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Key Considerations in Developing Strategy for Geothermal Exploration Drilling Project in Indonesia

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ABSTRACT

Exploration phase has the highest uncertainty thus highest risk in a geothermal development project. Drilling cost is one of the critical components that significantly affect geothermal project development cost. In general, there are two major risks associated with drilling, consisting of resource risks and other risks. Resource risks are mainly associated with temperature and permeability. A robust conceptual model built from reliable data is necessary to assess both of resource risks and assist the well targeting process. Other risk are ones that related to regulation, drilling infrastructure, drilling operation issues, environmental aspect, and local community issue. The variation of drilling objectives in each stage of the project (exploration, appraisal, development) requires different strategies in order to minimize the associated risk and project cost.

This preliminary study aims to summarize the thinking process or main considerations when developing the exploration drilling strategy, which accommodate subsurface, environmental, drilling, construction perspectives based on literature reviews, and authors experience. This study also presents a generic guideline developed by the authors to assist the decision-making process in developing strategy in a geothermal exploration project in Indonesia.

1. INTRODUCTION

1.1 Indonesia Geothermal Energy Development

Indonesia, situated on the Pacific 'Ring of Fire, is considered as one of the countries that has considerable amount of geothermal energy potential. The estimated geothermal energy capacity is around 28 Gigawatt electric (GWe) (Bertani, 2015), which are spread on 331 locations across the archipelago (Apriani et.al, 2018). Total geothermal power plant installed capacity up to 2017 is 1698.5 Megawatt electric (MWe) (EBTKE, 2016; EBTKE, 2017). Indonesia's National Energy Plan (Rencana Umum Energi Nasional/RUEN) emphasizes that in 2025 the renewable energy source should account for 23% in the energy mix, including 7,421 MW (16% of total energy mix) of geothermal energy (Umam et al., 2018). The current installed capacity of geothermal power plants (PLTP) until the end of 2018 was only 1,948.5 MW (ESDM, 2018) or less than 7% of the available potential. The ~5,000 MW increase in around 6 years period is an ambitious target, particularly due to the current rate of geothermal development in Indonesia. Previous studies have concluded that there are several identified geothermal development challenges in Indonesia (Darma, 2016):

1. Insufficient geological, geophysical, and geochemical data in the area makes the early assessment of resource potential inaccurate.
2. High resource risk especially in upstream sector.
3. High upfront investment cost combined with uncompetitive energy price (pricing policy), limited equity funds, and lack of sufficient mechanism of incentive (i.e. fiscal incentive) and funding.
4. Several uncertainties in legal aspects and the lack of cross-sector coordination (i.e. government guarantee for the obligations of PLN against the developer of geothermal power plants, location of the projects in conservation forests and or national parks).
5. Limited number of human resources with specific competences in geothermal sector.
6. Social issues such as community rejection.
7. Lack of infrastructure (i.e. in Sumatera).

Several issues and challenges mentioned above turn out to be serious considerations for new investors that plan to enter geothermal industry and for investors that have already invested on geothermal exploration in Indonesia. Extra effort is required from every stakeholder; central and local government, geothermal developer company, and academic community to resolve all of the challenges mentioned above in order to achieve 7000 MWe installed capacity target in 2025.

Objectives

This study assesses several considerations and challenges when developing geothermal exploration drilling strategy in Indonesia, which has high risk due to the limited data availability during early exploration phase, combined with the significant upfront cost of drilling activity.

This study is initiated by using the following questions:

1. What are the main factors affecting the decision-making process for determining drilling strategy in geothermal exploration phase (with regards to geothermal play type in Indonesia)?
    a. From subsurface perspective;
    b. From surface facilities perspective (i.e. well type, drilling operation and infrastructure, logistic and environmental issue).
2. Is there any standard or guideline available worldwide or in Indonesia regarding decision-making process or procedure in geothermal exploration drilling strategy?

The objectives of this study are:

1. To discuss the exploration risks in general and how to implement an appropriate exploration drilling strategy with regard to emerging risks, either by using small-size hole diameter or standard size hole
2. To list several factors in Indonesia's geothermal system influence the decision-making process in the drilling plan.
3. To summarizes them into a generic guideline that might be useful in geothermal project development in Indonesia, particularly at exploration stage.

As the most commercial geothermal prospect in Indonesia is associated with volcanic arc system, this paper discussion will be focused on managing the uncertainty during exploration drilling in geothermal field associated with volcanic area.

GEOTHERMAL ENERGY DEVELOPMENT

Geothermal Development Process

Geothermal resource is different with other natural resources such as oil, coal, gas, or mineral. It is indigenous, which means the resource cannot be transported like fossil fuel or mineral; hence, can only be used solely for the development of the producing area (Sanyal, 2007). In addition, unlike oil or gas commodities, geothermal energy contained in steam cannot be directly sold and must be converted to power first to generate revenue, as the hot water or steam is only acting as medium of heat from the reservoir to the power plant.

According to Best Practices Guide for Geothermal Exploration by International Geothermal Association (2014), a geothermal resource development process can be classified into eight phases:

1. Preliminary 3G (Geology, Geochemistry, Geophysics) survey.
2. Exploration 3G (may include temperature gradient drilling) survey.
3. Exploration drilling.
4. Project review and planning.
5. Field development.
6. Power plant construction.
7. Commissioning.
8. Operation.

Several geothermal consultants or developer might have different number of stages, but the basic concept is the same. Indonesia, as with other different countries also have its own general development stages guideline to grant concession license for any companies that want to invest in geothermal development in the area according to its own law and policy. From several development stages mentioned above, the exploration phase is widely considered as the most critical phase due to its highest risk and uncertainty while the investor will have to invest a considerable upfront capital during exploration (Figure 1).

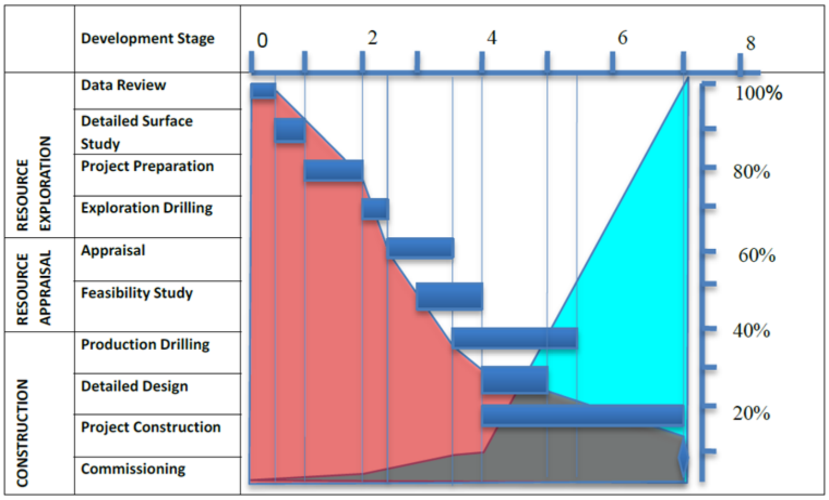

Figure 1. Typical risk profile in a geothermal project (Ngugi, 2014)

Figure 1 illustrates the typical uncertainty (red) and cost profiles (blue) in a geothermal project where the risk is still very high before exploration drilling and decrease overtime as more information on the field characteristic gathered. On the contrary, the expenditure profiles increase rapidly as the project progresses especially during construction stage (Ngugi, 2014). Similar illustration that showed geothermal project risks profile in each phase is developed by ESMAP (2012).

In Table 1, GeothermEx (2010) illustrates the percentage of various cost component during every stage of geothermal development. It assumes that field developer will need 3-5 temperature gradient wells and 1-3 deep wells during exploration to confirm the resource, therefore the total exploration cost may reach up to 15% from total project cost. While based on Sanyal et al. (2011) geothermal wells in Indonesia are usually 1,000 to 2,800 m in depth and the drilling success rate appears to range from 63% to 73%.

Table 1. Cost and risk allocation in geothermal exploration and wellfield development. Cost does not include cost of bidding and licensing, permitting, and other company overheads (modified from GeothermEx, 2010).

Stage	Cost (thousands USD)			Cost Percentage from Total Project	Risk Allocation
1.Regional reconnaissance: selection of prospects for exploration.	250-500			~1	Typically borne by government agency, may be borne in part by private developer.
2.Detailed surface exploration: Geology, geochemistry, and geophysics.	1,000-1,500			2-6	Often borne by government agency, usually augmented or borne largely by private developer.
3.Drilling temperature gradient holes: 3 to 5 wells, @ 200-500 depth.	300-2,000			~1	Occasionally borne by government agency, usually borne by private developer
4.Drilling deep exploratory hole: 1-3 wells @ 1.5 to 2.8 km depth.	7,000-23,000			3-7	Occasionally borne by government agency, usually borne by private developer
5.Long-term flow testing & numerical simulation of reserves (produces bankable document)	500-1,000			> 1	Very rarely borne by government agency, almost always borne by private developer.
TOTAL EXPLORATION COST	**9,050-28,000**			**~7 – 15%**	
	POWER PLANT SIZE (MW)				
	20	**50**	**100**		
6.Drilling of the development wellfield: production, injection & unsuccessful holes @80% success rate and 7 MW output/well	32,000-36,000	50,000-64,000	100,000-108,000		Very rarely borne by government agency, almost always borne by private developer.
TOTAL POWER PLANT COST	41,050-62,500	50,000-64,000	69500-90-950	85-92%	
TOTAL COST (MILLION USD/MW)	**1.08-1.35**	**1.38-1.80**	**2.05-3.12**		

Regarding success criteria of a geothermal project, Geothermex (2010) mentions that there are at least four fundamental requirements that must be satisfied for any commercial geothermal development project, which are adequate resource base, adequate well productivity, acceptable drilling cost per well, benign fluid chemistry.

Geothermal Resource Risk

Resource risk is defined as the uncertainty regarding the magnitude and quality of a geothermal reservoir (Matek, 2014). The lack of subsurface data prior to deep drilling activities implies that until there are sufficient number of wells have been drilled, the risks will remain high. Possessing several convincing thermal manifestations is not enough to prove that the area has an economically feasible geothermal resource to develop, as the commercial viability of an area can only be proven by drilling deep well (Ngugi, 2014). According to Matek, the drilling activity cost is typically around 35% to 40% from the total project capital cost. The stellar cost required for exploration activity especially drilling during the early phase of the project without any means to generate revenue (up to 10 years or more) is what makes the geothermal development project have a high upfront cost and high upfront risk.

Exploration drilling in geothermal industry basically aims to prove the existence of considerable temperature as well as delineate the resource area for further development. This activity is usually conducted by using slimholes or core holes; however recent trend in industry shows that some developers are conducting exploration drilling using standard hole with the objective for obtaining production well after the desired temperature is proven. Both methods are fundamentally influenced by the uncertainty level of both resource and non-resource risk aspects. The resource risks cover the uncertainty of obtaining temperature and permeability.

As mentioned earlier, the first two fundamentals requirements to meet a commercial geothermal development project are adequate resource base and adequate well productivity (GeothermEx, 2010). These two requirements associated with temperature and permeability of the geothermal prospect. Furthermore, temperature and permeability are the two main resource issues that must be addressed prior to commence exploration drilling. At early exploration stage with the absence of any information from deep well, the prefeasibility study becomes essential information that can be used to measure those risk.

PREFEASIBILITY STUDY

Prefeasibility study is an initial stage of geothermal development that significantly affects the exploration drilling strategy. This stage generally covers geology, geophysics, and geochemistry survey, or better known in the industry as 3G surveys. A further action should be performed in order to minimize the resource risks associated with temperature and permeability. According to Hadi et al. (2010); Finger and Jacobson (2000); White (2015), temperature and permeability are the two of main resource risks during prefeasibility study and before exploration drilling. Given that the information acquired at prefeasibility study are mostly from surface measurement and observation, it is necessary to distinguish which data are directly or indirectly indicate the reservoir temperature and permeability.

Temperature

There are several terminologies that are used to classify the geothermal resource, but it is generally accepted that the geothermal systems with temperature more than 220℃ are classified as high enthalpy geothermal system (Hochstein, 1988; Sanyal, 2005). Meanwhile, from development perspective, Hadi *et al* (2010) pointed out that reservoir temperature above 200℃ are needed for cost-effective electrical generation from a green field. A robust conceptual model constructed based on integration of 3G data is needed to interpret subsurface temperature.

In addition, it is important to differentiate the information into direct and indirect since only a few of surface data can directly indicate the reservoir temperature. This approach will also be helpful in reducing the uncertainty associated with the presence of high-temperature geothermal system, as the more direct data we have the more confident we estimate the temperature. Nevertheless, indirect data can be valuable information especially for the geothermal prospect that have poor information of the reservoir.

<u>Direct Data</u>

The term direct data here can be described as any data that have direct connection with the target reservoir, hence can be used to infer the reservoir temperature. During early exploration stage, geochemistry survey is the most powerful method to analyse the fluid chemistry of thermal manifestations in order to estimate the subsurface temperature (Hadi et al, 2010).

However, Hadi et.al (2010) mention that there are only few thermal features can be used to estimate the reservoir temperature, for example fumaroles and boiling chloride springs, which are compared in Figure 2.

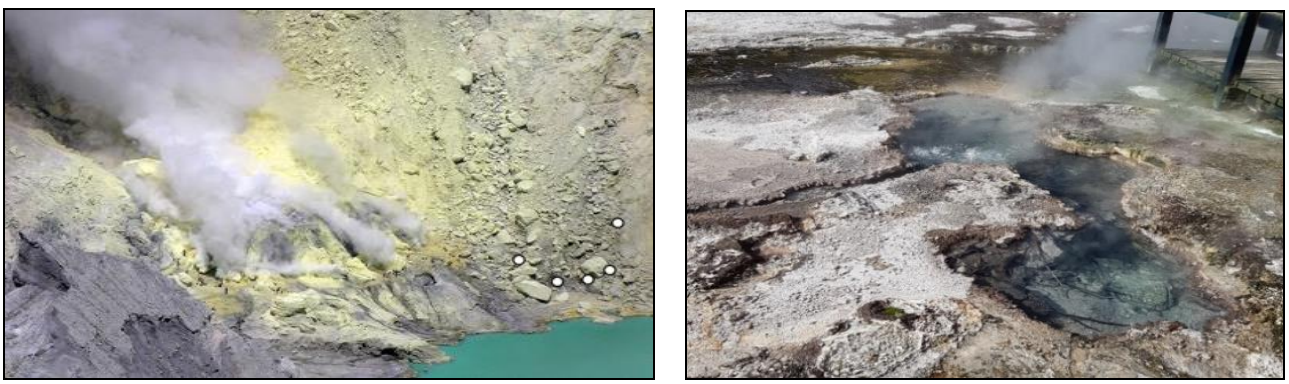

Figure 2. Comparison of fumaroles in Ijen crater (left) and boiling chloride spring at Orakei Korako, New Zealand (right).

Fumaroles are usually used to indicate the existence of high temperature geothermal system in the high-relief terrain (Figure 3), such as Indonesia and Philippines. In contrast, boiling chloride spring is the main key feature that can directly indicate high temperature as well as upflow of geothermal system in the low-relief terrain like many geothermal field found in New Zealand.

The presence of those thermal features will increase the probability of having high reservoir temperature in geothermal prospects. Therefore, it is essential to combine all the geothermometer methods to define subsurface temperature and lower the uncertainty as well.

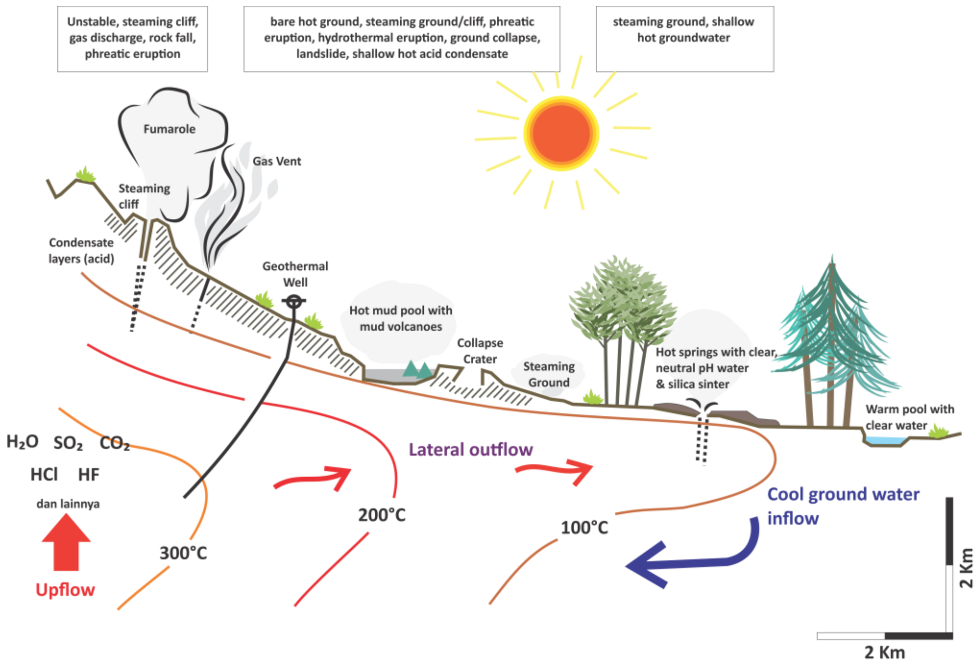

Figure 3. Schematic illustration of geothermal system in high-relief terrain (modified from Utami, 2011)

<u>Indirect Data</u>

Unlike direct data, the indirect data such as some of the geologic and geophysics data cannot be used to directly infer the reservoir properties but can be utilized to support the initial prognosis regarding the reservoir properties. Geology and geophysics are other methods to interpret high temperature zone within geothermal prospect indirectly. Although both data cannot directly estimate the subsurface temperature, combining those data can be helpful in determining high-grade geothermal resource both vertically and laterally.

Furthermore, a benchmark study to other proven fields, which possess similar geothermal setting and surface features is important in order to have the range of estimated temperature of the reservoir. This approach also gives information on the exploration pitfall that will be beneficial for developing exploration strategy before commencing exploration drilling.

The occurrence of volcanic center as well as intrusion rocks that are defined during geology survey can be used to indicate the source of geothermal system as both features commonly associated with heat source. Whereas Magnetotelluric (MT) survey is considered as the most powerful geophysics method because it yields deeper penetration with relatively high resolution. MT is commonly utilized to figure out the distribution of low resistivity layer associated with the clay cap of geothermal system. One of the most distinct resistivity anomaly produced by MT analysis is the uplift of the base of conductive layer, which usually relates to a temperature of about 180℃ in a geothermal system (Anderson, Crosby, & Ussher, 2000). This indication therefore can be used to define how far the geothermal reservoir extend in both vertical and lateral direction.

Permeability

Reservoir permeability can be described as the ability of the reservoir to flow fluid, thus if the reservoir rock is penetrated by the well borehole, the permeability value will directly affect the well output (Finger & Jacobson, 1999; Hadi et al., 2010; White, 2015). The term permeability on this discussion refers to secondary permeability. Although defining permeability is not as easy as temperature, several approaches can be applied to identify some aspects associated with permeability.

Concerning the geothermal system, the structure setting is not the only element that plays the role, but also the major structure. This approach will assist to interpret the typical structure that is associated with interesting geothermal field. Bogie et al. (2010) identified several obvious volcanic structures that are associated with many proven fields in Java Island, such as caldera, sector collapse, and volcanic maar. In addition, active major structure associated with tectonic process can be a good target for exploration. Sarulla field, one of the proven geothermal fields in Sumatera, is not only associated with volcanic landforms but also controlled by Great Sumatran Fault (Hickman, Dobson, van Gerven, Sagala, & Gunderson, 2002). This structure information can be identified by its geologic properties, such as morphology offset, slickenside associated with fault plane and fractures. Another geophysics method (i.e. gravity survey) can also be used to determine the basement structure and high-density intrusion body that is usually associated with geothermal prospect.

The presence of active thermal discharge and alteration can also significantly lower the uncertainty of permeability (Ramos & Rigor Jr, 2005). Both features can appear at the surface due to structure-controlled permeability. The general rule is the more active the thermal features, the higher the permeability is expected. Fumaroles found in higher elevation can be a strong indication not only for temperature but also indicates permeability. Similarly, boiling chloride spring with high flowrate also can be used as a good indication of high permeability.

Lastly, the benchmark study to other fields that have similar tectonic setting is also important to obtain a general idea on how much the structure affecting the permeability. This approach can also provide information about the permeability related to the exploration pitfall that will be useful for developing exploration strategy before commencing exploration drilling.

EXPLORATION DRILLING

The final target of drilling activity is to tap the geothermal energy resource underneath the surface. However, in the exploration phase, the drilling objectives are not mainly to exploit the geothermal resource but rather on defining the resource by its key system characteristic, such as heat source existence near surface, hydrological system, geological setting and areal extent of the prospect (Ngugi, 2013).

In order to achieve those mentioned objectives in exploration drilling, geothermal developer may select various type of well based on the well size (Hole, 2015; Nugroho, Hermawan, & Lazuardi, 2017; Sunarso, Sunu, Muhammad, Purba, & Adityatama, 2018; Þórhallsson, 2012b), as illustrated in Figure 5:

- Big/large hole – wells with 13-3/8" production casing size.
- Regular/standard hole – wells with 9-5/8" production casing size.
- Slimhole – wells with smaller diameter than standard hole.

Whereas the classification of drilling methods based on its well trajectory are as follow:

- Vertical wells – wells drilled with the standard 90 degrees from horizontal trajectory.
- Directional/deviated well – wells that are intentionally deviated from vertical to hit a predetermined subsurface target.

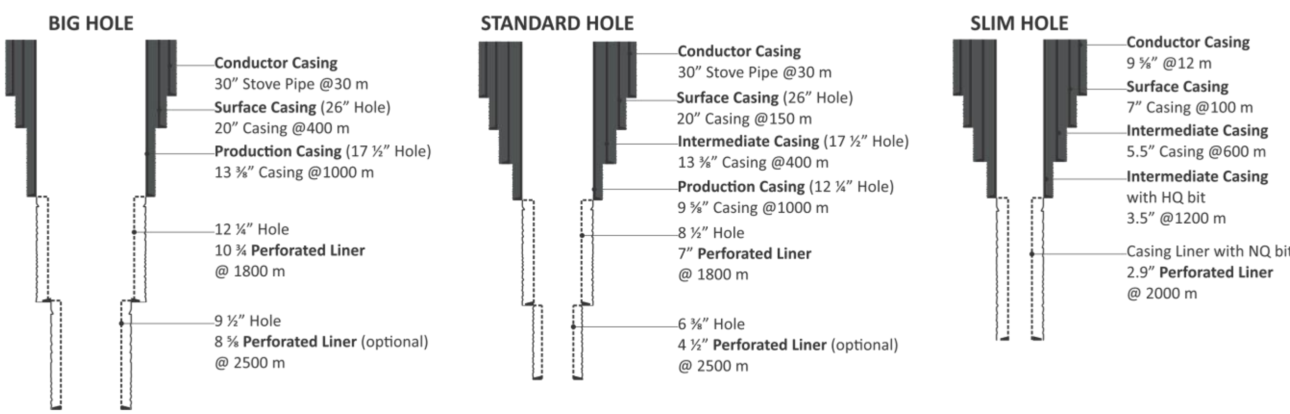

Figure 4. Common well classification according to the well diameter with typical casing depth.

Comparison of Several Types of Wells

As briefly discussed earlier, wells could be categorized based on diameter (big/large hole, standard/regular hole and slimhole) as shown in Figure 4. While based on its trajectory, wells could be divided into vertical well and directional well. Several well types, shown in Figure 4, are not only differ in diameter size but also require different types of rig, materials, and wellpad area size. Various difference for those wells is shown in Table 2.

Main Consideration in Developing Exploration Drilling Strategy

Understanding both temperature and permeability risks is very critical in preparing exploration drilling strategy especially in relation to determining well pad location and well type. The more direct information associated with high grade resources include in the conceptual model, the more confident to define appropriate well type, whether to use small size holes, standard holes or combination of them.

<u>Selection of well pad location</u>

The more information obtained during prefeasibility study, the more confident to sit the well pad. Similar approach also must be applied for determining the exploration target area as part of well targeting strategy. The area with the highest probability to have high temperature and permeability (upflow zone) which supported by conceptual model and direct data might be a very good candidate for the first exploration well to be drilled, and then step out toward the outflow zone conservatively based on the emerging risks during assessment.

Nevertheless, it is also necessary to consider not only findings given by 3G results but also operational and environmental aspects during decision-making process on the wellpad location such as existing access road, water source location and volume, land acquisition issue, soil and rock properties, landslide hazard, terrain characteristic, distance to settlement, distance to thermal manifestation, rig availability, etc.

Table 2. Comparison parameters of various well size.

Area of Comparison	Big/Large hole	Standard/Regular hole	Slim hole	References
Typical Drilling depth	Total drilling depth may range from 1,500 - 3000 m	Total drilling depth may range from 1,500 - 3,000 m	Total drilling depth may range from 1,200 - 2330 m (2,330 meter reached by slimhole in Sarulla field, Indonesia)	Nielson and Garg, 2016; Atlas Copco, 2016; Þórhallsson, 2016; Delahunty et.al., 2012; Þórhallsson, 2012; Finger et.al, 1996; Finger et.al, 1997; Finger and Jacobson, 2000; Gunderson et.al., 2000; Mackenzie et.al., 2017; Sunarso et.al., 2018.
Rig capacity	May require rig with capacity of 1,000 - 2000 HP (depend on well total depth and inclination)	May require rig with capacity of 550 - 1,500 HP (depend on well total depth and inclination)	Could be drilled using rig with capacity less than 550 HP	Þórhallsson, 2016; Þórhallsson, 2012; various internal/unpublished drilling reports
Rig footprint/wellpad	Depend on the rig size, the wellpad may require area around 10,000 - 15,000 m^2 (useable area)	Depend on the rig size, the wellpad may require area around 7,500 - 12,000 m^2 (useable area)	Due to more compact and simple rig, commonly wellpad required much smaller, around 2,000 - 4,000 m^2 (useable area)	Þórhallsson, 2016; White and Hole, 2015; Sunarso et.al., 2018; Mackenzie et.al., 2017; various internal/unpublished drilling reports
Drilling preparation time	Might require longer time to prepare access road, laydown area and wellpad due to bigger size, compare to smaller rig	Might require longer time to prepare access road, laydown area and wellpad due to bigger size, compare to smaller rig	Shorter preparation time compare to bigger rig due to compact size and less number of rig equipment	Þórhallsson, 2016; White and Hole, 2015; various internal/unpublished drilling reports
Rig mobilization time	Rig mobilization time took longer than smaller rig due to number and size of the loads (with the similar mobilization distance)	Rig mobilization time took longer than smaller rig due to number and size of the loads (with the similar mobilization distance)	Shorter mobilization time compare to bigger rig due to compact size and less number of rig equipment	Þórhallsson, 2016; various internal/unpublished drilling reports
Water supply requirement	Depend on the hole size, may ranging from 60-95 litre/second (maximum requirement usually occurred in the reservoir zone with total lost circulation / blind drilling situation)	Depend on the hole size, may ranging from 60-95 litre/second (maximum requirement usually occurred in the reservoir zone with total lost circulation / blind drilling situation)	Less water supply required, may ranging from 5-30 litre/second (water requirement in rotary mode is higher that coring)	Þórhallsson, 2016; White and Hole, 2015; Mackenzie et.al., 2017; various internal/unpublished drilling reports
Casing and cementing materials	Casing required is around 200 tons Cement volume required is ± 84 m^3	Casing required is around 135 tons Cement volume required is ± 55 m^3	Casing required is around 80 tons Cement volume required is ± 26 m^3	Þórhallsson, 2016
Logging tool pass	Able to pass all kind of logging tool	Able to pass all kind of logging tool	Most logging tools are either 35 mm or 42-44 mm in diameter which still good for slimholes, except for CBL probe with 70 mm diameter.	Þórhallsson, 2016
Lithology definition	Using drilling cuttings as the media to determine lithology, alteration mineralogy and fracture characteristics. Note that during total loss circulation there will be no cutting return to surface.	Using drilling cuttings as the media to determine lithology, alteration mineralogy and fracture characteristics. Note that during total loss circulation there will be no cutting return to surface.	Using core sample as the media to determine lithology, alteration mineralogy and fracture characteristics (core sample give better definition than cuttings)	Finger and Jacobson, 2000; White, 2015
Directional drilling ability	Able to accommodate directional drilling technology to deviate the well	Able to accommodate directional drilling technology to deviate the well	Commonly drilled vertically. More difficult to be drilled directionally compare to big or standard well type	Þórhallsson, 2016; various internal/unpublished drilling reports
Discharge capability	Representative to possible actual disharge capacity. Might give greater output than standard well due to its large diameter casing	Representative to possible actual disharge capacity	Require further study to assess its discharge characteristic to actual production well size	Finger et.al., 1996; Finger et.al., 1997; Nielson and Garg, 2016; Þórhallsson, 2016; White, 2015
Production/ Injection/ Monitoring Capability	Able to serve as production or injection well when reservoir characteristic allows. May serve as monitoring well.	Able to serve as production or injection well when reservoir characteristic allows. May serve as monitoring well.	May be difficult to induce flow and it may be too low to serve later as production wells. May serve as monitoring well.	Nielson and Garg, 2016; Þórhallsson, 2012; White, 2015
Estimated drilling days	Ranging from 30 - 45 days (from spud to rig release with 2,000 meters total depth)	Ranging from 30 - 45 days (from spud to rig release with 2,000 meters total depth)	Ranging from 60 - 120 days (from spud to rig release with 2,000 meters total depth)	Finger et.al., 1996; Finger et.al., 1997; Þórhallsson, 2012; Delahunty et.al., 2012; Sunarso et.al., 2018; Mackenzie et.al., 2017; various internal/unpublished drilling reports
Estimated total cost per meter (US$/m)	US$ 3,000 - 4,500 / meter (include rig and all drilling support cost)	US$ 2,000 - 4,000 / meter (include rig and all drilling support cost)	US$ 400 - 1,000 / meter (include rig and all drilling support cost)	Finger and Jacobson, 2000; Nielson and Garg, 2016; Atlas Copco, 2016; Delahunty et.al., 2012; various internal/unpublished drilling reports

Well type selection

Standard hole option is used when the conceptual model clearly defines hydrology of the geothermal system with sufficient amount of direct data support the presence of high temperature as well as permeability. The existence of temperature is not only indicated by the occurrence of key manifestations like fumaroles and boiling chloride springs but also need to be supported by the geology and MT signatures. Having strong permeability indicator will not only good for exploration target but also will be more effective for drilling using standard holes as this increasing the probability of well flowing (deliverability) than using slim or core holes.

In contrast, for the 3G result that not fully confirmed the existence of high-grade resource and permeability, drilling using slim or core hole is better to implemented. Lack of direct information about high temperature system and permeability will rise the uncertainty of obtaining good well. Small size well is not only more effective in term of the resource consideration but also more efficient in relation to drilling cost than using standard well. For this case, it is necessary to start drilling on the lowest risks and step out conservatively.

Another drilling strategy is using combination of standard hole and slim or core holes. This strategy can be applied when the direct information of high temperature and permeability is limited in certain area of the geothermal field. For the area where it is fully supported by the data, the option of using standard holes is more effective, whereas for the higher risk location, drilling using small size well is better option.

To simplify and make it easier to apply, the considerations above can be summarized into the flowchart on Figure 5.

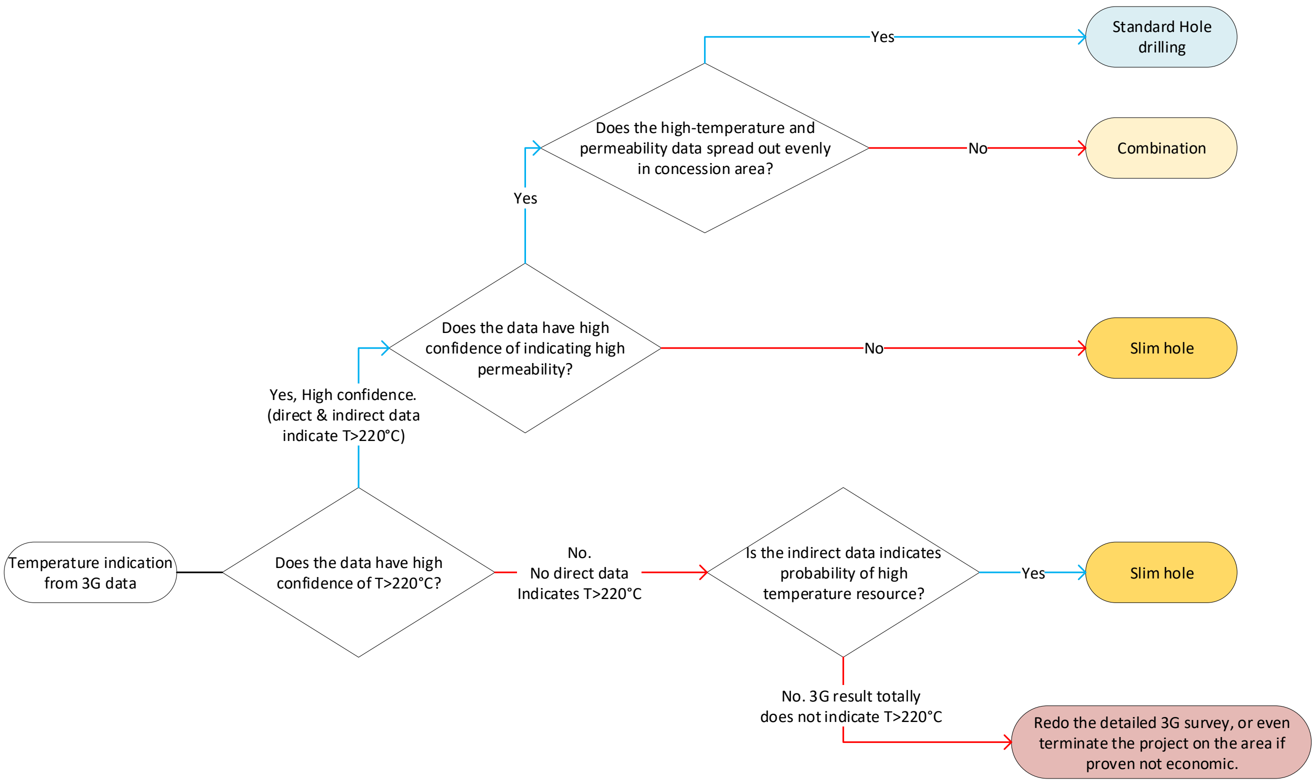

Figure 5. Simplified decision-making process flowchart on determining exploration well type.

Other Consideration in Developing Geothermal Exploration Drilling Strategy

Aside from data availability regarding geothermal resource, there are several other factors that must be considered in developing exploration-drilling strategy, related to select wellpad location and well type. Those considerations, from operational and environmental aspects, are shown in Table 3.

Table 3. Other operational and environmental considerations on developing geothermal exploration drilling strategy.

Considerations on well pad location selection	Other considerations on well type selection
Existing infrastructures	Existing infrastructures
Water source to support drilling operation	Water source to support drilling operation
Land acquisition issues	Well discharge capability
Geotechnical and geohazard issues	Rig availability
Distance to other features	Rig crew experiences and certification
	Possibilities of public rejection issue

Existing infrastructures

Drilling rig for big hole and standard hole are generally require wider access road compared to drilling rig for slimhole, especially due to their massive rig mast and substructure size (Þórhallsson, 2016; White and Hole, 2015). Geothermal project in Indonesia in particular is commonly located in mountainous terrain with minimum existing access road, thus may require extra capital and time allocation to improve the infrastructure for rig mobilization purpose, especially big size drilling rig (1,000 – 2000 HP).

Beside access road, basecamp area and warehouse for drilling material storage and laydown is typically unavailable during early phase of exploration. The bigger the rig used for drilling, the bigger the area that must be acquired for drilling operation and basecamp/warehouse.

Geotechnical and geohazard issue

The result of soil and rock physical properties investigation on the area is another important factor in deciding wellpad location, as the intended area should be able to support the massive weight of rig equipment (White and Hole, 2015). Several areas in volcanic environment have very thick topsoil, which are not suitable for construction as they provide little support for the foundation. Similar condition is also applied to areas with a lot of hydrothermal alteration evidence, as those areas are generally weak and not suitable for wellpad area.

In designing well pads, the access roads, existing surface facilities, and topography of the area is an important factor. Steep slopes terrains will require levelling and potentially form landside problem. Noorollahi, (2008), Utami (2010) and Kristianto et al (2018) discussed how a geothermal area is commonly marked by a thermal manifestation area where fumaroles, steaming grounds, hydrothermally altered grounds, hot springs, volcanic gas vents, craters, and mud pools occur. These surface thermal manifestations bring geohazards such as landslides, unstable slopes, hot groundwater, poisonous gases, hydrothermal eruptions, and ground collapse. Therefore, it is necessary for geothermal developer to put these factors into consideration as well before making decision on the wellpad location.

Land acquisition issues

As shown in Table 2, big-sized rig is typically required around 7,500-15,000 m^2 wellpad area, whereas for slimhole drilling might be done in the area as small as 2,500 m^2. To reduce the high cost of land acquisition in high uncertainty level of exploration phase, the geothermal developer could opt for slimhole drilling option.

Wellpad layout comparison for standard slim hole well is shown in Figure 6. Besides rig size, wellpad size difference is also affected by the size of water storage or reserve pit required, as the standard / big well requires 3-4 times more water than slim hole well.

Other consideration is the effort required for land acquisition, some community lands or especially *tanah adat* or communal land might be difficult if not impossible to acquire. In exploration phase where local people are not familiar yet with geothermal project, there is high possibility that they will hesitate to sell or lease their land to the geothermal developer, particularly if the land are being used to cultivate productive plant like rice, coffee, cocoa, etc.

As the vertical drilling is impossible to be done if the area right on top of upflow zone is not acquired due to land acquisition issue, then the alternative for geothermal developer is they must find other location that a bit further and perform directional drilling. However, directional drilling is more difficult to be carried out in slimhole drilling method.

Drilling water source

Other than apparent wellpad area acquisition problem, drilling big hole or standard hole also require higher amount of water supply for drilling operation compare to slimhole wells (Table 2), thus potentially create another problem with the local people for interfering with their water source. Several key considerations in designing drilling water distribution system is discussed by Putranto et al (2018).

Distance to other features

The distance of intended wellpad to other existing features such as public settlement must be considered. Standar Nasional Indonesia (Indonesia National Standard, SNI) number 13-6910-2002 on *Drilling Operation For Safe Conduct of Onshore and Offshore in Indonesia Implementation* stated that “wells should be located at least 100 meters away from public roads, railways, public works, houses or other places in which a source of ignition may arise”. The rationale behind this regulation is to prevent any source of ignition in close proximity from wellpad area, is not necessarily applicable in geothermal. However, the 100-meter safe distance could be applied as general rule of thumb when deciding the wellpad location, as the 100 meter safe distance can be applied to mitigate noise hazard to surrounding environment and people especially in bigger rig operation.

Discharge capability

Several studies and publication have been conducted to study the discharge/production characteristics of slim wells compared to standard hole wells. Although slim hole wells might be difficult to induce flow, but it was found that in Japan and USA, the production characteristic of slim wells are scalable to production size wells, thus the reservoir characteristic and downhole fluid sample can still be obtained (Garg & Combs, 1993; Þórhallsson, 2012b).

Rig availability

The selection of well type during exploration drilling is often limited by the availability of the drilling rig at the time. The common practice in Indonesia is that the rigs used for geothermal drilling are the same rigs used for petroleum industry. When the oil price reaches a high level, there is a high probability that the rig for big hole or standard hole drilling will be fully occupied by oil and gas company.

Smaller drilling rig like the ones for slimhole drilling are not always readily available, as this type of rig is more common for mining industry usage. The surface coring rig used is also usually not comply with the regulations and standards in petroleum and geothermal. For instance, the Blow Out Preventer (BOP) is not a mandatory in mining industry, thus retrofitting it to the rig might need extensive modification and additional equipment.

Rig crew experiences and certification

As discussed previously, the rigs for standard hole / big hole or slimhole are derived from either petroleum or mining industry, whereas those industries drilling have several different practice and knowhow compared to geothermal drilling. Therefore, geothermal developer company should consider this before selecting rig because the rig crew competence and experience in geothermal drilling is very crucial for drilling operation, especially in the exploration phase where the sub-surface hazards in the area is not fully identified yet.

Rig crew certification, especially driller, is different between mining industry and petroleum or geothermal. This certification matter should be seriously considered when selecting the rig that will be used for drilling.

Public rejection issue

During exploration phase, local community near the project area are usually not familiar yet with geothermal development project, thus in many cases they even oppose the project presence near their home. If the mass rejection is occurred during drilling operation is on progress and halting the drilling activity, the standby cost of bigger size rig will be much higher that the smaller rig used in slimhole drilling.

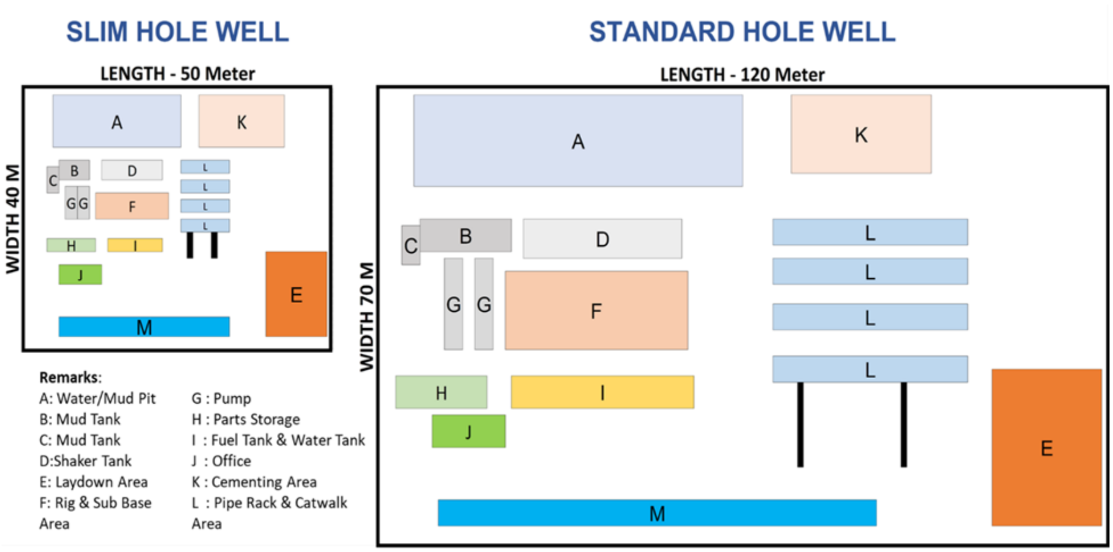

Figure 6. Comparison of typical well pad and rig layout for slim hole and standard well drilling (simplified).

SUMMARY AND PATH FORWARD

This study is an attempt to establish a generic guideline in developing exploration-drilling strategy for geothermal development in Indonesia. This early guideline is expected to be able to support any field developers in Indonesia to develop a sound exploration drilling strategy, thus helps to prevent more delays in exploration activity and bring the Government of Indonesia (GoI) target in 2025 into fruition.

Several discussions regarding this study:

1. GoI target to generate 7,000 MWe from geothermal energy in 2025 requires best efforts from all stakeholders, especially after most of the main challenges in geothermal development have been identified. One of the main challenges during exploration stage is the high upfront capital cost where the real resource quality is still in very high uncertainty state.

2. Temperature and permeability, from subsurface perspective, are the two main resource risks that must be carefully considered before exploration drilling commenced. Furthermore, these resource risks are highly influenced by the drilling cost; hence, it

is important to consider all factors before selecting type of wells used in confirming the geothermal resource. This paper has present the comparison of three well types that may be used in exploring a geothermal prospect.

3. This study managed to create a preliminary list of various other factors, from operational and environmental aspect, that must be considered when developing geothermal exploration drilling strategy.

4. As far as this literature goes, there has been no publicly accessible comprehensive standard practice or guideline to develop exploration drilling strategy, especially for Indonesia. However, authors found that there are several publications and studies discussing the topic in partial (Hadi et al., 2010; IGA, 2014).

5. An early concept of decision-making process for drilling strategy during exploration phase in Indonesia generic guideline is presented in this paper based on literature review and authors' experience.

6. Method and technology to give higher accuracy and faster result in resource assessment, combined with faster and less costly drilling could bring significant impact in reducing the risk in geothermal exploration.

This study is in very early stage and requires further investigations and research for improvement. The path forward for this study are:

1. Deep slimhole wells may become an interesting option for geothermal developer in exploration phase due to relatively low cost, shorter preparation time and sufficient geological information that can be obtained. However, more studies should be conducted in order to investigate the slimhole wells characteristic in Indonesia in general whether it is scalable to production-sized well like in Japan or not.

2. Further collective continuous efforts are required between government, geothermal developer, and academic community to establish a standard or at the very least guideline / best practice guide in developing national exploration drilling strategy. The established standard or best practice guide is expected to be able to help accelerate the geothermal development in Indonesia.

Authors welcome any feedbacks or critics to improve this study.

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