

Potential Closed-loop Geothermal Power Generation Application for Non-commercial Well in Indonesia: A Preliminary Study

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ABSTRACT

The current conventional geothermal power generation typically involves the extraction of geothermal fluid from the subsurface to the production facility on the surface. Therefore, a commercial geothermal production well needs to encounter high enough temperature, benign fluid, and sufficient permeability to allow the geothermal fluid to flow. However, sometimes the wells drilled may not find all those three criteria, e.g., high bottom-hole temperature but tight permeability. Such wells are often considered non-commercial wells, as they often cannot be used for the injection well.

The closed-loop geothermal concept offers a solution to utilize such a well by extracting the heat only from the wellbore. It introduces external fluid flowing through a downhole heat exchanger to extract the heat to the surface, where the heat is converted into electricity. Apart from non-commercial well utilization, a closed-loop geothermal concept is touted to extract heat from hot dry rock (HDR) system, conventional two-phase or vapour dominated well, and declined geothermal system.

This preliminary study provides an overview of closed-loop geothermal power generation, the types of closed-loop system and their associated technology, and their advantages and challenges. The potential application of a closed-loop geothermal system in Indonesia is assessed by a preliminary analysis of several non-commercial wells with high temperatures. The design concept, consideration, and challenges in technology and geothermal resources are also presented. This study is expected to provide a preliminary study of future potential closed-loop geothermal applications in Indonesia.

1. GEOTHERMAL POWER GENERATION

For hundreds of years, mankind has been incorporating geothermal energy in their daily life. People have been using geothermal manifestations such as hot springs for bathing, heating, and cooking. Later in the early of twentieth Century, people begin to consider the geothermal as a practical source of energy, marked by the first geothermal energy generator in Larderello, Italy (IGA, 2018). From then, the use of geothermal for electricity production started to spread to worldwide, with New Zealand, USA, the Philippines, Indonesia, etc. developed their own geothermal plant for power production.

The utilize geothermal for power production, the heat should be extracted from the subsurface and converted to other forms of energy, i.e., to kinetic energy then to electric energy. The most common geothermal power generation involves extracting the naturally occurring geothermal fluid (can be hot water, steam, or mixture of both in a hydrothermal system) and converting it to into mechanical power to turn the generator and produce electricity (Watson, 2013; Bronicki, 2016) as illustrated in Figure 1.

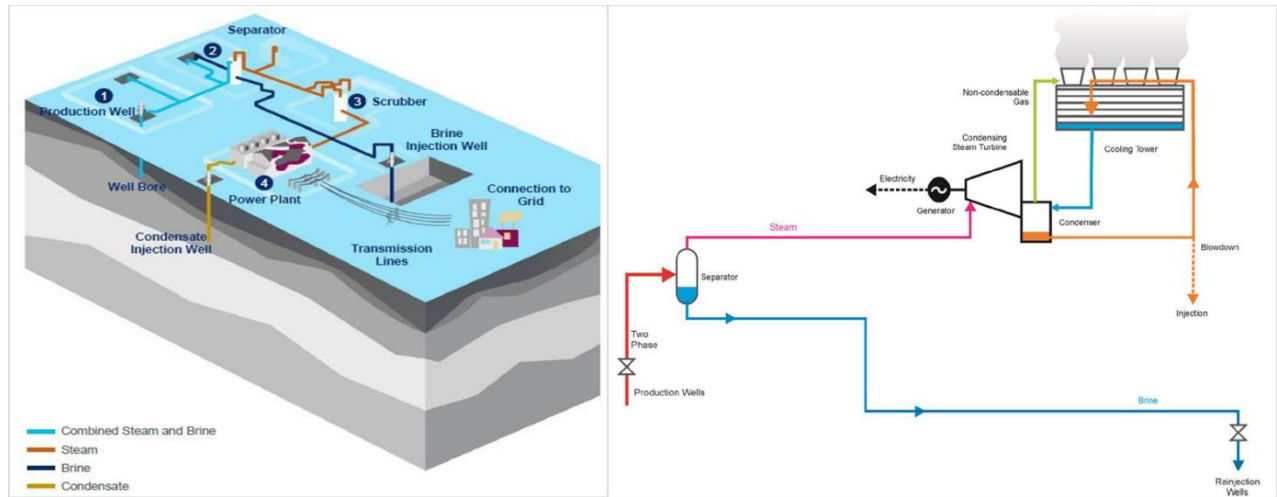


Figure 1. Right: illustration of typical geothermal power plant (modified from Liebert, 2019). Left: Simplified diagram of single flash geothermal power generation (modified from Jacobs, 2020)

The geothermal fluid can be naturally discharged from the well or may require artificial pumping, while the geothermal fluid can be directly used to drive the steam turbine (in a dry steam or flash-type power plant) or used to heat other working fluid in the binary or Organic Rankine Cycle power plant (Watson, 2013; Febrianto et al., 2019). Regardless of the turbine type, conventional hydrothermal systems require sufficient temperature, benign fluid, and a high level of subsurface permeability to be economically used for power generation.

Those aforementioned requirements or constraints make not every place can be used for geothermal power generation, even though the heat beneath the ground exists everywhere on the earth. This has prompted many researchers and companies to develop new ways to extract geothermal energy from the ground. Apart from the Engineered Geothermal System (EGS) that wanted to artificially create subsurface permeability in a hot rock, another explored alternative is the use of closed-loop geothermal system. Closed-loop geothermal systems offer a solution to utilize such a well by extracting the heat only from the wellbore. It introduces external fluid flowing through a downhole heat exchanger to extract the heat to the surface, thus removing the high subsurface permeability requirement (Scherer, Higgins, Muir, & Amaya, 2020).

1.1. Current Geothermal Power Generation in Indonesia

As Indonesia is located in the Pacific Ring of Fire, most of Indonesia geothermal areas is an island arc type (Figure 2), with relatively high temperature resources, but at deeper depth compared to other countries such as New Zealand (Jacobs, 2021). The resources such as in Java and some of Sumatra Island is predominately andesitic formation with high local permeability but not so well connected across whole reservoir (Lawless, 2017). This makes the well targeting more difficult, as targeting a high permeability zone may not be as straightforward as in geothermal fields in other countries. Some of the exploration and even development wells drilled encountered high enough temperature, but the lack of permeability renders them uneconomic. Therefore, the closed-loop technology provides the alternative in utilizing the uneconomic wells rather than let them become unusable sunk cost.

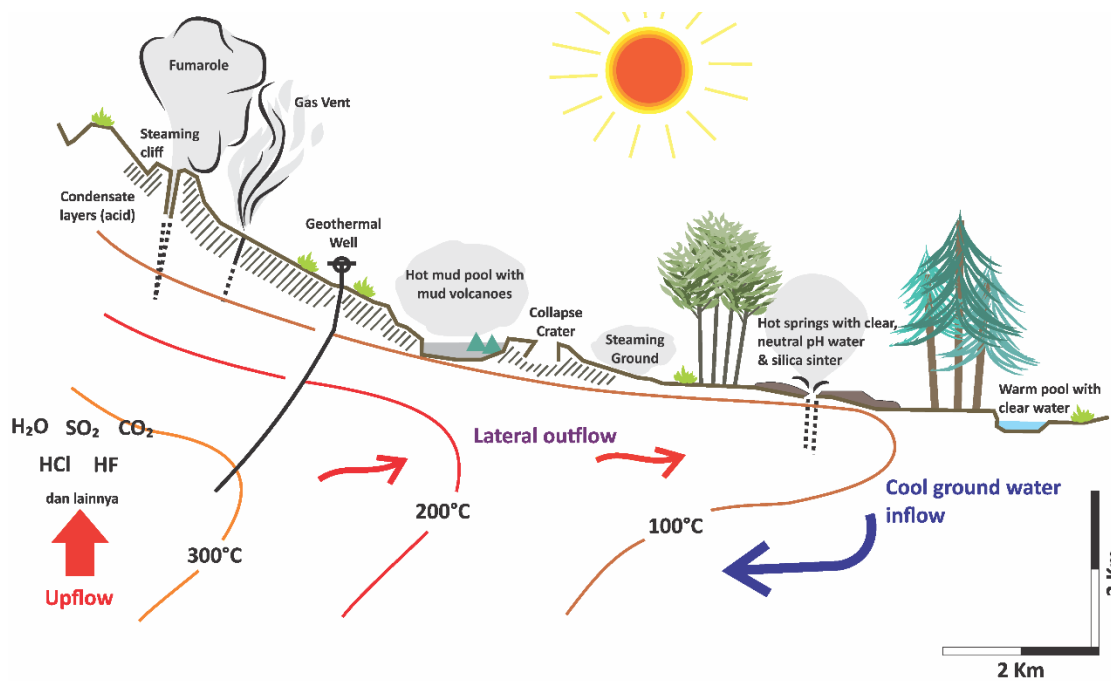


Figure 2. Illustration of island arc geothermal system commonly found in Indonesia. Modified from Utami (2017).

1.1. Objective of the Study

The objective of the study is as follows:

1. Provide an overview of closed-loop geothermal concept.
2. Populate the list of available closed-loop geothermal types and their associated technology and challenges.
3. Identify potential application in Indonesia.
4. Identify the challenges and path forward for closed-loop applications in Indonesia.

2. CLOSED-LOOP GEOTHERMAL POWER GENERATION

Closed Loop Geothermal System (CLGS) is a method to extract geothermal energy by circulating a working fluid continuously into sealed/closed wellbore and the closed system to avoid fluid leakage and reservoir blockage (Muir, J. R., 2020). In general, a CLGS well works as an indirect heat exchanger in which the circulating fluid absorbs energy from the rock formation as it flows through the well (Fallah et al, 2021). As illustrated in Figure 3, the fluids that injected in CLGS well basically use artificial fluid (such as water and supercritical CO₂) that injected from surface continuously and circulated back to the ground in the same wellbore, without direct contact with geothermal reservoir and in situ water (Hu et al, 2020).

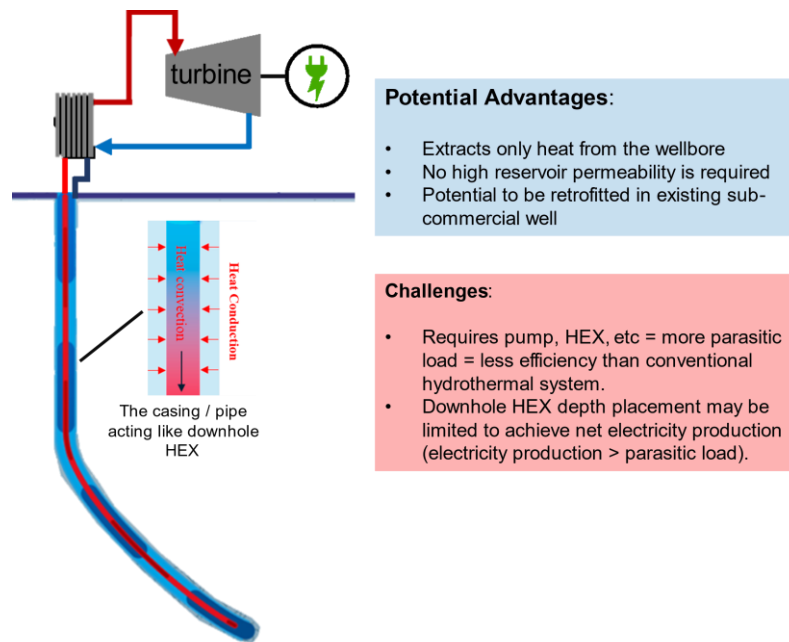


Figure 3. Schematic diagram of CLGS. Modified from Riyanto (2022)

Closed-loop was introduced early as the solution to generate electricity from non-productive well, but the potential development also can be applied to new wells or in greenfield (Amaya et al., 2020; Higgins et al., 2019; Raihi et al., 2017; Fox et al., 2016; Higgins et al., 2016). According to (Muir, J. R., 2020; Horn et al., 2020), close loop can become alternative solutions since it can greatly expands the potential of electricity generation by geothermal energy by several fundamental ways that become advantages which the detail as follows:

- Closed-loop systems can operate in a significantly broader variety of temperatures and rock compositions than conventional hydrothermal projects, from relatively low-temperature sedimentary zones to hot, dry rock formations. This variability of viable CLG operating parameters not only increases the number of viable geothermal projects, but also enables the use of high-temperature resources (300°C and higher) that significantly improve power output.
- Closed-loop systems can produce power from previously unproductive geothermal wells that might be caused by poor permeability and the fluid is not benign, the application also can be played out oil and gas wells in hot strata.
- Closed-loop geothermal systems baseload and flexible power generation capabilities can help stabilize the grid by providing consistent, reliable, and sustainable energy, capacity, and ancillary services.
- While reducing greenhouse gas emissions that supports climate environmental policies, closed-loop geothermal systems can improve industrial applications such as lithium extraction and hydrogen production.

Moreover, not only from the technical aspect that explained early in this section, CLGS has several additional advantages related to environmental and social aspects as summarized in Table 1.

Table 1. Environmental and Social Advantages of Close Loop Geothermal System (Muir, J. R., 2020; Horn et al., 2020)

Aspects	Advantages
Environmental	<ul style="list-style-type: none"> • Does not interfere and contaminating subsurface water. • Only consume little amount for processing water. Figure 1 and Figure 2 shows that conventional hydrothermal system typically need large amounts of water traversing highly permeable rock for pressure support and mass balance to ensure the sustainability of steam production. Then the closed loop system does not require subsurface permeability because a engineered sealed pipe well system conducts the working fluid through hot rock and up to the surface, where it is used to generate electricity. • Might be fewer effluent and waste disposal problems and permitting issues. • Reduce problems with corrosive and saline brines inside the system
Social	<ul style="list-style-type: none"> • Little to no waste streams • Little to no surface subsidence • Little to no risk of induced seismicity

- | | |
|--|---|
| | <ul style="list-style-type: none"> • Little to no hazardous chemicals used compared to EGS |
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2.1. Types of Closed-Loop Geothermal Design

In terms of design, closed-loop geothermal well can be categorized into three types (Figure 4): co-axial design, multiple string, and u-shaped or well known as u-loop design (Sun, F. et al., 2018; Yu, H. et al 2019).

- Co-axial design:

This design consists of two tubes and an annulus between the inner and outer tubes. During co-axial CLGS operation, low temperature working fluid is injected through the outer tube from the wellhead, heated by the surrounding formation as it descends to the well bottom, and then extracted with good adiabatic performance from the inner tube. Currently, this design is very massively to be developed since the development cost more efficient than other design (Hu et al, 2020).

- Multiple string design:

This design consists of the bottom part of the well is filled with liquid (e.g., water) and the upper portion being filled with gas (e.g., nitrogen). However, geothermal wells with multiple string designs always require a large borehole diameter due to the difficulty of constructing geothermal wells with two tubing. Multiple string configurations are typically suitable for shallow geothermal resources (Hu et al, 2020; Riahi et al, 2017; Hasan et al 2016).

- U-shaped design (U-loop):

U-shaped well design consists of two vertical wells connected by a horizontal well. As shown in Figure 4, U-shaped wells have a greater contact area than other well designs, which can improve thermal efficiency. However, the cost of two vertical wells and one horizontal section are significantly higher than that of other single-well designs, creating economic concerns for the development of CLGS using this design. (Hu et al, 2020). The difficulties of joining the wells in the horizontal section is also currently one of the major challenge for this concept.

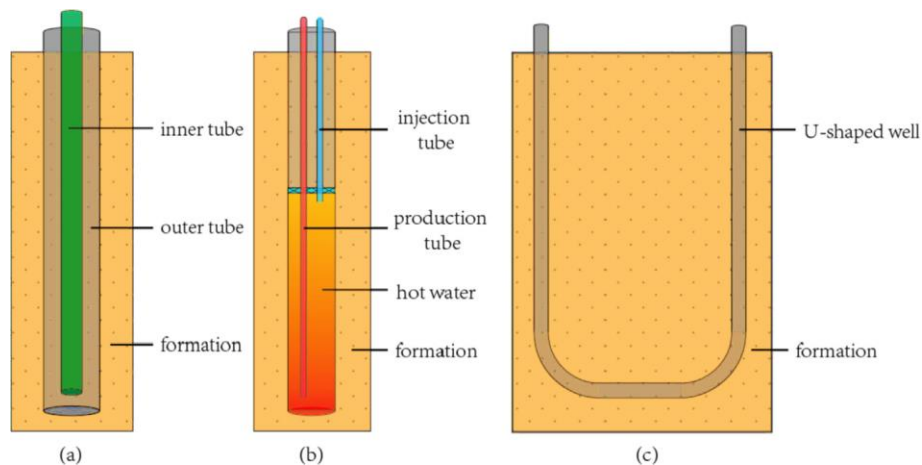


Figure 4. Fundamental designs of CLGS: co-axial design (left), multiple string design(middle), U-shape design (U-loop) (right) (Hu et al, 2020).

In summary, the closed "U-Loop" system does not require subsurface permeability because sealed wells "pipe" the heat transport fluid through the hot rock and to the surface for energy production. An alternative CLGS well configuration includes a tube-in-tube assembly (an insulated concentric tube), generally a vacuum-insulated tube (VIT), that can be put within a single well bore. Heat is transferred from the rock to the well casing and then to the working fluid via conduction. (Muir, J. R., 2020; Horn et al., 2020).

2.2. Closed-Loop Configuration

Figure 5 shows current potential application of closed loop geothermal systems:

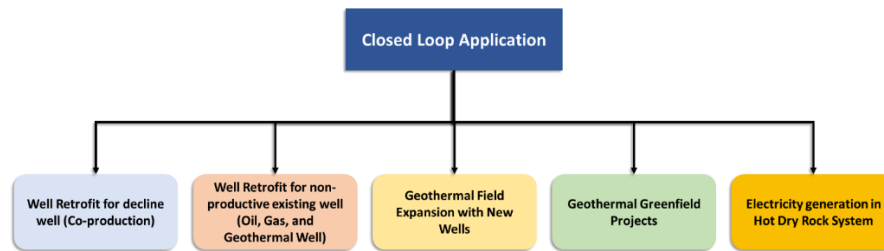


Figure 5. Closed loop potential applications for electricity generation.

2.2.1. Retrofit for declined geothermal well

Study by the World Bank revealed that approximately 22 percent of geothermal wells worldwide "fail" due to insufficient brine production, high non-condensable gases (NCGs), low wellhead pressure, corrosive brine, and inadequate permeability. Often, remedial well "workovers" involve costly and hazardous additional drilling (World Bank, 2003). CLGS well retrofit is proposed to become a solution, it can generate electricity from unproductive wells with less risk and expense than workovers. This becomes more appealing as the price of plugging and abandoning wells rises. Moreover, the possibility of repairing failed new wells with low-cost, closed-loop retrofits effectively reduces the risk of new projects as tested in Coso geothermal field in US (Muir, J. R., 2020; Horn et al., 2020).

The retrofit of CLGS Down-Bore Heat Exchangers (DHX) in theory can raise electrical generation at underperforming geothermal wells (Horn et al., 2020). The primary benefit of DHX is that the working fluid is exposed to higher brine temperatures near the bottom of the DHX compared to surface temperatures. Consequently, the working fluid reaches the surface at a higher temperature than the geothermal brine produced. A key advantage of using water as the working fluid is the production of steam that does not contain contaminants transported from the subsurface, such as natural chlorofluorocarbons, salts, radioactive isotopes, or metals. Similarly, when sCO₂ is the working fluid, expansion of heated sCO₂ generates power (Muir, J. R., 2020). In short, water or alternative working fluids, such as ORC fluids and supercritical CO₂, are used in this configuration. It helps to maintain power delivery at contracted levels and improves infrastructure and transmission return on investment (Greenfire, 2022).

2.2.2. Retrofit for non-productive geothermal or oil and gas well

As discussed previously, the well for conventional power production needs to encounter high temperatures and high permeability to be able to economically produce. Currently, geothermal well with high temperatures but low or tight permeability cannot be used for production. If the heat from such wells can be extracted economically, it may give new life for those wells and increase the overall productivity of the geothermal field.

The other application is for relatively high temperature oil & gas well. Indonesia has thousands of mature oilfields that have been exploited for many years and reaching the end of productive life. Some of the wells have a high percentage of water-cut with above 95% and categorized as high pressure and high temperature well with current status is abandoned or plan to be abandoned later. Since several mature oilfields have the potential to be extracted due to their high temperature, the produced water-cut also can be utilized as the working fluid for the geothermal power plants.

2.2.3. Geothermal field expansion

CLGS also have potential to be applied in existing conventional geothermal field by drilling new wells in the hot but tight permeability area to gain additional generation of electricity. However, it should be noted that robust financial modelling is required to determine the feasibility of CLGS application in proposed field compared to with targeting conventional hot and high permeability area.

2.2.4. Geothermal greenfield projects

CLGS can become solution of extraction limitation in geothermal field that previously might be concerned as "non-prospect area due to low permeability and acidic fluid" by geothermal developers and governments since its applicability does not rely on the permeability and fluid type (Horn et al., 2020). CLGS with multiple coaxial wells driven by multiple pads in a coaxial tube-in-tube configuration might be suitable. There is no requirement for process water as only heat is extracted. The only form of heat transfer is conduction, but convection will improve performance.

2.2.5. Electricity generation in Hot Dry Rock System

Closed loop geothermal system is on of alternative solution for extracting heat energy from hot dry rocks system, instead of the more common fracturing concept to introduce artificial permeability and fluid flow.

2.3. Worldwide Experience

Closed loop geothermal system is still considered as a new solution and technology that makes application is still few in worldwide. Based on published literature, some of the pilot project of CLGS for power generation are in Alberta by Eavor Technologies and in Coso geothermal field at United States by Green Fire Energy. The list of pilot projects, study, modelling, sensitivity, and the proposed method is summarized in Table 2.

Table 2. Summary of worldwide experiences in applying closed loop geothermal system (CLGS). (Modified and updated from Beckers et al., 2022).

Country/ Field	BHT	Depth	Closed loop Implementation Type	Closed loop Design	Flowrate	Fluid type	Summary
Alberta- Canada/- (Pilot Project)	75 °C	2.4 km	Greenfield Projects	U-loop	N/A	Not reported	Eavor-Loop technology demonstration project in Alberta, Canada; thermal output on the order of 800 kWth (Eavor, 2021; Vany et al., 2020)
California – United States / Coso (Pilot Project)	120 °C	330 m	Well Retrofit	Co-axial with brine flow in annulus	23 to 30 kg·s ⁻¹ for water; 1.5 to 5.5 kg·s ⁻¹ for sCO ₂	Water and sCO ₂	Green Fire Energy Inc. conducted a field demonstration of a CLG system using a DHX to extract heat from an existing but unproductive well in Coso, California. The DHX included the insertion of a VIT string and associated surface equipment into the well. Both water and sCO ₂ were evaluated as potential replacement working fluids. The project team conducted a variety of tests. Although power generation is directly proportional to thermal surface area, the DHX could only be 1,000 feet long due to financial constraints. Clearly, the production of energy could increase with a longer well (Muir, J. R., 2020). sCO ₂ tests solely driven by thermosiphon effect with power production ranging from 5 to 30 kWe validated their models and indicated a maximum power output of 1.2 MWe. (Amaya et al 2020; Higgins et al., 2019)
China/Weihe Basin (Simulation Study)	69.8 °C	2.6 km	Greenfield Projects	Co-axial	N/A	Water	The tentative heat performance capacity increases from 246.72 kW of 2,000 m DBHE to 548.45 kW of 3,000 m DBHE (Cai, 2022).
United States /Newberry (Simulation Study)	330 °C	879.5 – 3,067 m	Well Retrofit	Co-axial	3 to 5 kg·s ⁻¹	sCO ₂	The best-case scenarios that offered maximal thermal efficiency was: 5 kg/s, with a resulting thermal output qTh = 1.50 MW. (Doran, 2021)

3. POTENTIAL CLOSED-LOOP APPLICATION IN INDONESIA

3.1. High Temperature, Tight Permeability Well

The difficulties of finding the “sweet spot” with high temperature, sufficient permeability, and benign fluid for geothermal production in Indonesia is one of the major exploration challenges in Indonesia. Even during the development phase, due to the significant heterogeneity of the subsurface condition, the drilling success rate cannot reach 100% (Purba, Adityatama, Umam, & Muhammad, 2019; IFC, 2013; GeothermEx, 2010).

Figure 6 shows the temperature profile of two exploration wells in East Nusa Tenggara (left) and East Java (right). Note the conductive temperature profile in those two wells, indicating the tight permeability. Even though lack of permeability and currently cannot be produced, the temperature in those two wells is still very high with relatively shallow depth compared to the closed-loop concept that aims to drill up to thousands of meter deep.

The closed-loop geothermal application is one of the alternatives to bring new life and use for this type of well, which are commonly found in geothermal exploration in Indonesia.

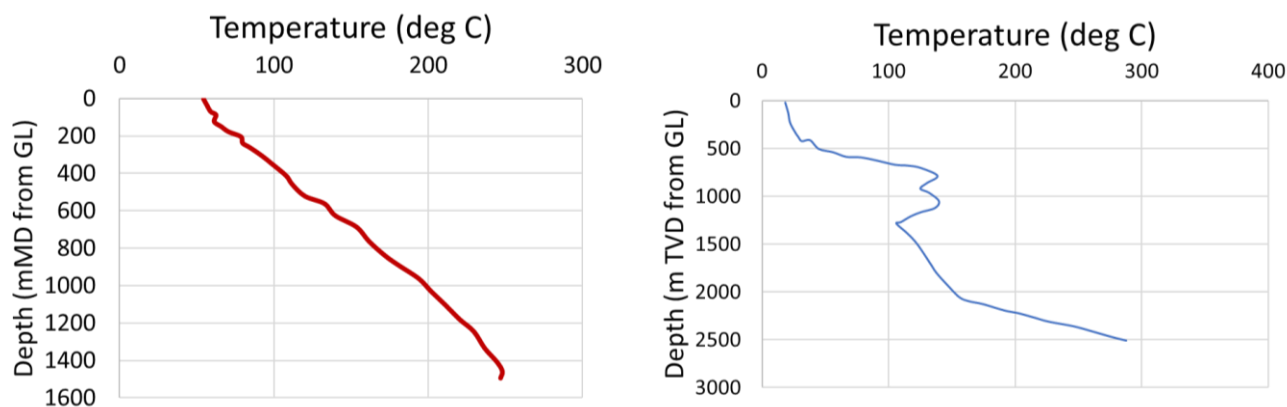


Figure 6. Left: temperature profile of an exploration well in East Nusa Tenggara. Right: temperature profile of exploration well in East Java.

3.2. Wells with Declined Production

Apart from the hot but tight permeability wells discussed previously, there are some wells in Indonesia that has severely declined production. Even though those wells are still hot, they cannot be produced economically anymore, and some of them are only routinely bled to prevent gas accumulation.



Figure 7. Declined wells in East Nusa Tenggara. Those wells are not connected to the production facility anymore, and just being bled to prevent gas accumulation.

4. SUMMARY, CHALLENGES, AND PATH FORWARD

- There are numerous non-commercial geothermal wells in Indonesia with high temperature but limited permeability.
- Worldwide pilot projects such as in Coso has demonstrated that the existing wells can be retrofitted with CLG technology.

- CLG has the potential to be applied in non-commercial or non-productive geothermal wells in Indonesia.
- Further research on heat transfer parameter between formation, pipe, and working fluid is required. After that, the simulation model can be made for designing the pilot project.
- After further research done, pilot project can be done to prove the technical and financial feasibility of the concept.
- Indonesia has lots of non-commercial well that can be used for pilot-project.

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