have different company cultures, values and standards. Rig company (green boxes), as the main equipment provider in a drilling operation, manages the largest number of personnel, ranging from 50-100 personnel in a single drilling rig operation depending on the rig size/capacity. Typically, the rig company will assign one person as the crew leader to operate the drilling rig equipment and carry out drilling operations in the field, which usually held by “rig superintendent” or “toolpusher”.

In any drilling operation, drilling rig requires many other supports in the form of personnel, equipment, tools or materials. The various companies that provide drilling support services are usually referred to as "drilling service companies" illustrated with blue box in Figure 7. Each of these drilling services usually has 3-10 personnel, depending on the service type, placed on the drilling site to assists the rig company carry out the drilling operations.

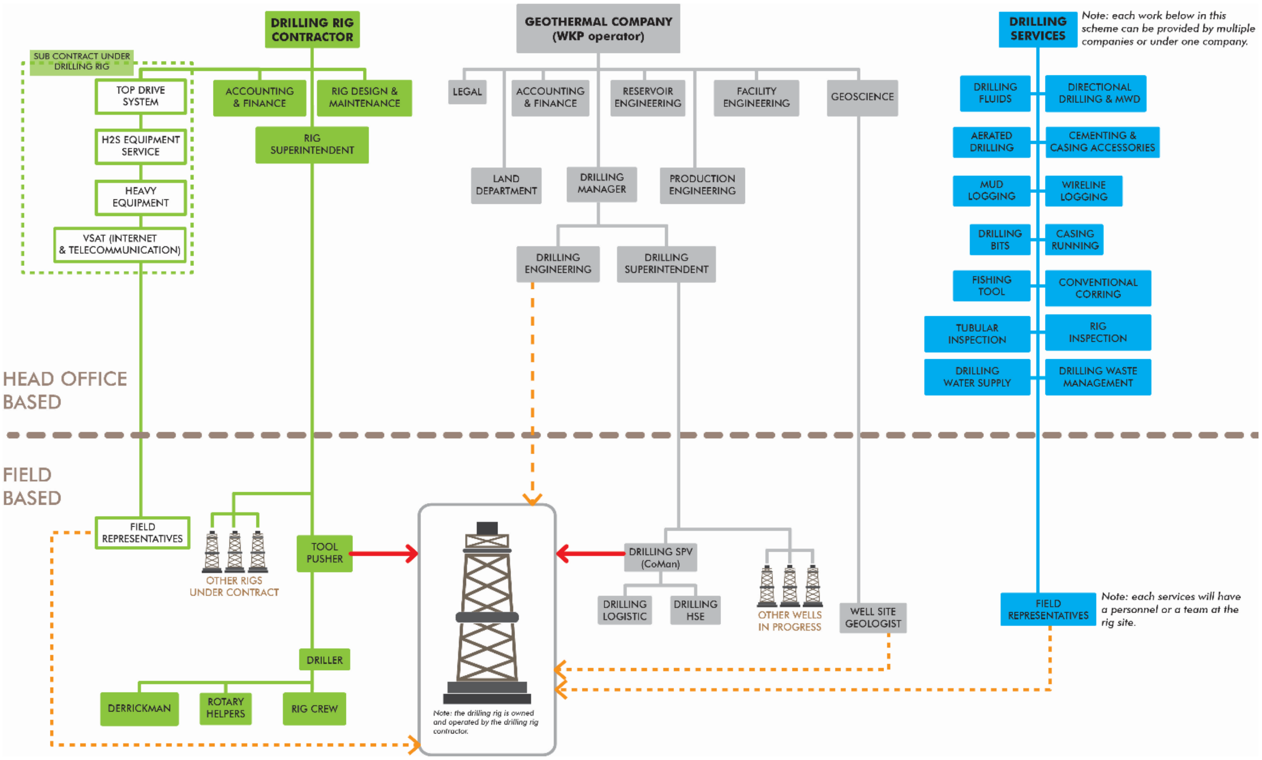

Figure 7: Typical drilling organizations in a geothermal drilling project in Indonesia

The entire team or company involved in a drilling operation will be led and organized by a field representative assigned by the geothermal developer company / WKP owner (gray boxes in Figure 7). The field representative, usually called "Drilling Supervisor" or "Company Man", is responsible for all activities that occurred at the drilling site, where they must submit daily report on the project progress or delays to the head office. All in all, Figure 7 implies that different ways of managing these groups of drilling personnel with different background (i.e. company cultures, values and standards) potentially create variations in the total drilling cost at the end of the project.

2.3 Geothermal Drilling Cost Components

The drilling project complexity, as an implication of multiple parties involved (Figure 7), have to be managed by the geothermal company by legally translate the verbal agreements, with all related parties, into a written contract document formulating the collaboration mechanism. Typically, in a geothermal drilling project in Indonesia, there are about 18-25 contracts required if each services and materials are treated individually (Purba et al., 2020a), including tangible such as casing, wellhead and master valves. Figure 8 shows the example of actual cost distribution based on drilling services. The chart summarizes actual drilling cost from two geothermal fields in Indonesia that authors have on hand at the time of this study.

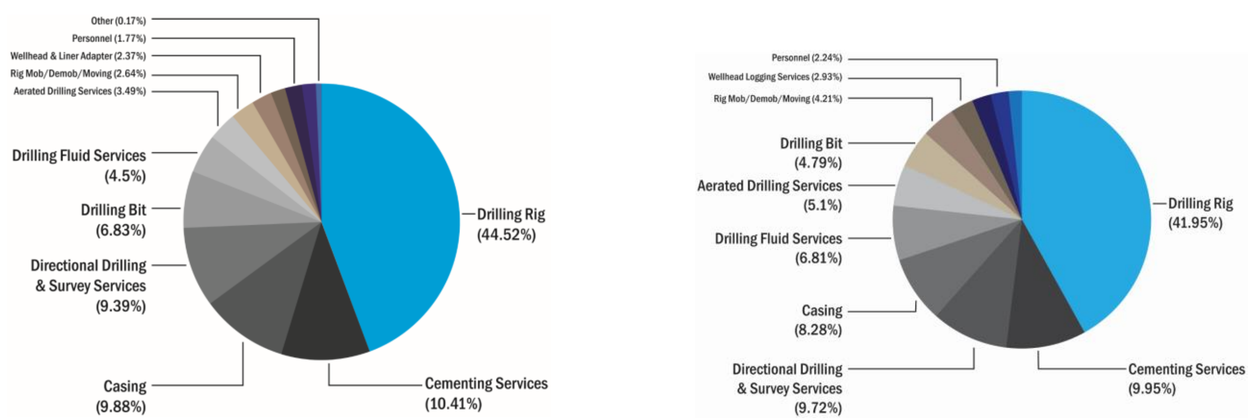

Figure 8: Summary of actual drilling cost from two geothermal fields in Indonesia. One field is in Central Java (left) and the other is in West Java (right).

The chart shows that both fields have relatively similar drilling cost allocation. The top contributors are drilling rig, cementing, directional drilling, casing, drill bit, and drilling fluid/mud, which in total contribute to roughly 80% of total drilling cost. This is consistent with Pareto law stating that "80% of the effects come from 20% of the causes". If the pattern of this cost distribution is always consistent throughout all geothermal drilling operation in Indonesia, then the drilling team should focus more on managing these six drilling service contracts that influence more than 80% of drilling costs instead of invest equal portion of time and effort to all 25 contracts.

Cost wise, same rules apply for the drilling project, as in any project, that the total cost incurred is the result of multiplication of unit price with quantity. The higher the unit price that we agreed in the contract with our drilling partners, the higher the total cost that will occur. Similarly, with quantity, the more drilling days, tools, equipment, drilling materials, consumables and personnel we consume or utilize, the higher the total drilling cost appears in our project. In this study the authors chose to discuss the top four drilling cost contributors; (1) drilling rig, (2) cementing, (3) directional drilling, and (4) casing, which are responsible for approximately 70-80% of the total drilling cost.

2.3.1 Drilling Rig Cost

Since the rig accountable for the largest portion, 40-45% of total drilling cost (Figure 8), it become the first priority in this discussion. With limited access to actual geothermal project cost in Indonesia, the authors decide to conduct simple mapping on various factors that might influence the rig cost. The mapping process always start with one question in mind: "what are the factors that influence unit price and quantity?". In the case of rig cost, the price is the rig operation daily rate (ODR) agreed in the contract while the quantity is the number of drilling days.

Drilling rig is the main equipment in any drilling operation. It is important that the drilling engineer in charge properly calculates the maximum anticipated load and pressure to avoid procuring over-specification rig and eventually lead to higher overall drilling cost. Generally, in terms of load and pressure rating, the 1,500 HP and 2,000 HP rigs are considered to have more than enough capacity to drill standard wells/big holes to the depth of 2,000 - 2,500 meters in Indonesia. But those capabilities require higher fuel consumption, larger footprint and higher ODR compared to a 1,000 HP rigs. Table 3 shows a comparison of several types of drilling rigs used in Indonesia, based on their capacity, which are commonly expressed in horsepower (HP).

It is uncommon for geothermal companies in Indonesia to own and operate the rig. They usually rent the rig and crew from a rig company, which serves both geothermal and oil and gas industries. This is the reason why many geothermal projects are also affected by the continuously changing rig rental price following oil price fluctuations as mentioned by Gul and Aslanoglu (2018). When oil price is high, the oil and gas industry will be most likely executing drilling activities aggressively, which creates difficulty for geothermal companies to get drilling rigs. Thus, in such circumstances, the geothermal drilling engineer often will be forced to contract a rig with the capacity higher-than-required due to rig availability issue.

Table 3: General comparison of conventional rotary drilling rig capacity (land operation) that typically available in Indonesia

Comparison Items	750 HP	1,000 HP	1,500 HP	2,000 HP
Hookload	410,000 lbs	550,000 lbs	750,000 lbs	1,000,000 lbs
Hoisting capacity	10 Lines - 300,000 lbs	10 Lines - 400,000 lbs	12 lines - 750,000 lbs 10 Lines - 640,000 lbs 8 Lines - 530,000 lbs	12 lines - 840,000 lbs 10 Lines - 700,000 lbs 8 Lines - 560,000 lbs
Setback capacity	200,000 lbs	250,000 lbs	500,000 lbs	600,000 lbs
Mast standing	1 stand - 2 joints	1 stand - 2 jts or 3 jts	1 stand - 3 joints	1 stand - 3 joints
Rotary table opening	27.5"	27.5"	37.5"	37.5"
Clearance height under rotary table	16 feet	20 - 24 feet	27 - 29 feet	27 - 29 feet
Mud pump size	2 x 800 HP	2 x 1,000 HP	3 x 1,300 HP	3 x 1,600 HP
Top Drive System (TDS)	TDS250 Ton	TDS350 & 500 Ton	TDS350 & 500 Ton	TDS350 & 500 Ton
Number of loads	60 - 80 loads	80 - 100 loads	80 - 120 loads	80 - 140 loads
Minimum footprint size	80 x 70 meter	100 x 80 meter	130 x 90 meter	130 x 90 meter
Daily fuel consumption (average)	4,000 - 6,000 liter	6,000 - 8,000 liter	7,500 - 9,000 liter	8,000 - 10,000 liter
Typical drill pipe stock	5,000 feet (1,524 m)	7,500 feet (2,286 m)	10,000 feet (3,048 m)	12,000 feet (3,658 m)
Mud system capacity	1,000 bbl	1,000 - 1,500 bbl	1,500 - 2,000 bbl	2,000 bbl
Typical standpipe pressure rating	4" at 5,000 psi	4" at 5,000 Psi	4" at 5,000 - 10,000 psi	4" at 5,000 10,000 psi

Nowadays, most Indonesian drilling engineers use number of US$18-22/HP to roughly estimate the rig ODR, which assuming that cost is a function of capacity. For example, a 1,500 HP rig will most likely offer ODR of roughly between US$ 27,000 – 33,000/day. Considerations in selecting the drilling rig for geothermal project in Indonesia have been discussed by Purba et al. (2019) and Hartono (2019). A deep understanding in the type of well to be constructed, the sub-surface hazards and the operational issues that will be encountered will be beneficial in determining the appropriate rig size/capacity since it will impact directly to the rig cost. To summarize, the authors have collected several factors that potentially affect the rig rental price (ODR) and the number of drilling days (Table 4).

Table 4: List of potential factors affecting rig cost

Cost Component	Cost Impacting Factors	Price and Quantity Factors	Individual Impacting Factors	Remarks on the individual impacting factors
Drilling Rig Cost	PRICE Rig Daily Rate and Mob/Demob	Rig size/capacity	Casing design	Well type (i.e. big hole, standard hole, or slimhole). The bigger the hole size the higher rig capacity required.
			Casing setting depth	Depends on casing setting depth for each hole section / casing size. Mainly defined by the Top of Reservoir (TOR) and deepest feed zone targeted. Hole problems (i.e. reactive formation, unconsolidated formation and shallow permeable zone) contributes to the casing setting depth decision-making.
		Procurement strategy	Rig availability during tender / procurement	It usually defined by market condition of oil and gas, which influenced by the oil price fluctuation. Most likely, the higher the oil price the less available the rig in the market and the higher the rig rental rate will be.
			Contract type	Turnkey, IPM, Semi IPM, Bundled, Discrete, etc. See the discussion of contract type in Purwanto et al. (2018) and Purba et al. (2020a).
			Rate definition	Operating rate, stand by rate, moving inter-well rate, and zero rate.
			Project scale	The number of wells might impact significantly to the rig rental rate.
		Mobilization/ Demobilization	Project distance and accessibility	Distance from yard/existing location to project site, the infrastructure condition (port, road, bridges, etc.), and social acceptance level.
	QTY Number of Drilling Days	Casing design /Well depth	Deepest feed zone depth	Mainly defined by the Top of Reservoir (TOR) and deepest feed zone targeted. Hole problems such as reactive formation, unconsolidated formation lost circulation, and shallow permeable zone are some considerations used in defining the casing setting depth.
		Drilling duration	ROP	Drilling rate of penetration (ROP) is a function of drilling parameters (GPM, RPM, WOB), BHA design and bit type (IADC).
			Tripping, circulating, reaming	Defined by the Top Drive System (TDS) capacity, mud pump capacity, rig crew experiences, and formation problems.
		Flat time	Casing running time	The duration usually impacted by the casing size, casing connection type, casing running tool, and rig crew competencies/experiences.
			Cementing time	Defined by downhole temperature profile, formation problem (lost circulation), cementing job technique, casing design, well depth, cementing crew competencies/experiences and cementing equipment capacity & reliability.
		Non-productive time (NPT)	Lost circulation	Defined by number of attempts made to cure lost circulation problem.
			Stuck pipe related	Defined by number of days spent to free stuck pipe, fishing and sidetrack the well.
			Other NPT	NPT caused by downhole tool failure (non-rig), cementing equipment breakdown, wait on material/tool/equipment (non-rig), wait on personnel (non-rig), wait on construction, wait on decision or social acceptance issues.

2.3.2 Cementing Cost

The second cost component discussed in this study is cementing, which includes cement material, chemical additives, equipment, tool and personnel of cementing services. This cost component contributes around 10% of total drilling cost (Figure 8). Similar to rig, the type of cement, additives, equipment and personnel is largely determined by the type of well, depth and formation conditions (downhole temperature, pressure, sub-surface hazards, and gas content). Unit price of cement is usually not too volatile, especially when using local product. However, the hidden cost of cementing that often forgotten is that the longer and the more cementing job performed in a geothermal well the higher the rig time consumption will be. The other hidden cost is poor cementing job could lead to casing failure such as water-trapped in annulus and corrosive formation fluid/steam leakage, which eventually shorten the well lifetime.

The main function of cement in the well construction process is to protect and support the casing and to prevent the movement of fluid through the annular space outside the casing (Bourgoyne et al., 1991). In geothermal wells, the performance of cement (setting time and strength development) will be greatly influenced by the temperature development that occurs in the downhole (Kutasov and Eppelbaum, 2012). Not only cement slurry design, the cement placement technique must also be carefully planned and executed to ensure good cement bonding in place to protect the casing. The longer the well lifespan the better the overall project economics.

It is widely known that geothermal wells are not only exposed to high temperatures but also subnormal subsurface pressure. This is the reason why geothermal driller frequently find the condition of total loss of circulation (TLC), even when using only fresh water as the drilling fluid. In this situation, cement is occasionally used as a downhole plug to cover the loss of circulation zone or unconsolidated formation before continuing drilling into the deeper zone. However, it is very common that the lost circulation condition is still happening at the time cementing engineer performing casing cementing job. Consequently, the ability to combine a fit-for-purpose slurry design with suitable cement placement technique is crucial. Study by Restrepo et al. (2019) showed that inappropriate centralization and cement voids will bring additional substantial stresses in casing and cement, which can affect the casing life.

Other challenge encountered by geothermal drilling engineers related to cement design is on selecting between various cement additives, which often do not appear in generic names because they have been specifically modified by each cementing company. Although variations in trade names (brand) have not been a major issue, it is still a good idea to carefully study the main functions of any cement additive products offered by the market since it potentially gives significant impact to the total cementing cost. Table 5 shows the list of factors, compiled by the authors, that might influence cementing costs in a geothermal drilling project, in terms of unit price and quantity.

Table 5: List of potential factors affecting cementing cost

Cost Component	Cost Factors	Price and Quantity Factors	Individual Impacting Factors	Remarks on the individual impacting factors
Cementing Cost	PRICE Equipment, material, additives and personnel rate	Type of tool and equipment	Cementing job type	Cementing job purpose: casing cementing, squeeze cementing, downhole cement plug.
				Cement placement techniques (through casing, stage cementing, tie-back, inner string cementing/sting-in, annulus cementing/top job).
		Personnel specification	Job difficulties	Depends on cementing job type (see above). Since casing cementing job is very critical then the personnel competencies and experiences need to be assessed according to the job difficulties.
		Type of cement material and additives (cement design), including casing accessories	Subsurface/ formation/ downhole conditions	Temperature, pressure, lost circulation rate (permeability), pH, H_2S content, CO_2 content, etc. These downhole parameters will drive the required design of slurry properties (compressive strength, thickening time, fluid loss, etc.) which might involve various type of cement chemical additives.
		Procurement strategy	Availability during tender	It usually defined by market condition of oil and gas, which influenced by the oil price fluctuation. Most likely, the higher the oil price the less available the reliable cementing unit in the market.
			Contract type	Turnkey, IPM, Semi IPM, Bundled, Discrete, etc. See the discussion of contract type in Purwanto et al. (2018) and Purba et al. (2020a).
			Definition of rate	*For equipment and personnel* - operating rate, stand by rate, moving inter-well rate, and zero rate. *For cement material and additives* – agreed discounted price
	QTY Cementing time and material volume	Cementing duration	Casing design / well depth	It depends on casing setting depth for each hole section / casing size. Mainly defined by the Top of Reservoir (TOR) and deepest feed zone targeted. Hole problems such as reactive formation, unconsolidated formation and shallow permeable zone are some considerations in define the casing setting depth.
			Pumping time	It depends on cement slurry design, placement technique and equipment capability, with consideration of downhole condition.
		Number of cementing jobs, cement materials & additives volume	Casing design	Well type (big hole, standard hole, and slimhole) and casing setting depth (the deeper the higher the material volume required).
			Hole problems	Attempt to cure lost circulation zone, attempt to cement plug the hole (i.e encounter swelling clay zone or unconsolidated formation).

2.3.3 Directional Drilling Cost

The third cost component discussed by the authors is directional drilling (Table 6), which includes equipment, tool and personnel of directional drilling (DD) and measurement while drilling (MWD) services. This cost component contributes to around 9-10% of total drilling cost (Figure 8). Since geothermal areas in Indonesia are generally associated with volcanic activity and are located on high-relief terrain, it is often very difficult to find flat land areas for drilling wellpads. This condition makes directional drilling methods is desirable in many geothermal drilling operations in Indonesia since it gives the drilling engineers flexibility in designing the most optimum well trajectory in intersecting or hitting the subsurface target.

However, despite its benefits, the use of DD and MWD tools in geothermal drilling often becomes boomerang because of the expensive replacement costs in the case of lost in hole (LIH) as a result of stuck pipe incidents that quite common happens in geothermal drilling operation (Purba et al., 2020b). Hartono (2019) discussed several hidden costs related to directional drilling other than LIH cost. Same like aforementioned cementing job, these DD and MWD services potentially creates additional rig time due to (1) reaming activities as a result of aggressive build-up rate, (2) tool make-up and calibration duration, (3) tool cooling down duration due to high downhole temperature, (4) unnecessary gyro run, and (5) tool failure due to poor quality control. The other hidden cost is the tool/equipment standby cost resulted by unnecessary backup tool/equipment stored at the drilling site.

2.3.4 Casing Cost

The last cost component discussed by the authors is casing cost (Table 7), which contributes roughly 8-10% of the total drilling cost (Figure 7). Hole (2008) mentioned that the selection of casing depths and specification of the materials weights and connections are critical to the success and safety of the well drilling process and to the integrity and life of the well. Casing specifications are generally driven by the mapping results of the anticipated load that potentially occur during the casing installation.

Generally, the casing price will depend on the casing size and specification (pipe manufacturing method, material grade, weight, connection type, special features, etc.). While the quantity will depend on the number of casings needed to cover each hole section. However, the selection of casing with higher specifications than required, to anticipate various subsurface uncertainties, can result in a significant increase in total cost. It is widely known that geothermal formation generally has relatively low pressure, but higher temperatures compare to oil and gas formation. Therefore, it is very important for drilling engineers to conduct proper subsurface hazard mapping and market surveys of various types of casings available in the market when carrying out the casing design process. Offset wells data, if available, will greatly help in deciding not only casing specifications but also setting depth.

Table 6: List of potential factors affecting directional drilling cost

Cost Component	Cost Impacting Factors	Price and Quantity Factors	Individual Impacting Factors	Remarks on the individual impacting factors
Directional Drilling Cost	PRICE DD/MWD tool, equipment and personnel rate	Type of tool and equipment	BHA design	Well trajectory/inclination and well profile (2D or 3D).
			Formation issue / hole problems	Downhole temperature and pressure, lost circulation zone, swelling clay zone, formation collapse/unconsolidated zone.
		DD/MWD personnel specification	Well difficulties	Well trajectory/inclination and well profile (2D or 3D) and anticipated hole problems (see above) will define the level of DD/MWD engineer competencies and experiences required to deliver the well.
		Procurement strategy	Availability during tender	Usually defined by oil price (market condition of oil and gas and geothermal).
			Contract type	Turnkey, IPM, Semi IPM, Bundled, Discrete, etc. See the discussion of contract type in Purwanto et al. (2018) and Purba et al. (2020a).
			Definition of applied rate in the contract	Below rotary table rate, stand by rate, redress cost, lost in hole (LIH) price, depreciation value, equipment damage claim, insurance, etc.
	QTY number of running hours	Well design	Length of directional section	Defined by sub-surface target (top of reservoir and fault target depth), which drives the kick-off point (KOP) depth, build-up section length, and tangent section length.
		Drilling duration	ROP	Rate of Penetration (ROP) is a function of drilling parameters (GPM, RPM, WOB), BHA design and bit type.
			Tripping, circulating and reaming duration	Mainly impacted by the top drive system (TDS) capacity, mud pump capacity, rig crew experiences, formation problems, downhole condition, and drilling practices.
	QTY number of stuck pipe lead to Lost in Hole (LIH)	Number of LIH cases involving mud motor and MWD tool	Hole problems	Lost circulation zone, swelling clay zone, formation collapse zone that lead to stuck pipe event, which leaves the BHA inside the hole and ultimately sidetrack the well. The cost of the DD/MWD tool in the case of LIH should be predetermined in the contract.

Table 7: List of potential factors affecting casing cost

Cost Component	Cost Factors	Price and Qty Factors	Affecting Factors	Remarks on the individual impacting factors
Casing Cost	PRICE casing size, connection, weight and grade	Size	Well objective	If it is for sub-surface data acquisition, monitoring purpose – may prefer *slimhole* type. If it is for production or injection purpose – may prefer *standard* or *big hole* type, depending on the anticipated production rate
			Anticipated production or injection capacity	Casing size is designed with "bottom-up" approach meaning the most bottom casing size (production liner/production casing) considering the production or injection capacity expected from that well, then continued with the upper section going up to the top.
		Connection, Weight (ppf), and Grade	Formation prognosis	Formation pressure, formation fluid type (pH, H2S and CO_2 content), formation temperature.
			Anticipated load	All possible scenarios of loads to which the casing will be exposed need to be addressed: well control situation, cementing operation, lost circulation, maximum casing weight when run in hole, temperature cycle during production/injection.
			Casing setting depth	Mainly defined by the Top of Reservoir (TOR) and deepest feed zone targeted. Hole problems such as reactive formation, unconsolidated formation and shallow permeable zone are some considerations in define the casing setting depth.
		Procurement strategy	Availability during tender	Usually defined by oil price (market condition of oil and gas and geothermal). Availability of raw material may also impact the price.
			Bidding type	International or national bidding (see Fininda et al., 2020).
	QTY Joints required to cover all hole section(s)	Casing / well design	Casing setting depth	Mainly defined by the Top of Reservoir (TOR) and the deepest feed zone targeted with consideration of subsurface hazards (reactive clay, unconsolidated rock, fractures dan faults, etc.).
		Casing excess margin	Company policy/offset wells	This the number of casing excess procured as the contingency plan. The excess can be up to 15% for each casing size depends on company policy or historical statistic from offset well analysis (if any).

2.4 Proposed Methodology for Future Drilling Data Analysis

The main limitation of this discussion is the difficulty of accessing actual drilling data from geothermal developers in Indonesia due to the absence of a mechanism that requires geothermal developers to submit their drilling data into an integrated database. Authors also had difficulty finding publications reporting the geothermal drilling operations in Indonesia. Nevertheless, if in the future actual geothermal drilling data (breakdown costs, daily drilling activity reports, well schematic and end of well reports) are available, the authors suggest the cost analysis is conducted using a methodology as illustrated in Figure 9.

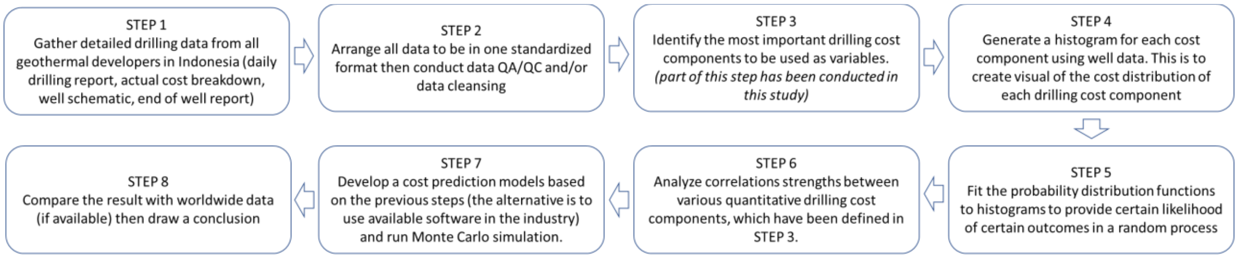

Figure 9: Flowchart illustrating the proposed methodology to analyze the drilling cost (modified from Lukawski et al., 2016)

3. SUMMARY AND POTENTIAL PATH FORWARD

One of the challenges that need to be addressed by Indonesia is how to optimize the current drilling cost, which is the second biggest components in a geothermal project after power plant cost. It is believed that the drilling effectiveness, both in planning and operation phase, plays important role in achieving the desired geothermal project economics. It is easier said than done since drilling project is complex due to involving numerous personnel with different background (i.e. company cultures, values, competencies, language, and standards).

The first four geothermal wells in Indonesia were drilled 94 years ago and then continued with zero geothermal drilling activities for around 40 years. During the period of 1970s to present, more than 700 geothermal wells have been drilled in Indonesia but with very minimum published reports on the drilling activities. The authors believe that the combination of inconsistent frequency of geothermal drilling projects with minimum publication on drilling activities in Indonesia have contributed to the slow learning curve within Indonesia drilling community and ultimately affect the variation of drilling cost. This wide variation of geothermal drilling cost in Indonesia has been confirmed by study by Purwanto et al. (2018) and indicates that there are rooms for improvement for geothermal drilling projects in Indonesia. This widely spread geothermal drilling cost also creates difficulties in drawing a clear baseline to benchmark drilling performance between geothermal drilling projects in Indonesia. Purwanto et al. suggest US$3,960/meter as current baseline based on 2011-2018 data analysis.

The authors, using available drilling data on hand, have mapped components that contributing 80% of total drilling cost; which are drilling rig, cementing, directional drilling, casing, drill bit and mud. If this is the case in most of geothermal drilling projects in Indonesia, then the project complexity can be reduced. Referring to Pareto law, this finding suggest that the drilling team could put more focus on managing these six drilling service contracts that influence roughly 80% of drilling costs instead of spending equal portion of time and effort to all 25 contracts.

Furthermore, this study has developed a list of factors that might influence unit price and quantity in 4 (four) top cost contributors, which are drilling rig, cementing, directional drilling, casing. The factors listed in this study could then be investigated as variables to the total drilling cost in the next study. Additionally, authors have discussed several hidden costs in each drilling services that could be subjects for further investigation. This is the furthest the authors could do with the available data, as the detail drilling cost breakdown of Indonesia geothermal projects are not yet accessible to the public. Without the detail drilling cost breakdown data, the cost predictive model for geothermal drilling in Indonesia cannot be generated.

Limited access to geothermal drilling data has been the main obstacle for any drilling engineer or researcher in Indonesia attempting to find ways in optimizing the geothermal drilling cost. Therefore, authors suggest several path forwards as follows:

1. Collaboration between government, geothermal companies and universities/academics in collecting all available geothermal drilling data in Indonesia to be stored in an integrated drilling database system. The data gathered are then cleansed and organized in a standardize format and structure.
2. Conduct a study on geothermal drilling cost using data stored in the database mentioned above to find out the critical variables impacting cost in Indonesia geothermal drilling projects. Once critical variables are defined, a drilling cost baseline and cost prediction model suitable for geothermal drilling project in Indonesia could be resulted.
3. Geothermal companies in Indonesia are encouraged to publicly share lessons learned and best practices from their geothermal drilling projects by using various media such as conference papers, academic journal, trainings, books, videos, etc. This knowledge sharing practices are expected to improve Indonesia geothermal drilling personnel capability in managing drilling project.
4. Develop a standard format for the drilling cost structure for all geothermal drilling projects in Indonesia. This way, government (in this case EBTKE) will be able to easily compile and compare the drilling cost. In the short term, it can be used for benchmarking the drilling performance of drilling projects, and eventually can be used to optimize the drilling cost.

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