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Assessing Drilling Rig Options for Conducting Geothermal Exploration Slimhole Drilling in Indonesia

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ABSTRACT

Drilling slimhole well is commonly used for conducting geothermal exploration drilling, as it has the potential to reduce the drilling cost while still fulfilling the exploration objectives but was rarely used in Indonesia for the last two decades. With the recent increase in geothermal exploration activity in Indonesia, slimhole drilling is once again considered as a promising alternative for exploration, especially in the fields with less convincing surface manifestations. However, with only one slimhole drilling campaign in the 2000-2020 period, the availability of drilling rig capable of drilling slimhole well in Indonesia is currently very low. The readily available drilling rigs such as conventional rotary rig and coring rig commonly used for mineral exploration might require extensive modifications, while multipurpose rigs are not available in Indonesia. This complicates the drilling planning process, as the cost for modifications or importing the rig can affect the total exploration cost.

The purpose of this paper is to assess the options of conducting the slimhole drilling for geothermal exploration in Indonesia, whether by using coring rig, conventional rotary rig, multipurpose rig, or the combination of them. Various aspects such as estimated well cost, capability to satisfy the subsurface objective, estimate market acceptance, and operational risk and challenges were evaluated. Finally, a Multi-Criteria Decision Analysis was used to demonstrate the decision-making process that can be used to determine the most optimum method to conduct slimhole drilling in Indonesia.

1. BACKGROUND

Slimhole drilling is considered as one of the promising alternatives to conduct geothermal exploration. This is especially true for Indonesia, as the "low hanging fruit" geothermal fields in Indonesia have already been exploited (Mackenzie, et al., 2017). Slimhole drilling offers a lower cost drilling options to confirm the presence (or the absence) of geothermal resource in the area (Adityatama, et al., 2020), thus can lowering the cost of failure, or improve the probability of success for future drilling campaigns (e.g., for appraisal, delineation, and exploitation/development drilling). Government of Indonesia even incorporates the deep slimhole drilling for their geothermal exploration program, or commonly known in Indonesia as Government Drilling Program (Apriani, Randle, & Paripurna, 2018).

1.1 Geothermal Slimhole Drilling Challenges in Indonesia

Despite its advantages and a Government Drilling Program, slimhole drilling has not gained any traction yet in Indonesia. To date, there is only one slimhole drilling campaign in Indonesia from 2000-2020 (Adityatama, et al., 2020; Mackenzie, et al., 2017). Some of the identified challenges for conducting geothermal slimhole drilling in Indonesia are as follows:

- Few or no readily available rig for geothermal slimhole drilling. Geothermal slimhole drilling is usually drilled by using coring rig common in mineral exploration. However, the rig itself should be modified to accommodate requirements in geothermal drilling, e.g., BOP, handling tools for bigger drilling tubular. Other alternative is by using multipurpose rig that can drill with all methods such as rotary drilling, reverse circulation, and full coring operation. However, to date, this kind of rig is not available yet in Indonesia. Bring in the rig from overseas is a big commitment and require a lot of investment, things that some rig contractors hesitate to do considering the sustainability uncertainty of the project.
- Lack of personnel and industry experience. With only one slimhole drilling campaign in the last two decades, the contractors and experts to thoroughly plan the geothermal slimhole drilling is very limited. The personnel and contractor's expertise become increasingly important due to the modifications required for some of the drilling rig available in Indonesia.

The combination of the limited readily available drilling rig and lack of experienced personnel and contractor in geothermal slimhole can halt the geothermal development in Indonesia, as most of current exploration programs are planned to be drilled with slimhole drilling. Therefore, it is important to populate and assess all possible alternatives for drilling geothermal slimhole well in the most optimum way that will not negate the advantages of the slimhole well itself.

1.2 Purpose of the Study

The purpose of this paper is as follows:

- Assess the challenges of utilizing each type of rigs for slimhole drilling (rotary drilling, coring rig, and multipurpose rig).

- Populate several options for drilling geothermal slimhole well.
- Simulate the decision-making process for selecting the drilling rig type based on several aspects such as estimate well cost, ability to fulfil subsurface objective, and potential operational challenges.

2. DRILLING RIG FOR GEOTHERMAL SLIMHOLE DRILLING

While most of slimhole wells were drilled with mineral coring rig, the design for geothermal slimhole well is substantially different from a mineral exploration well. One main factor for this difference is the necessity to have a competent cement at least to the surface casing (typically ~200-300 m depth for geothermal well in Indonesia). This requires a slimhole well to have enough annular clearance between wellbore and casing. The large annular clearance can only be drilled with rotary drilling, as diamond coring drilling will have a very small annulus clearance (~0.1”-0.15”). The needs to combine rotary drilling and full coring poses a problem for rigs commonly used in mineral exploration and rigs used in oil and gas or geothermal drilling. They require modifications or additional equipment to accommodate the difference of drilling conditions and tools.

2.1 Mineral Coring Rig

Typical core rigs (Figure 1) drill hole ranging from 6” to 2” with corresponding core diameters of 4” to 1”. This hole size is significantly smaller than typical rotary drilling rig which can drill from 6” to 26” in diameter. Hence, some of the tools and equipment that come with the core rig may not be sufficient for rotary drilling, such as the mud pump and the drilling tubular handling tools.

Figure 1. Example of mineral coring rigs.

The typical limitation and modification required for utilizing coring rig for geothermal slimhole are described in the Table 1.

Table 1. Limitation and modification required for a typical coring rig to drill geothermal slimhole well.

Items	Remark
Hook load	Coring rig typically has significantly smaller hook load capacity (or pullback capacity in the terms commonly used in mineral industry) than the conventional rotary rig. This can be problematic if the rotary drilling section is long.
Mast length	Typical mast length of coring rig is around 10 m, and can only accommodate the R1 drill pipe. This can be problematic as R1 drill pipe is not as common as R2 and R3 drill pipe. The lead time of R1 drill pipe should be carefully considered during drilling planning.
Limited mud pump capacity	As most of the rocks drilled are retrieved in the form of a core, coring operation does not rely on drilling fluid to lift the cutting to the surface. Therefore, almost all coring rig comes with much smaller mud pump. The smaller mud pump cannot be used to drill rotary as the flow rate will not be enough to lift the cutting to the surface.
Limited torque capacity of the top drive	The coring drilling mainly operates on low torque but very high RPM. The top drive torque capacity should be assessed whether it is enough or not to carry out a rotary drilling operation.
Limited table clamp / foot clamp opening diameter	The limited foot clamp opening on the rig floor is not designed for larger casing/bit. This is problematic if the well design incorporates larger diameter casing (e.g., 12-1/4” bit and 9-5/8” casing).

Items	Remark
Drilling tubular handling tool	The typical coring rig does not come with a handling tool with enough torque capacity to make up rotary BHA such as drill collar or HWDP. The required make up torque capacity for the casing and BHA should be carefully considered during drilling planning.
Substructure	Drilling geothermal has to use BOP stack for well control equipment. The typical coring rig does not come with a substructure to accommodate the BOP stack.

2.2 Rotary Drilling Rig

Smaller rotary rig (can be ranging from 350 HP to 750 HP rig) as shown in Figure 2 can be considered for conducting slimhole drilling for geothermal exploration. This type of rigs is commonly used for workover and well intervention instead of drilling. As with their bigger counterparts, they are mainly designed for rotary operation and not for full coring operation. Therefore, they may need some modification as well for conducting coring drilling in the reservoir section.

Figure 2. Example of smaller truck-mounted rotary drilling rig (350-750 HP)

The challenges and modifications that may be required to utilize smaller rotary drilling rig is shown on Table 2.

Table 2. Challenges and modifications required for rotary drilling rig.

Items	Remark
Top drive	The rotary rig is typically equipped with a high-torque low-RPM top drive for rotary operation. The rig contractor should procure and fit a top drive for coring operation in their rig. To date, this is not common in Indonesia. Authors' experience and correspondence with top drive providers in Indonesia shown that currently no top drive providers have this kind of top drive in stock, while the top drive used in coring drilling is typically come bundled with the rig itself.
Hoisting mechanism	In contrast with coring rig where the weight on bit (WOB) is precisely controlled by a hydraulic feed cylinder, the rotary rig controls the WOB by holding back a portion of the drill string weight. This difference in the working mechanism should be assessed whether it is suitable for coring drilling.
Rig footprint	Even though it is smaller than bigger rotary rig used for drilling, the footprint of the rig is still significantly bigger than typical coring rig used in mineral exploration. This should be assessed whether this will negate the advantages of drilling slimhole well for geothermal exploration.

2.3 Multipurpose Rig

Multipurpose drilling rig is capable to drill with multiple mechanisms such as coring, rotary, and reverse circulation. The characteristics of such rig is the flexible top drive type that can accommodate all of those drilling methods without requiring much modification. The mast of such rig is typically long enough to accommodate common drill pipe such as API R2 or R3 pipe (Figure 3). The hook load capacity is usually on par with 450-550 HP rotary rig, with the footprint size in between the mineral coring rig and 450-550 HP rotary rig. There may be some modifications or additional equipment required for drilling geothermal slimhole well, but the main problem with this kind of rig is that up to 2020 there is no such rig available in Indonesia. Authors' correspondence with drilling rig contractors revealed that they are hesitant to invest in such rig without a clear geothermal project roadmap in Indonesia. They argued that bringing in rig from overseas is a big investment, and without a reasonable number of wells (or projects) to be drilled, it is not economically feasible to do so.

Figure 3. Right: Epiroc Predator 250 (www.epiroc.com). Left: Bauer Prakla RB-T 135 (https://www.prakla-bohrtechnik.de/).

3. RIG ALTERNATIVES TO DRILL GEOTHERMAL SLIMHOLE WELL

To generate possible alternatives of drilling rig for conducting geothermal slimhole drilling, a scenario of an exploration drilling campaign is simulated. The workflow for the simulation is shown in Figure 4. This simulation is intended to show which scenarios are possible and to demonstrate the decision-making process to select the drilling rig type. Please note that the result may differs if different conditions or scenarios are used in the assessment.

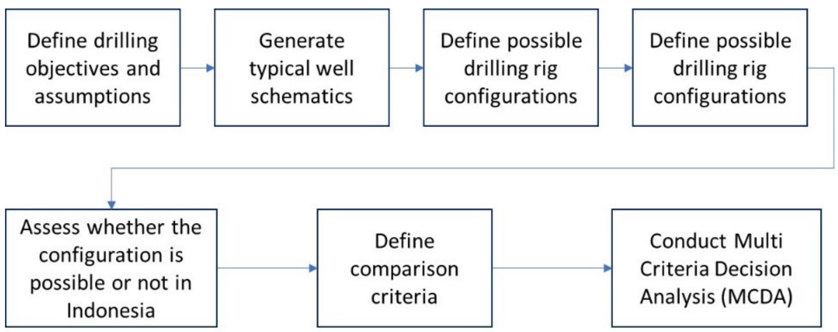


Figure 4. Workflow for generating drilling rig alternatives for slimhole drilling in Indonesia.

3.1 Drilling Objective and Assumptions

For this assessment example, the objectives of the slimhole drilling are as follow:

- Obtain formation pressure, temperature, and permeability data.
- Obtain lithology data on the reservoir (either by retrieved core or borehole imaging).
- Obtain reservoir fluid sample.

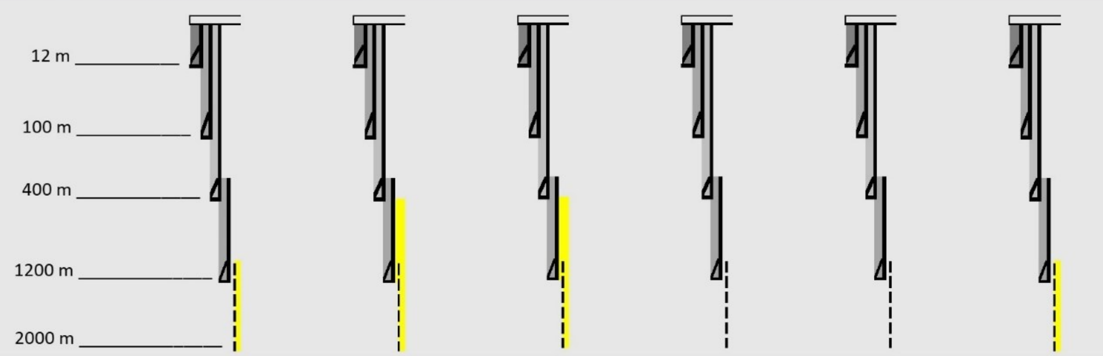
While the assumptions used for the assessment are as follow:

- Vertical well.
- Top of reservoir (production casing setting depth): 1,200 m.
- Target depth: 2,000 m.
- The hook load for 450-550 HP rotary rig is 110 ton or around 220,000 lbs.
- Spud date target: 2021-2022.
- The cost estimate is based on the market survey data per September-October 2020.
- Number of wells: 3
- Project location in Java.

3.2 Possible Well Schematics

There are six possible well schematics assessed for this simulation as shown in Table 3. The casing setting depth for the schematics are generalized for this assessment. Determining actual casing setting depth should incorporate the proper methods in the industry.

Table 3. Well schematics assessed.



Sections	Depth (m)	A	B	C	D	E	F
Conductor	12	13-3/8" csg	9-5/8" csg	9-5/8" csg	16" csg	20" csg	13-3/8" csg
Surface Casing	100	12-¼" hole 9-5/8" csg	8-½" hole 7" csg	8 ½" hole 7" csg	14-¾" hole 11-¾" csg	17-½" hole 13-3/8" csg	12-¼" hole 9-5/8" csg
Production Casing -1	400	8-½" hole 7" csg	6-½" hole 5-½" csg	6-½" hole 5-½" csg	10-5/8" hole 8-5/8" csg	12-¼" hole 10-¾" csg	8-½" hole 7" csg
Production Liner-1	1200	6-1/8" hole 5" csg	PQ hole HW csg	PQ hole HW csg	7-7/8" hole 6-5/8" csg	9-½" hole 7-5/8" csg	6-½" hole 5-½" csg
Production Liner-2	2000	PQ hole HW csg	PQ hole HW csg	HQ hole BW csg	4-¾" hole 4" csg	6-½" hole 5" csg	HQ hole BW csg

3.3 Possible Rig Configuration

The rig configuration assessed is as follow:

1. **Mineral coring rig**.
   The drilling will be carried out all the way using mineral coring rig. Several consequences of this options are longer drilling time and extra cost for rig modification.
2. **Combination of small rotary rig (450-550 HP rig) and mineral coring rig**.
   The rotary part of the hole section will be carried out by 450-550 HP rig, and the drilling for reservoir section (below production casing) will be done by coring with a mineral coring rig. The modifications for this scenario are minor, as the rigs will be required to drill as per their original purpose. However, there is an extra cost for double mob-demob of the drilling rig.
3. **Multipurpose rig**.
   The drilling rig will be carried out all the way using multipurpose rig. Since the rig should be able to do all kind of drilling methods, the modification required is minor. However, the availability of the rig in Indonesia is one major obstacle for this scenario. Up to 2020, there is no multipurpose rig available in Indonesia yet.
4. **Rotary drilling rig (450-550 HP rig).**
   The smaller rotary rig is used to drill the way from the surface to the target depth. The potential issues for this scenario are the availability of the suitable top drive for coring operation. Without a proper top drive for coring, the reservoir section will be drilled by rotary drilling. This negates the one advantage of slimhole drilling, which is that the coring drilling can still be done in total loss condition. With a rotary drilling, drilling a reservoir section requires other equipment such as aerated drilling and big mud pump to prevent stuck pipe. This complicated set of equipment will inflate the drilling cost and contradicts the objective of doing the exploration inexpensively.

The 4 possible rig configurations are then assessed whether it is possible or not to be done in Indonesia based on the following aspects:

- Hook load capacity of the rig to drill the schematics shown on Table 3.
- The availability of the drilling rig in Indonesia as per December 2020.
- The modification required. If the configuration requires major modification or additional equipment, then it is not preferable.

The result is shown in Table 4. The cells in blue are the feasible options in Indonesia as per November 2020.

Table 4. Rig configuration assessment result. The cells in blue indicates the currently feasible options in Indonesia. The schematic options refer to Table 3.

			Rig Configuration			
Schematic Option	Conductor to Last Casing Size	*Max. Load	Coring Rig (1)	Conventional Rig + Coring Rig (2)	Multipurpose Rig (3)	Conventional Rig (4)
A	13 3/8" – HW	68,728 lbs	Insufficient hook load capacity	Insufficient hook load capacity for the coring rig	Rig not available in Indonesia	Need major modification
B	9 5/8" -- NW	33,907 lbs	Suitable coring rig not available in Indonesia (e.g., Boart Longyear LF 350)	Suitable coring rig not available in Indonesia (e.g., Boart Longyear LF 350)	Rig not available in Indonesia	Need major modification
C	9 5/8" -- BW	33,907 lbs	ID 2000 KWL 1600 (99.4% of hoist capacity)	RIG 450 - 550 HP (13.7% of hoist capacity) + CORING RIG	Rig not available in Indonesia	Need major modification
D	16" – 4"	101,233 lbs	Insufficient hook load capacity	Not Applicable	Rig not available in Indonesia	RIG 450 – 550 HP (40.8% of hoist capacity)
E	20" – 5"	140,499 lbs	Insufficient hook load capacity	Not Applicable	Insufficient hook load capacity	May not be sufficient due to hook, block and MOP
F	13 3/8" – BW	68,728 lbs	Insufficient hook load capacity	RIG 450 - 550 HP (27.7% of hoist capacity) + CORING RIG	Rig not available in Indonesia	Need major modification

3.4 Feasible Well Schematics and Rig Configuration

As shown in Table 4, there are four feasible options to drill slimhole well for the scenario described in Section 3.1.

- **Option C1** → 9-5/8" conductor casing, 5-1/2" production casing, with BW as the last perforated liner, drilled with a mineral coring rig.
- **Option C2** → 9-5/8" conductor casing, 5-1/2" production casing, with BW as the last perforated liner, drilled with a combination of drilling rotary rig (45—550 HP rig) and mineral coring rig.
- **Option D4** → 16" conductor casing, 8-5/8" production casing, with 4" perforated liner as the last section, drilled with 450-550 HP rotary rig.
- **Option F2** → 13-3/8" conductor casing, 7" production casing, with BW as the last perforated liner, drilled with a combination of drilling rotary rig (45—550 HP rig) and mineral coring rig.

4. DECISION MAKING EXAMPLE

After the feasible options were obtained, the next step is to select which will be the preferred one. There are numerous methods for decision making, but for this study, the Multi-Criteria Decision Analysis (MCDA) was used. MCDA is one of the complex decision-making tool that involves both qualitative and quantitative factors, and has been widely used in many industries including geothermal energy (Purba, et al., 2020; Greco, Ehrgott, & Figueira, 2016). The advantages of MCDA compared to other DM tools such as cost-benefit analysis and cost-effectiveness analysis is that MCDA does not require a monetized measurement, hence making it more suitable and applicable for more complex decision-making situation (Raith, 2018).

One thing that should be noted regarding MCDA is as follow (Yadav & Paudel, 2017):

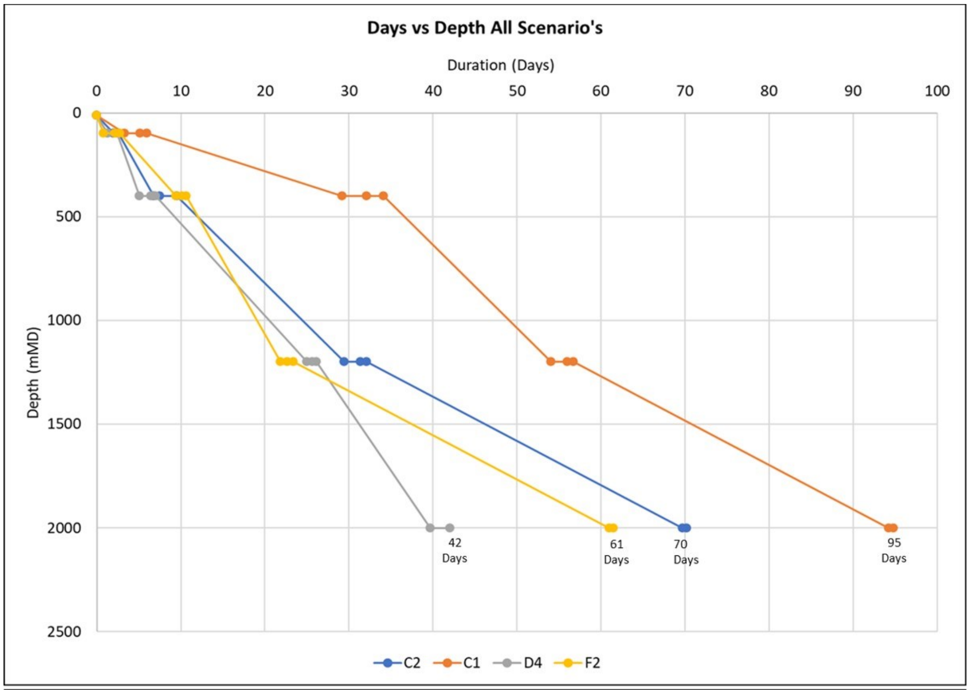
- It does not provide the "right" answer.
- It does not provide an objective analysis.
- It does not relieve the decision makers from the responsibility of making difficult judgements.
- It assists the decision makers to confidently decide by gaining a better understanding of the problem, integrating objective measurements with value judgement, managing the decision maker's subjectivity, and ensuring that all criteria and decision factors have been taken into proper account.

The decision maker can use the MCDA tool to assess their options, and each party can have different weight and priorities, thus will yield different result. Therefore, this study is not meant to give a clear answer on what is the best way for conducting a geothermal slimhole drilling, but to give a brief overview on how to apply the decision-making tools to select the preferred alternatives.

4.1 Defining Criteria

4.1.1 <u>Well cost</u>

Well cost is one of the most important factors to be considered during drilling, especially that the slimhole drilling is touted to be able to reduce the cost of geothermal exploration drilling. In this case, the well cost is affected by the drilling duration, contract value, mob-demob cost, and the additional expense required for the modification or additional equipment. The drilling duration is estimated from the drilling rate of the offset wells from several drilling campaign in Indonesia, both standard/big hole and slimhole or mineral coring drilling. The estimated contract value is derived from 2019-2020 market survey data and the contract value of previous drilling contracts in the last three years. The well cost consists of rig cost, fuel, cementing, drill bit, fishing, drilling fluid, casing, wellhead and master valve, drilling waste management, and water transfer pump. Note that the aerated drilling and MWD are not included in the well cost.



Option	Rotary days	Coring days	Total days
C1	32	63	95
C2	8	63	70
D4	42	-	42
F2	23	39	61

Figure 5. The estimated drilling duration for each alternative. Note that the drilling rate for coring rig is obtained from the only slimhole drilling campaign in Indonesia in the last two decades. Therefore, the data might not be representatives for the actual capability if the contractors and crew is experienced in drilling a geothermal well and already passed the learning curve.

4.1.2 Estimated cost and effort for modification

As described in Section 2, currently there are a few or no drilling rigs that 100% ready for geothermal slimhole drilling in Indonesia. They require modification or additional equipment to be able to drill the well. The less the modification cost or modification effort required, the more preferred it is for the decision maker. The value for the estimated modification cost is obtained by discussing with several drilling rig providers in Indonesia to get their perspective. It is admittedly a very subjective data that should be detailed and verified further once the drilling project preparation commences.

4.1.3 Operational risk

The operational risk is defined as the potential problems that can be faced during drilling. For example, drilling in the reservoir section using rotary drilling is considered riskier compared with using coring drilling, as a coring operation can still be done even if it encounters total loss circulation. The less the operational risk is, the more preferred it is by the decision maker. This criterion is a subjective evaluation as well. Other example is that the contingency plan in the case of a drilling problem, e.g., whether the drilling can be stepped down by using smaller-sized casing or not.

4.1.4 Rig availability, expertise availability, and market acceptance to the scheme

The rig and expertise availability in Indonesia is critical as it can be a deal breaker for the drilling project. Authors' experience shown that some slimhole drilling campaign in the pipeline is delayed due to the failed tender caused by no contractors able (and willing) to provide the said rig required. While the market acceptance for the scheme assessed in this study is also important due to the following reasons:

- The target market for mineral coring rig is obviously for mineral exploration, while the main target market for 450-550 HP rotary rig is for workover and well intervention. Therefore, the rig contractors typically hesitant to participate in the project if it is not economically interesting for them (e.g., small number of wells while the investment required for modifying the rig is too big).

4.1.5 Subsurface data obtained

Ideally, the more subsurface data that can be obtained, the more preferred the alternative is for the decision maker. The example of this is that whether the drilling can still retrieve formation data in the reservoir section (which is typically difficult to get in rotary drilling due to no cutting return to the surface. In contrast, it is not a problem for a coring drilling operation as the rocks are retrieved in the form of a core).

4.2 MCDA Result

The breakdown of the calculation and the result of the MCDA is shown on Table 5 and Figure 6 respectively. The result shows that the combination of the option F2 and C2 (drilling with combination of a small rotary rig and coring rig) are the alternatives with the highest scores. This is due to the factors of the cost and effort for modification is put as one of the important parameters (thus having more weight on them). The combination of two rigs requires fewer modification for each type of rigs, thus potentially easier to find the willing contractors on the market. But it should be noted that the F2 and C2 options really depends on the project place. The assumption for this scenario is that the project is in Java, thus having relatively good infrastructure and lower mobilisation cost. Has the project was set in other location such as Halmahera or other more remote location in Indonesia, the mobilisation cost and additional cost for infrastructure might make these two options less favorable.

Unexpectedly, the C1 option (drilling with core rig) fares the worst between the alternatives, even worse than option D4 (drilling with small rotary rig, no coring). This is due to the following factors:

- The estimated drilling duration is the longest. This is caused by the data derived from the only slimhole drilling campaign in the last two decades, which encountered a lot of problem during drilling. The design and operational optimization will potentially make this option more attractive as the drilling duration will not be as long as the current estimate (~95 days).
- The well cost is higher for this option. This is due to the relatively high modification cost that is spread onto 3 wells only. Even though coring rig has lower operation day rate than the rotary rig, but this modification cost significantly increases the total rig cost, especially because the cost is spread to only 3 wells. If the modification spread into more wells, the cost for a single well will be potentially lower. This was also confirmed during Authors' discussion with several drilling contractors that stated they are currently not too interested in the project because they have to invest a lot of capital for a relatively small number of wells. Should the contract for the rig can be made for several fields at once (thus having more well), the contractors said that it will be more appealing for them.

Option D4 (drilling with small rotary rig, no coring) fares relatively well compared to option C1. However, it should be noted that there are two main disadvantages of this alternative:

- The drilling in the reservoir section will be done with rotary drilling and not coring. This negates the one advantage of slimhole drilling, which is that the coring drilling can still be done in total loss condition. With a rotary drilling, drilling a reservoir section requires other equipment such as aerated drilling and big mud pump to prevent stuck pipe. This complicated set of equipment will inflate the drilling cost, and might make the option less favourable.
- The well design for this option (last production liner is 4" casing) is already at the limit for rotary drilling. This means that there is no contingency if the drilling encounters problem and cannot be stepped down to smaller size, thus risking not reaching the target depth. The smaller rig such as 450-550 HP is also most likely to have insufficient hook load capacity for overpull and activating drilling jar in the event of stuck pipe, which is common in geothermal drilling with rotary drilling. The operational risk for this option is the highest for this option.
- The data obtained by this drilling might not satisfy the subsurface and reservoir engineer, as no core is obtained from the reservoir. The cutting data from the reservoir is also most likely will not be retrieved due to the loss circulation during drilling.

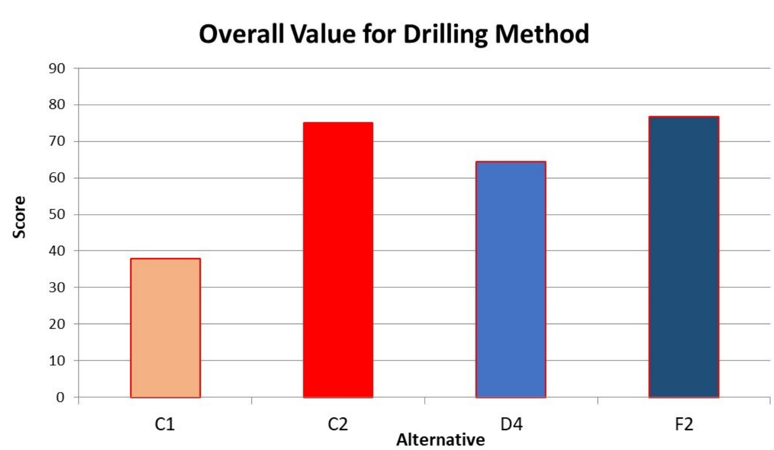


Figure 6. MCDA result for drilling method alternatives assesed.

5. CONCLUSION

Even though slimhole drilling has been widely used as a promising alternative for conducting geothermal exploration worldwide, but it has not gained enough traction in Indonesia. One major reason is the difficulties to find the suitable and readily available rig in Indonesia. The typical mineral coring rig requires several modification and additional equipment that the contractors should invest in, and without an economically attractive project, they might be hesitant to do so.

To address that issue, this study has populated the possible options for drilling slimhole well for geothermal exploration. There are four combination of well schematics and rig that are possible for the scenarios:

1. Drilling with mineral coring rig. The conductor pipe size is 9-5/8” with the last production liner is BW.
2. Drilling with the combination of 450-550 HP rotary rig for the section that requires rotary drilling, and then continued with coring rig for the reservoir section. The well design can vary from 13-3/8” or 9-5/8” conductor to BW as the last production liner.
3. Drilling with the 450-550 HP rotary rig with no coring. This option is feasible but comes with a lot operational risk associated with conventional geothermal drilling such as stuck pipe.

To select between those alternatives, the decision maker can use several decision-making tools available. This study has demonstrated the use of MCDA to obtain the most favourable alternatives based on the stated criteria and assumption. The MCDA has proven applicable to be used for this scenario that has both qualitative and quantitative factors.

5.1 Path Forward

This study is admittedly in the early phase, and there is a lot of improvement required in the future. The path forward for this study are:

- Define a more detailed modification and additional equipment required for each type of rigs. This way, the estimate for total modification cost and effort can be more accurately obtained and put into the decision-making tool.
- Analyse more offset data from mineral coring operation to get a more accurate estimation on the drilling rate (rate of penetration) of typical coring rig.

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Table 5. MCDA calculation breakdown.

performance matrix (collected data for all measurable criteria)									
	Well Cost (USD)	Est. Modif Spending	Modif Effort	Operational Risk	Personal Competency	Availability Option	Subsurface Objective (Downhole Data)	Market Acceptance	Estimated Drilling Duration
C1	$2,393,151	25	25	75	50	25	100	90	95
C2	$1,930,893	100	75	100	50	75	100	25	70
D4	$2,183,501	50	75	0	75	100	50	90	42
F2	$2,062,187	100	75	75	50	75	100	90	61

weights (as assessed by decision maker)									
weight (0-100)	100	75	75	100	50	100	25	80	80
weight (normalised)	14.60	10.95	10.95	14.60	7.30	14.60	3.65	11.68	11.68

Indicate preference: specify best and worst values (local or global scale)									
best	$1,930,893	100	100	100	100	100	100	100	$42
worst	$2,393,151	0	0	0	0	0	0	0	$95
	local	Global	Global	Global	Global	Global	Global	Global	local

matrix of scores

note: all scores here are calculated based on linear value functions:
Linear function = 100/(best-worst)*(criterion_value - best)+100

	Well Cost	Est. Modif Spending	Modif Effort	Operational Risk	Personal Competency	Availability Option	Subsurface Objective (Downhole Data)	Market Acceptance	Estimated Drilling Duration
C1 (coring rig, 9-5/8 to NQ)	0	25	25	75	50	25	100	90	0
C2 (conv + coring rig, 9-5/8 to NQ)	100	100	75	100	50	75	100	25	47
D4 (conv, 16" - 4")	45	50	75	0	75	100	50	90	100
F2 (conv + coring rig, 13-3/8 to NQ)	72	100	75	75	50	75	100	90	64

overall scores

overall scores: sum of weight * score

overall score	normalised score (out of 100)
3788.32	37.88
7503.44	75.03
6439.46	64.39
7681.28	76.81