PROCEEDINGS, 46th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 15-17, 2021
SGP-TR-218

Resource Assessment Methods Selection for Geothermal Exploration Project in Indonesia: What Are the Considerations?

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Keywords: geothermal, resource assessment, exploration, drilling, volumetric, numerical simulation, reservoir model, Indonesia

ABSTRACT

In developing a geothermal exploration strategy, as mentioned in many scientific publications, the selection of resource assessment methods become very crucial due to the high uncertainty level of this stage. Of the various resource assessment methods available in the industry today, the volumetric method is the most often used in Indonesia during the exploration phase, while numerical modelling is more common for the development phase where more sub-surface and production data have been collected. Other than those, there are several other methods such as surface heat flux, planar-fracture, magmatic heat budget, total well flow, mass-in-place, power density, decline analysis, and lumped-parameter.

The question that arises is when each of these many resource assessment methods should be used in the exploration stage. This paper aims to review some considerations and limitation of various geothermal resource assessment methods that can be utilized by the decision-making team in designing exploration strategies. The methods used in this study are literature review and direct interviews with geothermal practitioners in Indonesia. The summary of this study is expected to become a simple tool that able to assist new investor or geothermal developer formulating their exploration strategy.

1. INTRODUCTION

1.1 Geothermal Development in Indonesia

Located at the Pacific Ocean ring of fire, Indonesia is believed to possess an enormous amount of geothermal energy potential, around 28 gigawatt electrical (GWe) (Bertani, 2016; MEMR, 2017; Darma *et.al.*, 2010; Fauzi *et al.*, 2005; Suryantoro *et al.*, 2005; Ibrahim *et al.*, 2005) in 312 locations spread across the archipelago along volcanic areas of Sumatera, Java, Bali and several islands in eastern part of Indonesia. Unfortunately, until 2020, Indonesia has only succeeded in utilizing around 7% of the country's geothermal energy potential, which is contrast to Indonesia's national target of 8,000 MW in 2030.

There has been quite an amount of published studies and papers discussing the issues on the challenges that the Indonesian government and the geothermal developers will face in developing geothermal projects in Indonesia. Despite those challenges, it is clear that currently the exploration phase is the most critical phase that Indonesia needs to seriously take into action, in order to achieve the geothermal national target. Figure 1 shows that only few areas has been developed for geothermal power generation despite Indonesia's vast potential. Furthermore, IGA (2014) noted that the main challenge in developing geothermal energy is the high project risk upfront in the resource exploration phase, due to the uncertainty of available economic resources.

Table 1 shows that there is a total of 73 geothermal areas that are still in the exploration phase with the total potential of 3,520 MW (ESDM, 2020).

Table 1: Geothermal area status in Indonesia (ESDM, 2020)

Geothermal Area Status	Number of Area	Potential
Area Prospek Wilayah Terbuka (Prospect Area – Open)	17 prospect area	290 MW
Wilayah Penugasan Survei Pendahuluan dan Eksplorasi (Preliminary Survey)	14 PSPE area	920 MW
Persiapan Penawaran WKP dan Government Drilling (Prepared for Tender)	22 WKP	825 MW
WKP Eksplorasi Dengan Rencana Pengembangan (Exploration Area with Development Plan)	20 WKP	1,485 MW

Figure 1 (Pusdatin ESDM, 2020) shows the distribution of geothermal areas in Indonesia as according to the progress in each area. Areas that are coloured green, light green and yellow indicates areas that has been through a preliminary survey, which is commonly the 3G

survey, and in some areas, surveys such as the temperature gradient hole or deep slimhole might have also been conducted. Pink indicates the areas that are ready for development, whereas red shows areas that has already been developed.

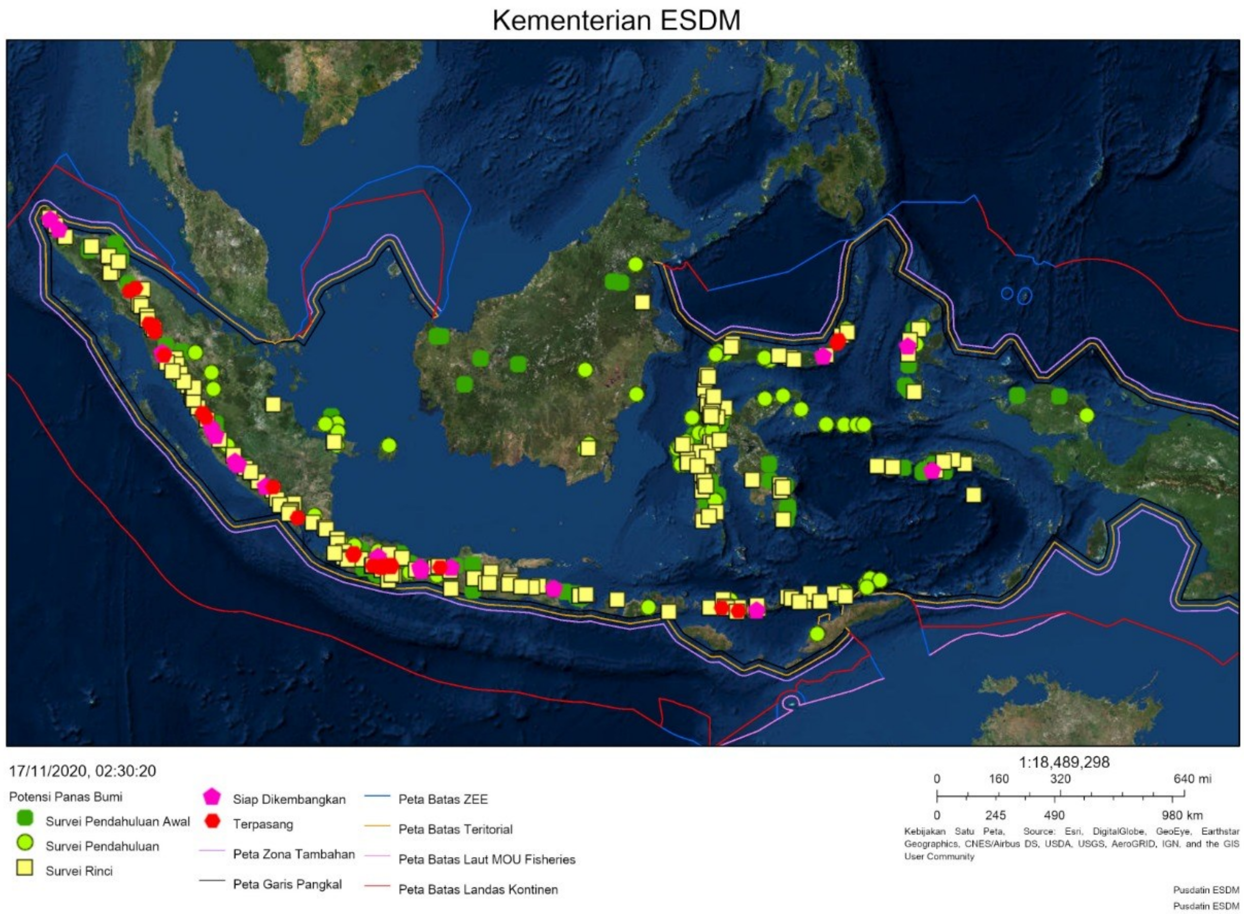

Figure 1: Maps of geothermal potential area in Indonesia with its status (Pusdatin ESDM, 2020)

1.2 The Importance of Geothermal Resource Assessment

The biggest risk in developing geothermal energy is resources overestimation, especially in an exploration phase when a deep well is not constructed yet. The greatest effort at the beginning of a geothermal project is always focused to understand the resource in conjunction with adequate capital allocation. The result of resource assessment can determine the sustainability of a geothermal project. Therefore, resource assessment must be conducted using a reliable method and must be carried out whenever more data enters. Figure 2 shows the "Go/No Go" activity which indicates that resource assessment must be performed to determine whether or not the project is feasible to be continued. As the confidence level on the resource availability increases, the risk decreases. Nevertheless, the strategy to extract heat energy must be planned carefully.

In the exploration phase, resource assessment highly depends on Geology, Geophysics and Geochemistry survey or well known as 3G Survey, which is commonly applied in the very early phase of the exploration of geothermal resources. The data acquired from 3G (geology, geochemical, and geophysics) surveys can be classified into two categories:

- *Indirect data* – represents data that 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 surveys can only interpret high temperature zones within a geothermal prospect indirectly but cannot directly estimate the subsurface temperature.

- *Direct data* – represents data that have direct connection with the target reservoir; hence can be used to infer the reservoir temperature. During the early exploration stage, geochemistry survey is considered as the most powerful method to analyse the fluid chemistry of thermal manifestations (fumaroles and boiling chloride springs) in order to estimate the subsurface temperature (Hadi *et al.*, 2010). In the next phase of exploration, direct data can be obtained from the various holes that has been drilled.

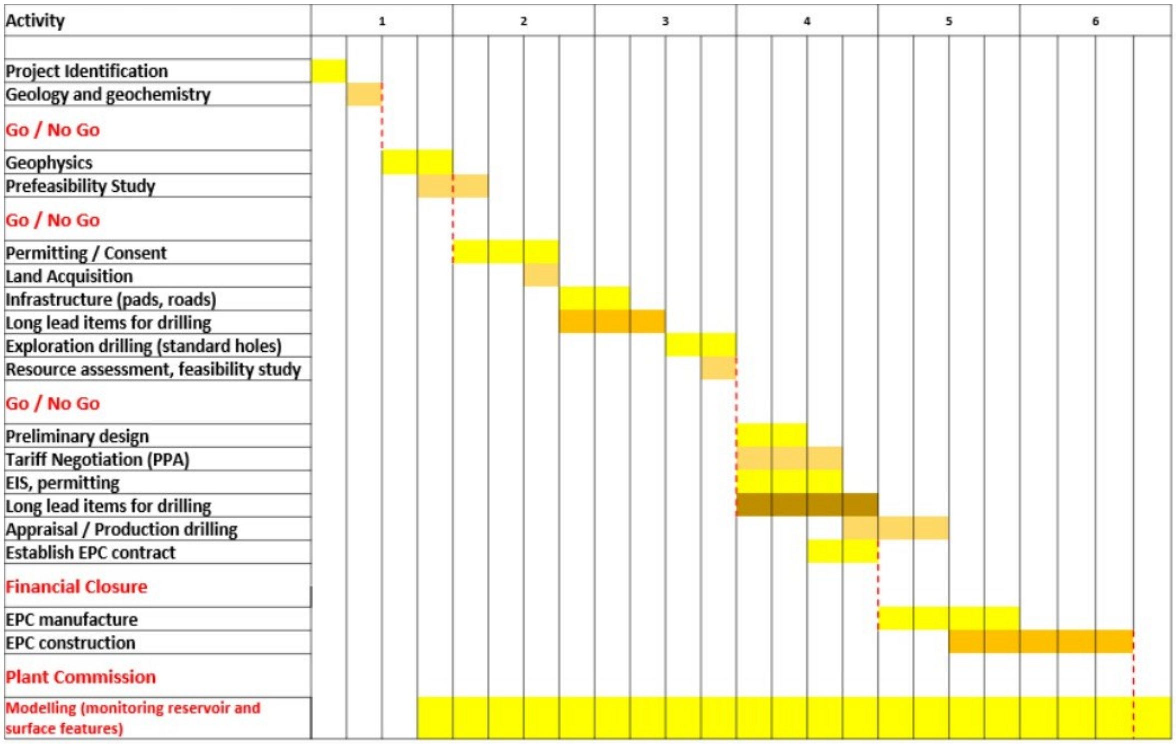

Figure 2: Example of typical geothermal project timeline. Note the go/no go decision point after each phase of the project is completed (Exergy, 2017)

Table 2 exhibits a summary of various activities in the exploration phase, that was conducted with the objective of obtaining information on the size of the geothermal energy potential that is below the ground.

Table 2: Exploration work cost and duration estimates (modified from GeothermEx, 2010; Kristianto, 2018; Purba et al, 2019)

Activity	Cost estimate (US$)	Estimate work duration	Cost estimate dan duration assumptions	Considerations
Geology survey	300,000 – 700,000	4-8 months	Geological mapping on an area of 400 km^2. The work package including pre-field-work study, rock sampling and identification, structural mapping, and reporting.	Accuracy might be affected by terrain, weather, and field personnel experiences.
Geochemistry survey	200,000 – 400,000	4-8 months	Work package including a pre-field-work study, liquid and gas sampling from 30 locations, laboratory analysis and reporting.	Accuracy might be affected by sampling method (minimize contamination) and laboratory competences.
Geophysical survey	1,500,000 – 2,000,000	4-8 months	Work package including pre-field-work study, 100 MT stations and 150 Gravity stations, interpretations and reporting.	Accuracy might be affected by noise during data acquisition and data processing method, including personnel interpretation.
Initial conceptual integration and well targeting	100,000 – 200,000	3-6 months	Integrate all report from 3G surveys to create several scenarios of conceptual models, including peer review.	Accuracy might be affected by 3G data accuracy and personnel experiences and interpretation.
Exploration drilling	10,000,000 – 25,000,000	24 - 36 months	Using 3 standard/big hole type or 5 slimhole type. The duration including preparation time.	Allow personnel to acquire downhole data directly from reservoir which is very valuable for more accurate resource assessment but require higher cost and time compared to 3G survey.

Many advantages and disadvantages of this survey in terms of interpretation of the geothermal resources due to this survey is a surface activity and considered as *indirect* data which used to interpret the subsurface condition. To get a better understanding, the *direct* data is highly required and can only be obtained by drilling the wells that required higher cost compared to 3G survey.

1.3 Geothermal Resource Assessment Code and Standard

The geothermal project development in Indonesia is regulated by Geothermal Law No.21/2014, but no reference to any resource assessment standard or code is mentioned in the regulation. The law mainly regulates the development of a geothermal field, in terms of phase and time, as illustrated in Figure 3. This regulation states that the geothermal explorations phase will last five years and can be extended twice in one-year extension period respectively. The results of 7 years exploration must be reported in a form of a feasibility study, submitted at the end of exploration phase. More importantly, the report should indicate geothermal resources available at the site.

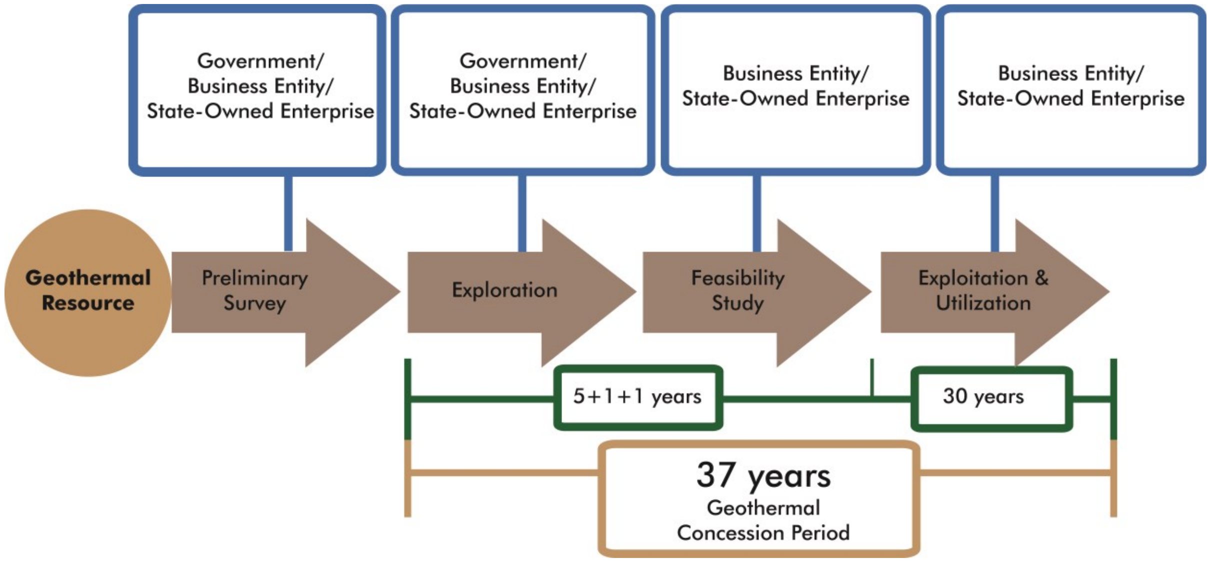

Figure 3: The geothermal development phases in Indonesia regulated by Law no. 21/2014 (Purba, 2018)

Currently, there are several attempts to standardize the geothermal resource assessment reporting code (Table 3), although none of these codes have been used as reference in Indonesia geothermal resource reporting requirements at the time of this study being conducted.

Table 3: List of standards or code worldwide on geothermal resource assessment method.

Resource assessment code	Country/Year	Remarks
Australian Geothermal Resource Reporting Code	Australia/ 1st edition – 2008 2nd edition – 2010	• Australian stock exchange (ASX) listing requires the definition of an industry code. • Supported by IGA and NZGA • Key principles: - The basis for the estimate should be clear (transparent) - All relevant issues disclosed in the report - Relies on the professional judgement of an accountable 'competent person'
The Canadian Geothermal Code for Public Reporting	Canada/ 2010	• Adopted from Australian code • To provide information in their public reports as comprehensive as possible • Key principles: - Provides a basis for transparency, consistency, and confidence in the public reporting of geothermal information - The report must be created by a "qualified person" as defined by the code and need to be certified by third-party evaluation professionals

Indonesia through the Indonesian National Standard (SNI) 6169: 2018 has provided guidelines for determining the potential for geothermal energy in Indonesia based on the results of geological, geochemical and geophysical investigations, reservoir characteristics and estimates of electrical equality. The methods used in this standard are the comparative, volumetric and reservoir simulation methods, but this standard does not regulate the value/magnitude or the assumptions that should be used for those parameters.

1.4 Research Objectives and Method

Authors of this study observed that with the absence of a clear guidance and regulation system in Indonesia, on the methods of how to conduct the resource assessment and reporting, may cause a significant difference between the estimation in the early phase of exploration, which is usually conducted by the government or state-owned enterprise, with the actual resource numbers derived from exploration drilling and delineation.

This paper aims to review some considerations and limitation of various geothermal resource assessment methods that can be utilized by the decision-making team in designing exploration strategies. The methods used in this study are literature review and direct interviews with geothermal practitioners in Indonesia. The summary of this study is expected to become a simple tool that able to assist new investor or geothermal developer formulating their exploration strategy.

2. RESOURCE ASSESSMENT METHODS

2.1 Overview on Resource Assessment Methods in Geothermal Industry

Authors, through literature study, have mapped out several geothermal resource assessment methods that are available in the industry as shown in Table 4.

Table 4: Summary of various geothermal resource assessments method.

Method	Short description	Recommended to be used in what phase?	Main advantages	Main pitfalls/disadvantages	References
Surface thermal flux	Estimate the reservoir enthalpy and reservoir temperature by deducting the thermal output from thermal manifestations, through the combination of conductive and convective heat transfer calculation.	Preliminary assessment, very early exploration phase	The simplest method that only require surface thermal effluents and conductive heat from soil to atmosphere/surface water data	The result of this method can only be assumed as the minimum natural heat flux from the system, thus it does not represent the whole reservoir system.	AGEA, 2010
Magmatic heat budget	Estimate the volume of the silicic magma chambers to appraise their age of emplacement, and to calculate the amount of geothermal energy remaining in the intrusion and adjacent country rock using conventional calculations of conductive heat loss.	Preliminary assessment, very early phase	Can be used in the very early phase	Only gives a broad overview of the accessible resource base with little quantitative insight that might be recoverable into the fraction of this resource base.	Muffler & Cataldi, 1978
Total well flow	Taking the total flow of drilled wells as the field capacity.	Only used when production wells are available.	No clear advantages identified. Could not be used to determine field capacity	Total flow of the wells is simply the current ability to deliver fluid. Does not represent the amount of fluid or steam in the resource.	Grant, 2000
Planar fracture method	Extraction of heat through flow of water along extensive, planar fractures, with heat being transferred to the fractures only by conduction.	Early exploration phase	Enable calculation of recoverable thermal energy from a minimum number of physical parameters without going through the intermediate step of calculating the accessible resource base	Only used in geothermal areas within flood basalt terranes but is not reliable to the most common geologic situation characterized by folding and faulting	Muffler & Cataldi, 1978
Lumped-parameter modelling	Simplest case of reservoir simulation where it estimates the resources by assuming the system as a single element with average reservoir properties.	After well(s) drilled or during production	More simple method than numerical modelling and can provide good estimates for a few years, but not for long-term	• Does not consider fluid flow and heat transfer as a response to spatial gradients of pressure and temperature • Not suitable to be used for long-term prediction	Grant, 2000; Sanyal and Sarmiento, 2005;
Power density/areal estimates	Approximation of the potential of a resource based on the power density distribution of known geothermal field production capacity.	Exploration or early appraisal stage.	Considered simple yet provide a reasonable value for a preliminary field sizing as it involves fewer assumption about the reservoir	• The calculation is based on MT resistivity survey or thermal manifestations that are not usually directly comparable to the area of the reservoir. • Applying power density data from several geothermal fields to other prospects, if it has a correlation.	Wilmarth and Stimac, 2015; Grant, 2000; Cumming, 2016
Decline curve analysis	Using production history data from production wells to assess individual well or field performance and to	On the production stage	Quick, easy and cheap implementation	• Applies to a constant number of wells. If	Grant, 2000; Ripperda and Bodvarsson, 1987

	predict future production. Adapted from the oil and gas industry.			• wells are added the decline rate increases • Only represents reserves of entire drainage area of the wells	
Stored heat (volumetric)	One of the oldest methods that use the isotherms to estimate the total amount of heat contained within the reservoir.	Initial stage of exploration phase, prior to drilling.	• Considered the simplest method • One of the most commonly applied methods in the industry. The other most commonly used is numerical modelling.	• No or very little experimental evidence to validate the recovery factor used. • The volume calculated may easily include the low permeability region. • Often lead to overestimate the field capacity.	Muffler & Cataldi, 1978; Grant, 2000; Zarrouk, 2013; Halcon *et.al.*, 2015
Numerical modelling	Dividing the geothermal resources into blocks that represent reservoir parameters. Well data on temperature, pressure, enthalpy and mass flow are calibrated with rock properties that are matched with the condition of the resource, from the pre-exploitation phase up to the present production data.	Starting as early as possible is useful to check the conceptual models and may help to guide the exploration and monitoring program.	Considered the most accurate method	• Require deep well or production history data • Calibration time and requirement of high-performance computer	Franco and Vaccaro, 2014; Grant, 2000; O'Sullivan and O'Sullivan 2016; Wisnandary and Alamsyah, 2012; Grant, 1983

2.2 Resource Assessment Method Utilization

All the resource assessment methods described previously require geoscientific data as inputs including geological, geochemical and geophysical data. Once all these data are acquired, a conceptual model that represents the geothermal system encapsulating geological framework, heat source, heat and fluid migration pathways, reservoir characteristics, and surface geothermal features need to be constructed. The integration process of all of the exploration data combined with possible resource assessment method used on each phase is summarized in Figure 4 based on previous works by IGA, 2014; Brotheridge, 2017; Grant, 2000, and Ciricao et al, 2020.

Figure 4 shows that in each phase of a geothermal project, the decision maker has several options in processing the data. These various methods might produce similar or totally different estimation outputs when compared to each other. Several considerations when performing a resource assessment can be summarized as follows:

1. The quality of the data used as input parameters. The higher the confidence level in the quality of the data inputted into the calculation, the higher the confidence of decision makers in the output produced.
2. Understanding of the resource assessment method used. The better the user's understanding of the pitfalls of each method, the easier it will be for the decision maker to assess the output of each method used.

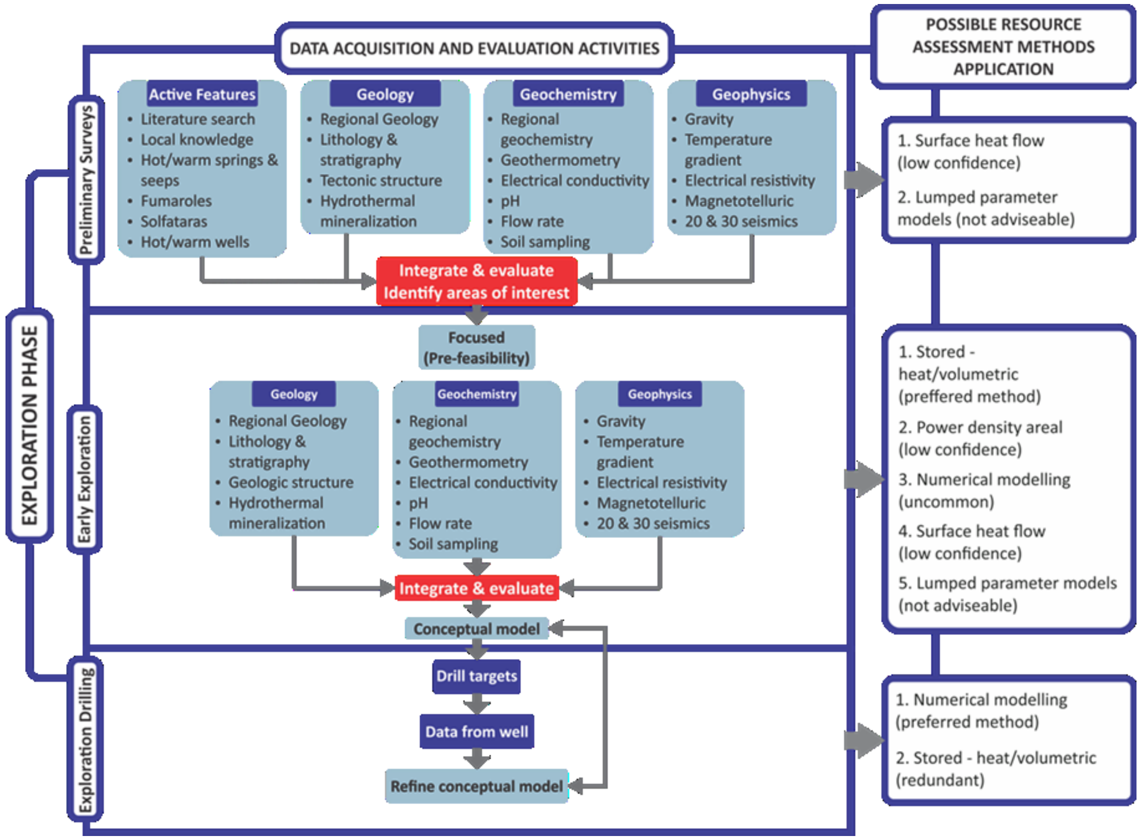

Figure 4: Exploration activities/phases with possible resource assessment methods application (modified from IGA, 2014; Brotheridge, 2017; Grant, 2000)

3. DISCUSSION

3.1 Which Resource Assessment Method is The Best for Exploration Phase in Indonesia?

During the creation of this report, authors were still in the process of directly interviewing several geothermal engineers and geoscientists regarding to the resource assessment method that is commonly used in the exploration phase in Indonesia. Based on the response gathered at the time, authors were able to summarize a few points for consideration:

- *Most common method* – based on the discussion with geothermal geoscientists in Indonesia, methods that are commonly used in the exploration phase are the volumetric method and the power density method, with the reason being is that both methods are the simplest and cheapest methods for the exploration phase. The authors found that only very few geothermal companies in Indonesia uses the reservoir numerical modelling method in the early phase of exploration.
- *Simplicity* –Power density does not require advance technology or sophisticated computer when it comes to the tools used, as Grant (2000) and Wilmarth and Stimac (2014, 2015) have provided the plot data from 53 producing fields. Both methods can be easily executed using any spread sheet application that is available in the market. On the contrary, numerical modelling is considered to be very complicated, as it requires a reservoir simulator (e.g., STAR, TOUGH2, AUTOUGH2, TETRAD), complex calibration process, and require a computer with a powerful processing power.
- *Work duration* – Power density is a method that is considered to be far more rapid in estimating a geothermal resource, compared to the volumetric method, as it uses a relatively simple calculating method. If the 3G data is available, the power density and volumetric method only needs around 1-2 weeks to get the result, while numerical reservoir model can take 8-24 weeks to build and calibrate the model.
- *Cost* – Numerical reservoir model is considered expensive as it requires dedicated personnel, dedicated software, tim-intensive, and a computer with adequate processing power.
- *Accuracy* – Even though power density is widely used in geothermal exploration, it is considered to be less accurate and is used for rough estimate. While the volumetric method is very dependent on various assumptions on its calculations. One of the parameters that should be assessed further is the Recovery Factor (Ciriaco et al, 2020), as the basis for this assumption is sometimes not clear. Apart from its complexity, the reservoir numerical modelling is considered to be the current most reliable for the geothermal resource assessment.

Ciriaco, Zarrouk and Zakeri (2020); Franco and Vaccaro (2014); Grant (2000); O'Sullivan and O'Sullivan (2016); Wisnandary and Alamsyah (2012); Grant (1983) and discussion with several geothermal geoscientists in Indonesia confirms that the reservoir numerical model is considered as the most accurate resource assessment method. However, authors found that the method is not commonly used in the early exploration phase. The answer for "which resource assessment method is the best for exploration phase in Indonesia?" cannot be easily answered with a straightforward manner, as each developer in Indonesia have their own reasoning and preferences for their decision-making process. To date, authors believe that the application of reservoir numerical modelling in the early phase of exploration is worth to be studied further.

3.2 Numerical Modeling Since Early Exploration Phase: Wise or Not?

Exploration is the early stage in geothermal development with aims to identify the existence, magnitude and viability of a geothermal system in particular area by conducting complete 3G (Geology, Geophysics, and Geochemistry) surveys and exploration drilling. The data derived from the surveys are gathered and integrated into an initial conceptual model. However, this initial conceptual model is still immature and in 2D version. A lot of interpretations are involved in this early version of conceptual model. The conceptual model will be comprehensive and complete after the subsurface data have been obtained. Exploration drilling is the next stage of the exploration process to obtain direct subsurface data such as lithology, hydrothermal alteration mineralogy, alteration zone, key reservoir parameters and validate the geoscientific information derived from the 3G surveys. Unfortunately, the well targets for exploration drilling are based on the initial 2D conceptual model which contains a lot of uncertainty due to the incomplete data and it makes the risk for doing exploration drilling are very high.

According to Nugraha (2020), geothermal modelling should be utilized since the early stage of geothermal development because it can help in visualizing the data from the 3G surveys and ease the analyzation process. This method utilizes the modelling best practice (Figure 5) developed by Geothermal institute, University of Auckland that have been applied on other geothermal projects around the world. Starting by integrating the 3G survey data into a 3D geological model using LEAPFROG geothermal software and this 3D model is used as the preparation of the reservoir model. This step is then continued by simulating the natural state condition of the numerical model using AUTOUGH2, a reservoir simulator developed by Geothermal Institute, and calibrating it with the 3G exploration data. The results from this simulation describe the fluid flow behavior and temperature distribution of the beneath formation of a prospective geothermal area. The simulation results are incorporated with the 3D geological model and used it as the basis for developing well targets of the exploration drilling. The well data from exploration drilling are utilized to refine the 3D geological model and update the natural state model. The resource assessment is conducted using the uncertainty quantification method for the updated model.

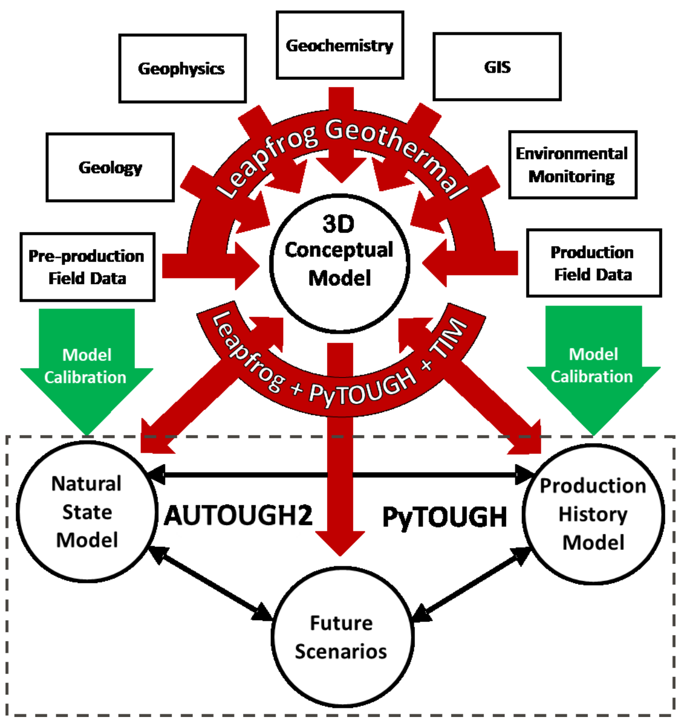

Figure 5: A new integrated geothermal modelling workflow modified from O'Sullivan et al., (2017)

This concept is also supported by Ciriaco et al. (2020), numerical modelling is beneficial and should be adopted from the early stage of development. Furthermore, O'Sullivan & O'Sullivan (2016) stated that numerical modelling is a key tool for planning and managing the project. It should be applied throughout the life of the geothermal project (including the exploration phase); the exploration and monitoring guidance can be constructed by applying sensitivity studies and data-worthy analysis to the computer model. Hence, the authors agreed that the development of a numerical model should start from the early exploration stage and be used as a guide to the exploration process.

4. CONCLUSION AND PATH FORWARD

Resource assessment is crucial for a geothermal project as it will drive the course of the project, whether to go ahead or terminate. The decision-maker's understanding on which resource assessment method to be used directly affects the success of a geothermal project. This paper has reviewed some considerations and limitation of various geothermal resource assessment methods that can be utilized by the decision-making team in designing exploration strategies. The methods used in this study are mostly literature review with small portion of direct interviews with geothermal in Indonesia. This paper presents the early phase results of a more thorough study that aims to formulate the most appropriate resource assessment method for geothermal exploration in Indonesia.

The preliminary conclusions so far shows that the most common resource assessment method for geothermal exploration in Indonesia is the volumetric method and power density. This is because those methods are considered to be simpler, cheaper, and can give results quickly compared to the reservoir modelling (or reservoir simulation). In terms of accuracy, the reservoir simulation is considered to be more reliable especially if the model has been calibrated to the actual well data. Reservoir simulation also can predicts future production scenarios. However, despite those advantages, reservoir simulation requires dedicated experts (the reservoir engineer/modeler), time-intensive, and require a lot of computer with enough processing power to do. This relatively more expensive investment is made the reservoir modelling to be less favorable to be used during exploration phase in Indonesia.

Interestingly, several studies and publications show that reservoir modelling can be very useful if done in the early stage of exploration, With the advent of faster computer and more sophisticated reservoir modelling program, the full-scale calibration process of geothermal field model can be done significantly faster than it was in the past.

Based on those findings, several path forward for this study are as follows:

1. Conduct more discussions to geothermal geoscientists and reservoir engineers in Indonesia regarding the best resource assessment method for geothermal exploration in Indonesia and why. This is to get a better mapping of the resource assessment practice by geothermal developers in Indonesia, especially that not all resource assessment methods for geothermal fields in Indonesia is published and can be accessed by public.
2. Further study regarding the reservoir modelling applicability in the early phase of exploration where there is no deep well data. The study scopes including populates the data required for calibrating the model, estimates the duration of the calibration process, assess the reliability of the method, and map the availability of the experts in Indonesia.
3. Case study from several fields in Indonesia to demonstrate the applicability of the reservoir modelling as a resource assessment method for geothermal exploration in Indonesia.

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