UNITED NATIONS UNIVERSITY
UNU-GTP
Geothermal Training Programme

Orkustofnun, Grensasvegur 9,
IS-108 Reykjavik, Iceland

Reports 2018
Number 26

DIENG GEOTHERMAL PROJECT: RISK ASSESSMENT FOR A DECISION ON 60 MW EXPANSION

Gloria Gladis Sondakh
PT Geo Dipa Energi (Persero)
Recapital Building, 8th floor, Aditiawarman Street, Kav. 55,
South Jakarta 12160
INDONESIA
Gloria@geodipa.co.id

ABSTRACT

Dieng is one of the prospected geothermal fields in Indonesia with an estimated field development potential of 350 MWe. Presently, one 60 MWe power plant unit has been installed and the current production is around 46 MW. Dieng geothermal power plant is owned and operated by PT Geo Dipa Energi (GeoDipa), a state-owned company. GeoDipa is implementing a phase development for the field. Unit 1 has been in operation since 1998 and now GeoDipa plans to add another 60 MWe unit. The Unit 2 project is still in feasibility stage and the feasibility study is currently being updated. In the development of Unit 2, there are risks that need to be considered before a decision can be made. Therefore, in this report, the risks associated with Unit 2 project are identified and appropriate mitigation actions are listed. The key risks have been identified to be resources and technical risks which are related to scaling and corrosion in production wells, turbines and the Fluid Collection and Reinjection System (FCRS). To mitigate scaling, methods such as hot water reinjection, pH modification, inhibitors, cold water injection and retention tank have to be studied further. Several environmental risks are also analysed and should be mitigated prior to a decision on the Unit 2 project.

1. INTRODUCTION

1.1 Background

The Dieng geothermal field is one of the most prospected geothermal fields in the Central Java Province, Indonesia. The area is 63 km^2 in size with an estimated field development potential of 350 MWe. It is a high-temperature field with surface manifestations such as fumaroles, hot spring and acidic mud pools. These are distributed in three areas, Sileri, Sikidang and Pakuwaja. Sileri is located to the northwest with fluid temperatures around 300˚C and acid-sulphate-chloride type hot springs. In the central Sikidang area, fluid temperatures at depth are around 300°C and content of non-condensable gasses (NCG) is high, mostly CO_2. Sileri and Sikidang are craters that consist of old Dieng volcanic rocks. To the southeast is the Pakuwaja area, the youngest volcano in the Dieng geothermal field which does not have the same high underground temperatures. The upflow areas of the hydrothermal systems are believed to be around Sileri and Sikidang where the fluid flows southeast, northeast and southwest along faults. These faults are the drilling targets for future production wells. Since 1975, 52 wells have been

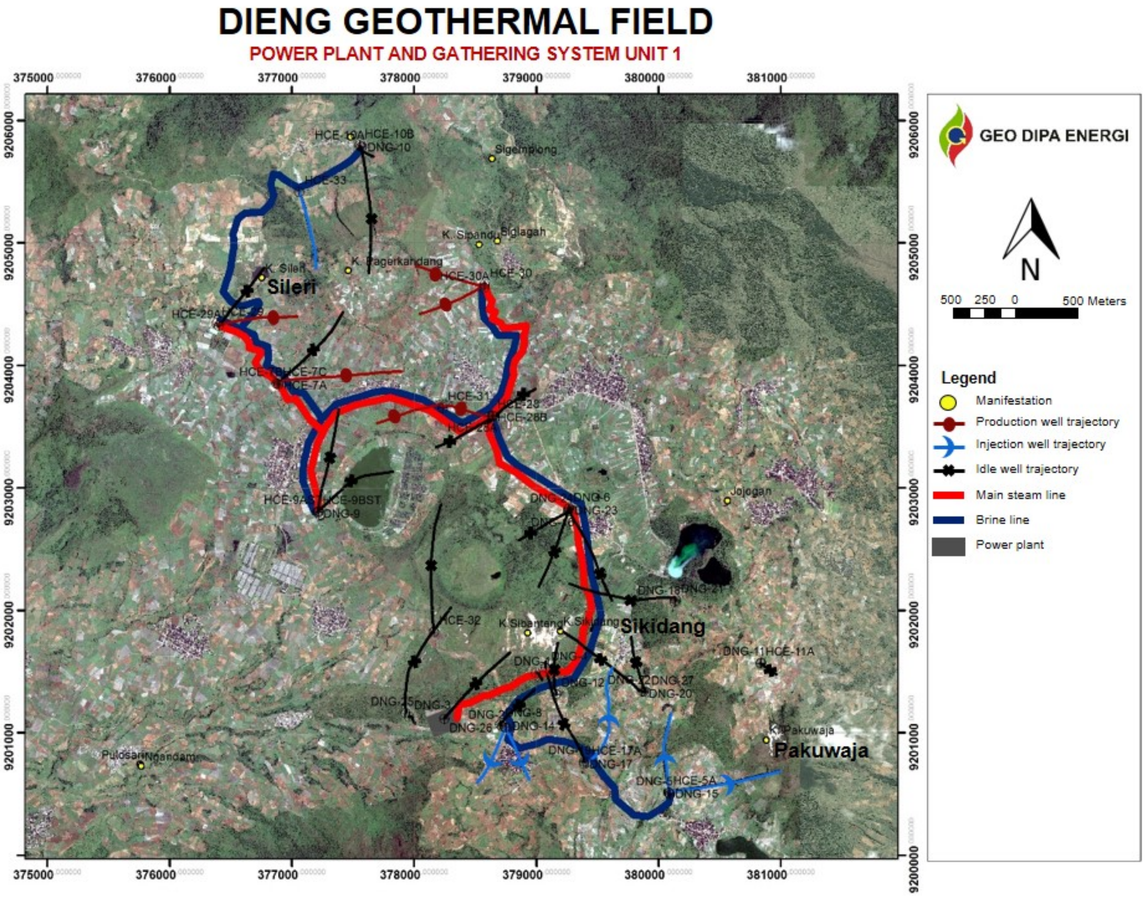


FIGURE 1: Location of manifestations, wells, steam line, brine line and power plant (PT Geo Dipa Energi, 2018)

drilled in Dieng, 27 wells by Pertamina, 20 wells by HCE and 5 slim holes for coring. Currently, only 5 production wells and 4 injection wells are operating for power plant Unit 1 (Figure 1).

The installed capacity of Unit 1 is 60 MWe and current production is around 46 MWe. In July 1998, this power plant was commissioned by Himpurna California Energy Limited (HCE). In 2002, GeoDipa, a joint venture between PT Perusahaan Listrik Negara (PT PLN) and PT Pertamina, took over the ownership of Dieng geothermal field. Since 2011, GeoDipa is a designated state-owned enterprise by Government Regulation no. 62/201.

For the operation of Unit 1, special attention is paid to the crucial issue of scaling in the production systems, turbines and the reinjection system. Deposition of silica scale has been identified widely in Fluid Collection and Reinjection Systems (FCRS), such as in two-phase flow lines, i.e. the separator and the brine line to the reinjection site. These scaling problems have affected the operational cost of the Unit 1 plant. Therefore, reliable scaling prevention methods are required to ensure future operation and development of the Dieng geothermal field.

In 2018, GeoDipa started the Unit 2 project by updating the feasibility study to identify the investment cost for a 60 MWe plant. Currently, the estimated investment cost is USD 150 million, including drilling (or workover) and testing of production and reinjection wells, the FCRS (steam, brine and condensate pipelines, valves, separators and pumps), the power plant installation (including all civil works), and the 150 kV transmission line from the power plant to PLN Dieng substation.

The GeoDipa management team and employees, who have long experience working for the Unit 1 power plant, are considered to be very well capable of operating Unit 2 in the future. GeoDipa would directly sell the electricity to PLN, since PLN is the single buyer for electricity generated from geothermal energy in Indonesia. PLN distributes the electricity from Dieng to Java and Bali.

GeoDipa has confirmed its intent to request a loan from the Asian Development Bank (ADB) which has shown interest to finance the Unit 2 project, depending on the outcome of the updated feasibility study. For the Unit 2 project, the business scheme will be semi-IPM (Intergrated Project Management), however, the long lead items will be provided by GeoDipa.

GeoDipa has the assignment rights under the Engineering Sales Contract (ESC) and obtained the PLN IUPTL (*Izin Usaha Penyediaan Tenaga Listrik /* Electricity Power Supply Business License). PLN and GeoDipa have signed a power purchase agreement for up to 400 MWe for 30 years. Before the market launch, GeoDipa needs to ensure the legal basis of the tariff adjustment in the form of an amendment to the ESC. In 1993, Environmental Impact Assessment (EIA) was carried out in Dieng area for the original 60 MWe Unit 1. For the Unit 2 development, the EIA was done in 1998 and needs to be updated.

Based on the operational experience from Unit 1, potential risks need to be assessed. In particular, GeoDipa has to emphasize risk mitigation with respect to scaling and corrosion. Moreover, GeoDipa should also consider the risks of legal and regulatory issues that may jeopardise the project (JBIC, 2006; PwC, 2013). In this report, risk assessment and mitigation on resource and technology will be discussed to ensure successful future exploitation and stable operation.

1.2 Development plan

In 2006, a feasibility study for Unit 2 was conducted by Japan Bank for International Cooperation (JBIC) in cooperation with West Japan Engineering Consultants (WestJEC). Later in 2013, PricewaterhouseCoopers (PwC) in cooperation with Electroconsult (ELC) updated the feasibility study. The feasibility study is currently being updated again and will be finished in mid-2019. This update includes a study of electricity generation and reservoir evaluation to assess the feasibility of developing the geothermal field. It will include technical designs of production wells and the design of an electric power generating system.

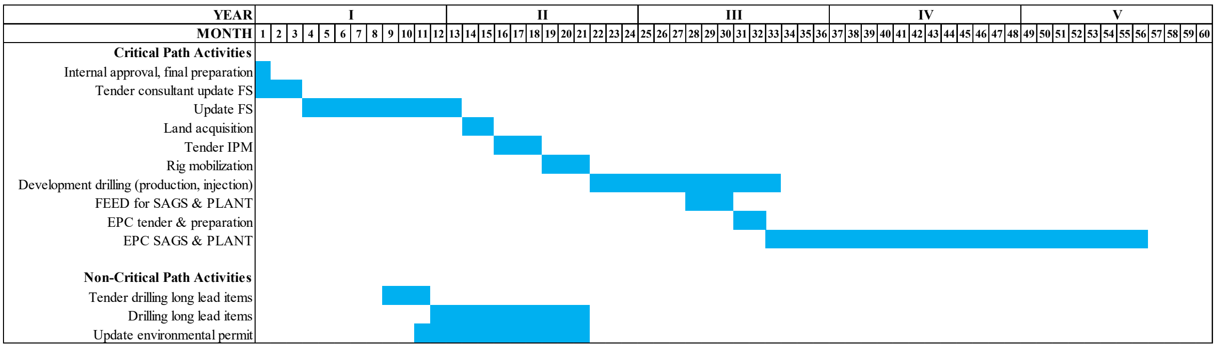
At present, geological data, geochemistry, geophysics, topography, hydrology, drilling wells, well pressure data and land use information are available on various scales and levels of detail. This data needs to be integrated to support conceptual models, reservoir modelling, well targeting, development scenarios, technology selection and drilling design. Information used in the geothermal conceptual model consists of the heat source and isothermal contour, lithology distribution, geological structure, permeability, fluid mixing and circulation patterns, upflow and outflow zones, location of rock cap and reservoir (JBIC, 2006; PwC, 2013).

In the feasibility studies done by JBIC (2006) and PwC (2013), new production and injection wells with average total depth of 2600-2800 m are proposed to be drilled to support Unit 2. The production wells should be drilled to greater depth whereas the reinjection wells can be drilled to shallower depth and be located near a separator to reduce the scale deposition problem in the reinjection system.

In the drilling program, determination of casing type, casing size, well trajectory, well depth, drilling activities, and estimated cost of drilling per well will be planned after obtaining sufficient information from geosciences and reservoir modelling. Production and reinjection drilling and subsequent well testing are needed to determine the well and field production capacity (tonnes/hour). The first tasks are to plan the procurement of items with long lead times, write documents related to the initial needs of the drilling campaign and prepare bid documents for drilling contractors, cementing and casing providers and all other supporting services needed for the drilling process. These tasks are planned to be finished in early 2021.

In addition, the feasibility study results will provide information regarding the selection of a Steamfield Above-Ground System (SAGS) and power plant by considering development scenarios, fluid characteristics, field conditions, conditions of equipment mobilization and its economy. Preparation for the SAGS and power plant will start in 2020 at the same time as the development drilling. Commercial operation is planned to start 2023 (Table 1).

TABLE 1: Dieng Unit 2 development plan



2. DECISION MAKING IN GEOTHERMAL PROJECTS

2.1 Stage gate process

The stage gate process is a set of methods that uses identifiable, systematic stages in form of a conceptual and operational roadmap to develop the project to the next "gate" or decision point. Each gate is characterized by a set of deliverables or inputs as well as a set of exit criteria and an output. This controls the process, serves as a quality check and controls the results of the process. The project team members carry out the main tasks to collect information needed to run the project from the beginning to the end. All tasks must provide information about the requirements that need to be known by the management to decide how to proceed and what actions to carry out. This ensures documentation, quality, comparability and improves project effectiveness and efficiency (Cooper, 2016).

In geothermal projects, there are several stages that must be carried out. The process is complex and takes a long time. Landsvirkjun, the national power company of Iceland, has applied stage gate in the past. An example of a stage gate process applied to geothermal projects by Landsvirkjun is shown in Figure 2 (Pálsson, 2017).

Based on the Standard National Indonesia (SNI, 1998), stages of geothermal investigation and development are related to the classification of the energy potential based on the results of geological investigations, geochemistry and geophysics, reservoir techniques and estimation of electrical equality. This can be referred to as a stage gate which in general consist of exploration, feasibility study, exploitation and utilization.

In the *exploration stage*, a series of activities is carried out to prove the existence of geothermal resources. The initial step is to do a preliminary study (reconnaissance). This study includes the analysis of geothermal manifestations (hot spring, steaming ground, fumaroles), fluid temperature at the surface and subsurface, geophysical properties and regional geology. Based on the preliminary study, an initial conceptual model of the geothermal reservoir is obtained.

Furthermore, a detailed 3G survey (geology, geochemistry, geophysics) is conducted. It contains a detailed geological mapping on a larger scale than the preliminary study. Information in the detailed geological map include rock type, geological structure, manifestation data collection, alteration

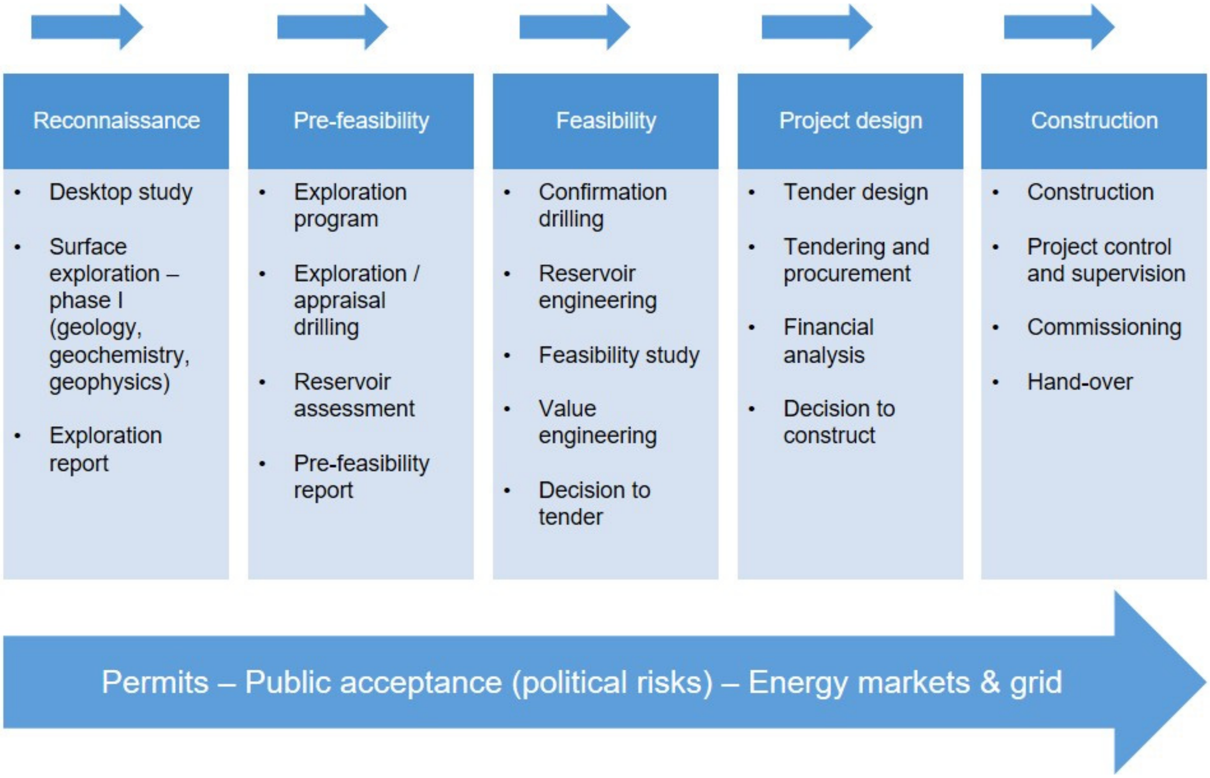


FIGURE 2: Stage gate for geothermal projects at Landsvirkjun (modified from Pálsson, 2017)

mapping, etc. Detailed geological surveys also produce information about heat sources, distribution of rocks on the surface, geological structures that control geothermal activity, permeability on the surface and reservoir rock types. In the geochemical survey, analysis of the chemical elements found in the manifestation fluids is conducted to find out whether the source is water or steam, to estimate the reservoir temperature and describe the hydrological system. This analysis is conducted to be able to estimate the up and out flow area of the geothermal resources and estimate the fluid phase (vapour, water or two phases). Geophysical surveys are carried out to map changes in the rocks' physical properties due to geothermal activity. Common methods are resistivity, gravity and magnetics.

Based on the 3G results, a reservoir study is carried out to create a conceptual model that describes the reservoir system in the geothermal area. Design of exploration wells can be included and the next step is exploration drilling. Exploration drilling is carried out to identify geological features, or collect subsurface physical and chemical data and to estimate fluid quality and quantity. Flow testing of wells and downhole logging provide vital information. The aim is to verify the conceptual model of a reservoir that was developed in the pre-feasibility study and to calculate the reservoirs' potential. Based on the results of the exploration drilling, the developer makes the decisions to continue or to abandon the project.

The next stage is *feasibility study stage* to assess the feasibility of developing the geothermal field. This study analyses technical, economic, legal and operational aspects. That includes reservoir evaluation, technical design of production wells, electricity generation systems and risk identification. The capacity of the geothermal power plant will be estimated. In addition, studies on the social and environmental impacts are also carried out at this stage. Output of this stage is a feasibility study report that can be used to acquire project funding (SNI, 1998; Azimudin, 2018). Referring to Pálsson (2017), a feasibility study report typically includes:

- Owners statements, presenting experience and financial, managerial and organizational capacity of the development company to execute the construction and operation;
- A brief project description;

- Project justification, such as market reasons;
- Project execution strategy, i.e. for procurement, funding, management, etc.;
- Timeline from project preparation to commissioning;
- Budget, i.e. funding required to run the project and a financial plan on how to pay for all costs;
- Financial models and assumptions.

The *Exploitation stage* is a stage to achieve capacity targets. During this stage, main activities are production and injection wells drilling. All wells are tested to determine production capacity. In addition, construction is also initiated by creating a FEED as the basis for the FCRS and power plant development. The construction period ends with power plant commissioning and the Commercial Operation Date (COD) between the developer and the buyer of the electricity production (SNI, 1998; Azimudin, 2018).

In the *Utilization stage* geothermal energy can be harnessed in two ways, direct and indirect. Direct use is the use of geothermal fluid for non-electrical purposes while indirect use is electricity generation by a power plant (SNI, 1998). For successful power plant operation, comprehensive monitoring of the geothermal field (production/injection, reservoir temperature, pressure, fluid chemistry and environmental effects) is required and the reservoir model needs to be regularly updated to predict possible changes in reservoir characteristics, to ensure good productivity/injectivity and to maintain suitable fluid chemistry during long-term operations (Steingrímsson, 2009; Richter, 2018).

2.2 Phase development

In the development of geothermal fields, especially in fields that have great potential, geothermal developers must be able to define the project. Developers need to optimize investment to get the highest income possible from the start of production onwards (Pálsson, 2017). Information regarding geological conditions, available information about resources, institutional and regulatory climate, access to appropriate financing and other factors greatly influence the development of geothermal projects (Gehringer and Loksha, 2012).

The development phase of a geothermal power plant can follow two approaches. The first approach is the single-phase development approach where the full capacity/size of the field is developed. The second approach is a phased development where the full capacity of the field is explored in stages over a period of time. For example, when a geothermal field has high potential, the developer has the option to start production by installing several geothermal power plants to achieve maximum capacity instantaneously (single-phase development) or by installing the geothermal power plants gradually in several relatively small steps (phase development). Development in the consecutive phase generally has a lower risk based on the experience from the initial phase (Pálsson, 2017).

Based on Gehringer and Loksha (2012), a potential project developer is essentially faced with three choices:

1. Go ahead immediately with production drilling and risk project failure;
2. Undertake test drilling and possibly reduce the risk of project failure through the knowledge gained;
3. Decide that the prospect is not sufficiently attractive to make it worthwhile risking money, even for testing purposes.

With the experience from Dieng Unit 1, GeoDipa plans to initiate the next phase which is building and operating of Unit 2, a new power generation unit for 60 MW. This project is included in the National Energy Plan and PLN Electricity Supply Business License (IUPTL) which reflects GeoDipa's commitment to support the Government of Indonesia's plan to achieve the energy mix target through the development of geothermal renewable energy. In the scenario of developing renewable energy according to National Energy Policy and General Plan for National Energy in Indonesia, electricity production from geothermal energy has to reach 7242 MW by 2025 and GeoDipa will contribute to achieve the target by developing Unit 2.

2.3 Risk and return

In geothermal power projects, there are two main risks which are interlinked: resource risk/exploration risk and financing risk. Resource risk relates to the difficulty of estimating the capacity of geothermal field resources. Resource risk will be discussed further in Section 3. Financing risk relates to the long lead time (time lag) between the initial investment and the start of revenue while the initial investment capital is very high.

Geothermal project costs increase gradually at each stage of development. Along with the progress of the stages in the project, uncertainty decreases. During the drilling stage, the investment costs required for each well are quite high with while certainty is low, especially when drilling in a green field. The risk of geothermal projects in green fields is higher than in brown fields, so the risk premium required by investors/financiers is higher in a green field. A high-risk premium on capital cost or risk sharing is required by the financier for the project (Gehringer and Loksha, 2012) and most of the developers are not able to fund 100% of the projects. Investors will provide loans for commercial rates and conditions when the existence of a sufficient resource has been proven. While the resources in geothermal projects have not been proven, investors will seek higher returns than their investments with a return range of 22-30% (base leverage-equity) or 14-18% (100% equity base) (Quinlivan et al., 2015).

Risks in operating power plants, such as prolonged breakdown and other downtime, generally affect the company's profit and investment. Therefore, it is necessary to make a proper prevention and maintenance schedule (Ngugi, 2014). Some geothermal projects have experienced events that have a major impact on the project economy and the most common mistakes are inadequate steam availability or reinjection capacity (Pálsson, 2017).

2.4 Decision making

From project planning to production, various obstacles can interfere with project development. In the initial stage, the most common constraints are land and environmental permits that can prohibit geothermal development in the area. Some geothermal fields are in protected forests, conservation forests and national parks. Or local communities can refuse geothermal development in the area (Ouko and Ómarsdóttir, 2015; Poernomo et al., 2015).

Key challenges are the availability of reliable resource information, access to transmission infrastructure and lack of policy sustainability, creating an ambiguous view of economic certainty. When development starts, geothermal developer must pay attention to various factors such as reservoir pressure and temperature, production capacity and injection, pipelines and power plants and all these factors must be monitored regularly. Lack of 3G data results in low accuracy when estimating the potential. In some cases, wells have been drilled that are not suitable for production purposes, causing financial losses. This adds to the high level of risk in the early stages of geothermal development. In addition, geothermal technology is generally a barrier to development due to high costs. Therefore, it is important to have experts involved in all stages of geothermal development (Ouko and Ómarsdóttir, 2015; Poernomo et al., 2015).

Together with the development of Unit 2 project, GeoDipa is also developing a small-scale generator (11 MWe gross) and a binary power plant as complimentary to Unit 1, so the commercial scheme (base price, escalation, contract period) can follow the existing Dieng ESC of Unit 1. The Commercial Operation Date (COD) for the small-scale generator is expected in 2019 and for the binary power plant in 2020. The Unit 2 project will increase energy efficiency in Dieng, i.e. increase the electricity production capacity and improve GeoDipa's profit and cash flow as well as strengthen cash flow for development of new units. Asset optimization will also be carried out for using less productive assets (damaged wells) in Dieng geothermal field.

During the operation of Unit 1, GeoDipa has encountered issues with silica deposition in two-phase facilities and the brine management system that are likely affect future power plants in Dieng. Therefore, it is necessary to carry out a risk assessment to mitigate the probability of the same problems as in the operation of Unit 1. A proper brine management system and other technology needs to be installed in Unit 2. GeoDipa has conducted problem mapping and discovered there are 4 other main possibilities to enhance power production from the Dieng geothermal field. These include clearing production well blockages, increasing Unit 1 steam supply to full load and thus increase production, improve steam field surface facilities and constrain the monitoring program. To overcome these issues, several technical solutions have been carried out simultaneously since 2012. There were investigations and workovers on production and injection wells, Front End Engineering Design (FEED), Engineering Procurement and Construction Commissioning (EPCC), tie-in facilities and supporting equipment. Performance tests and remaining life assessments of turbine equipment were also conducted in the power plant. As a result, production increased from 45.31 MW to 52.56 MW (Meliala et al., 2015).

3. RISK FACTORS FOR GEOTHERMAL PROJECTS

The cost of developing geothermal projects varies greatly between stages. Starting with low cost in the planning, mapping and survey stages, it increases significantly during the well drilling stage (up to 5-10 M USD per well) and the construction of power plants (Figure 3). The probability of success is low in the early stages of development, especially in the exploration stage which has a high level of uncertainty (Pálsson, 2017). The upstream stages and especially the test-drilling stage, are usually considered the riskiest parts of geothermal project development, reflecting the difficulty of estimating the resource capacity of a geothermal field and the costs associated with its development (Gehringer and Loksha, 2012). After test-drilling, the risk reduces but the cost becomes higher since the cost for SAGS and power plant construction constitute up to 60% of the total cost the project (Pálsson, 2017).

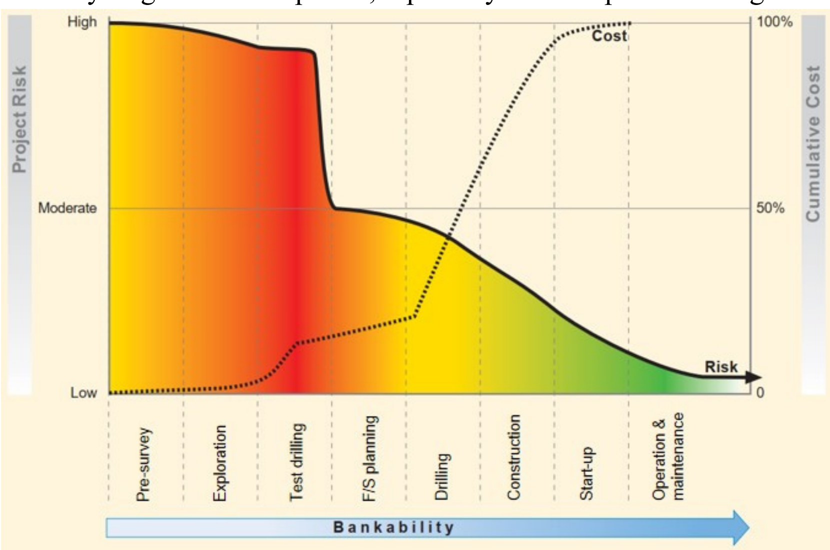


FIGURE 3: Project cost and risk profile during development stages (Gehringer and Loksha, 2012)

3.1 Resource risk

Resource risk is unique to the development of geothermal prospects where each field has different development characteristics and challenges. Resource risk falls into several categories, such as existence, size, suitability and utilization challenges. Exploration risk is related to geological risk where the certainty of a prospect is the key to success. In the exploration stage, information about the resource size, temperature and permeability is very limited (Ngugi, 2014).

Uncertainty about quality and quantity of resources affects parameters which determine the design and size of power plants, technology and other engineering aspects (Matek, 2014). However, uncertainty of resources and risk will remain high until a deep well has been drilled that actually penetrates the geothermal reservoir. There are three categories of geothermal resource risks, including drilling and well completion, initial well characteristics and resource degradation over time. Resource risks associated with the characteristics of the initial well are (IFC, 2013; Robertson-Tait et al., 2018):

- Well filled by drill cuttings or casing collapses;
- Inadequate flow capacity due to permeability and thickness of productive reservoirs that are too low for commercial production;
- Inadequate temperature which is the effect of lithological variation and convective heat flow that causes inaccurate temperature projections;
- Inadequate pressure where static reservoir pressure is too low and may not be sufficient to allow sufficient flow for commercial use; and
- Unacceptable chemical problems where the fluid produced contains high levels of total dissolved solids or non-condensable gases, presence of elements causing corrosion and scaling in reservoir or in power generation systems.

Failure of geothermal development and growth can happen when risk assessment and management are not carried out (Hadi et al., 2010). Decision making as the key to successful, low risk development can be supported by having proper work strategies in place. They include rigorous scientific studies both at reconnaissance and exploration stages, the integration of 3G data, recognition of hazards or barriers to development, and the regular testing and update of conceptual models incorporating newly gained information (Bignall, 2013). Three interrelated surveys (geological, geochemical and geophysical surveys) are needed to mitigate the risks (Sarmiento, 2011). With detailed information gained from quality 3G data in the early stages of the project, risks and uncertainties decrease. Resource characteristics that should be considered in the construction of power plants are as follows (Matek, 2014; Hadi et al., 2010):

- Reservoir temperature is obtained from geochemical data, specifically geothermometry surveys of samples from fumaroles and boiling chloride springs give direct access to the reservoir properties. Geochemical data is required to estimate the resource temperature at depth, the origin of the resource, locations of aquifers, mixing between aquifers, sources of recharge and pathways of discharge. Geochemical data is also useful to mitigate risks that have the potential to influence the operational activities of power plants, such as scaling, corrosion and concentration of non-condensable gases.
- Reservoir size (volume) is estimated from the reservoir area, thickness of the reservoir, and reservoir porosity. Reservoir size can be obtained from a geophysical survey which delineates the reservoir boundaries, later confirmed by drilling.
- Reservoir permeability is a measure of how easily geothermal fluids can move through a fault/open structure which is the exploration target and is confirmed by drilling. Data required to estimate the permeability are integrated surface and subsurface data and if available, correlation with drilling results from similar fields.
- Fluid enthalpy is the amount of thermal energy contained in the reservoir fluid per mass unit and is governed by temperature, pressure and chemical composition of the fluids. Fluid enthalpy is obtained from the geochemistry of fluids from surface manifestations. It is useful for selecting power generation technology, estimating engineering design costs, and deciding the number of wells.

When identifying promising drilling areas, there are several parameters needed to support good decision making, such as (Sarmiento, 2011):

- Suitable temperature estimated from chemical geothermometers;
- Existence of structural features and lineaments as possible source of permeability;

- Large size anomaly identified by MT/TEM or other resistivity surveys;
- Benign chemistry of reservoir fluids; trace of acid fluids is acceptable;
- Proximity to load centre and transmission grids;
- Exceptions are those that may be in conflict with government laws, ancestral domain or indigenous acts and other environmental restrictions.

According to Sanyal and Morrow (2010), there are several measures that can be used to describe the risk of geothermal resources, such as potential resource base (MW) and drilling success rate (%). In principle, the greater the resource base, the greater the potential for development and the larger the economic scale. The drilling success rate is defined as the percentage of successful wells in a series of drilling activities in a field. The drilling success can also be calculated from the average drilling cost per MWe capacity achieved in the drilling program. Another key figure is the unit capital cost (USD/kW) which is the capital cost per MW of installed power capacity. These costs consist of drilling, well testing and other resource supply costs as well as power plants and SAGS.

Average drilling success rate in the different project stages (exploration, development and operation) have improved from the 1960s to the 2000s (Figure 4). Geothermal developers and drilling companies are more capable of handling the drilling risks, resulting in decreased risks (IFC, 2013).

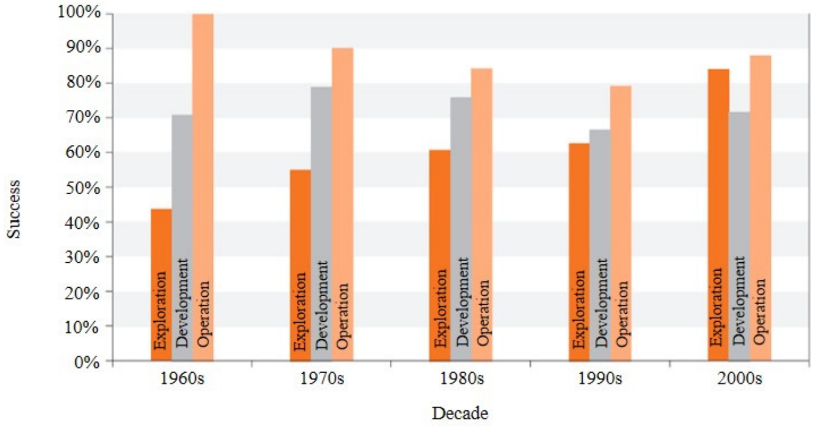


FIGURE 4: Drilling success rate (modified from IFC, 2013)

3.2 Technical risk

In geothermal utilization, various technical problems need to be addressed. Insufficient permeability is a problem where the production or reinjection wells are not intersecting fractures or permeable formations. Casings and pipelines can become damaged by thermal stress or bad cementing, leaks on wellhead flanges and valves, and leaks on valve glands and flanged connections (Thórhallsson, 2018).

A common problem in some geothermal fields is scaling. Scaling and corrosion in wells and surface installations is caused by the chemistry of geothermal fluids and flow properties such as pressure, velocity and flow pattern (laminar, turbulent, etc.). Fluids containing high concentrations of minerals and gases typically cause such problems (Gunnlaugsson et al., 2014). Geothermal fluids have different chemical characteristics and conditions. The chemical composition depends on several factors including geological resources, temperature, pressure and water sources. Most scaling is usually caused by precipitation of sulphide, calcium and silica depending on concentration, fluid pressure, temperature and pH of the system. Silica scales form in response to the concentration and cooling, sulphide forms in response to cooling, and calcite forms in response to degassing and pH change. Sulphide scales have been observed in high- and low-/medium-temperature resources and causes plugging of the brine flow in production wells with two-phase flow. The scale is usually very hard and difficult to handle. Calcium scales consist of calcium carbonate and calcium silicate. The calcium carbonate scale causes problems in medium-temperature wells. They are difficult to clean by drilling but dissolve easily in hydrochloride acid (HCl).

The most difficult and challenging scale type in geothermal operation is silica because it forms an amorphous silica scale. In flashed-steam systems, there is usually a significant drop in fluid pressure from the well to the turbine. In many cases, the geothermal fluid becomes supersaturated with silica as it is cooled. A pressure drop that exceeds the saturation limit can cause super-saturation followed by silica deposition in geothermal surface facilities. Further cooling can lead to higher silica saturation in disposal brine, so that greater scale silica precipitation will occur in reinjection wells, piping, heat exchangers and other production facilities. Risk of silica scaling around the turbine is related to minor concentration in the steam which causes the blockages, thereby reducing electricity production. Therefore, the separator needs to be designed as well as possible to avoid incomplete separation. Silica scaling formation and deposition is slower than carbonate scale but far more difficult to remove from the facilities (Koenig, 2016).

Corrosion attacks occur in some geothermal operations and cause damage to equipment which results in product loss, inefficient operation and downtime for equipment maintenance and replacement and increased production costs. In general, these problems are mostly localized in geothermal construction and installation, especially in the brine gathering system, injection lines and wells. Therefore, a proper material selection, operation and maintenance is important for the design of geothermal utilization to prevent the corrosion (Datuin and Gazo, 1989; Miller, 1980, Gunnlaugsson et al., 2014).

Another issue is steam purity caused by non-condensable gases (NCG) in the steam. Insufficient gas extraction capacity of NCG vacuum equipment will reduce the vacuum and affect the conversion efficiency. The gases are quite toxic, especially hydrogen sulphide (H_2S) and carbon dioxide (CO_2). In certain circumstances, NCGs, may need to be disposed of and this situation needs to be carefully considered and planned for in the design. Proper atmospheric dispersion is very common, but in some countries regulation require the installation of a gas abatement system (Hochwimmer and Kretser, 2015; Thórhallsson, 2018).

In cooling towers, clogging up by sulphitephylic bacteria is a known problem. From the condenser, some of the condensed steam is transferred to the cooling tower as make up water. Here, deposition of sulphur compounds and thriving of various bacteria can occur. The sulphur deposits and bacteria colonies are removed by using high-pressure washing and wet vacuum cleaners periodically to suck up the loosened material (Elíasson et al., 2008; Thórhallsson, 2018).

Thórhallsson (2018) describes solutions for technical risks as listed in Table 2:

TABLE 2: Solutions for problems in geothermal generation

Solutions	Method
Prevent scaling	Maintain high enough temperature to avoid silica scaling. Chemical modification (control of pH by acid injection). Scale inhibitors. Maintain good steam purity to turbine with low total dissolved solids.
Rehabilitation of a well or pipeline	Reaming with a drilling rig to remove scaling. Drill a new well – sidetrack. High-pressure washing. Clean with acid (carbonate) or caustic (silica) to dissolve the scaling. Install new liner or a casing that is cemented in place.
Good maintenance practices	Immediate sealing of leaks Maintain wells hot at all times Avoid outside corrosion on casing in cellar floor Programme to recalibrate gauges

3.3 Environmental risk

Geothermal activities, both in low-temperature and high-temperature fields, have impacts on the environment (Table 3). The exploitation stage, especially drilling operations, have the greatest impact to the environment as they can cause noise, fumes and dust that have direct effect on humans and animals. The environment is affected by the construction of access roads to drilling sites which can involve destruction of forests and vegetation which can cause erosion, especially in tropical regions with high rainfall, such as Indonesia and the Philippines (Hunt, 2000).

Health, Safety and Environment (HSE) risks in drilling activities relate to hazards that have the potential to affect personnel, property and the environment around drilling activities. The risks posed to personnel in form of toxic gases varies widely from reservoir to reservoir. The major constituents are CO_2 and H_2S which are release from the well. Exposure to atmospheric concentrations of these gases poses potential hazards to public and occupational health. The effect of H_2S depends on the length of exposure, frequency and intensity. and can cause respiratory paralysis, irregular heartbeat, collapse and death. The effects of CO_2 are shortness of breath, dizziness, mental confusion, headache and possible loss of consciousness. Further, there are risks to security of equipment and personnel such as exposure to falling objects from overhead works, derrick jobs and drilling personnel exposed to wild animals, especially in remote areas. Another risk that affects the environment is improper disposal of drill cuttings. Drill cuttings are not toxic but the amount of waste from drilling is very high. Air pollution due to diesel usage also affects the drilling environment in remote areas that have no access to electricity (Okwiri, 2017).

In the construction stage, the installation of gathering systems in volcanic environments that have high topography and terrain can be risky due to lahar flow paths, areas of steaming ground, and areas with hydrothermal eruptions (Hochwimmer and Kretser, 2015).

TABLE 3: Environmental impacts on geothermal fields (modified from Hunt, 2000)

	Low-temperature systems	High-temperature systems	
		Vapour-dominated	Liquid-dominated
Drilling Operations:			
Destruction of forests and erosion	●	●●	●●
Noise	●●	●●	●●
Bright lights	●	●	●
Contamination of groundwater by drilling fluid		●●	●●
Mass withdrawal:			
Degradation of thermal features	●	●●	●●●
Ground subsidence	●	●●	●●●
Depletion of groundwater	○	●	●●
Hyrdrothermal eruptions	○	●	●●
Ground temperature changes	○	●	●●
Water liquid disposal:			
Effects on living organisms			
surface disposal	●	●	●●●
reinjection	○	○	○
Effects on waterways			
surface disposal	●	●	●●
reinjection	○	○	○
Contamination of groundwater	●	●	●
Induced seismicity			
Water gas disposal:			
Effects on living organisms	○	●	●●
Microclimatic effects	○	●	●
○ No effect; ● Little effect; ●● Moderate effect; ●●● High effect			

In the utilization stage, noise is caused by the generation unit and toxic gases can be emitted by the power plant. In addition, cooling tower emission containing toxic water droplets derived from condensate vapour used as cooling water can cause a phytotoxic effect on vegetation.

Geothermal powerplants can pose health risks to local communities such as the inhalation of toxic gases and pollution of ground water. Ground water consumed by the local population can become contaminated with arsenic. With the existence of environmental risks like this, it is vital to increase awareness of the effects of geothermal operations.

The local community can reject power plant operation because they fear impacts on the tourism industry and farming. These conflicts can lead to the cancellation of the geothermal project. Therefore, developers must pay attention to the needs of the community (Berrizbeitia, 2014; Layton et al., 1981).

In the development of geothermal energy, there are risk associated with every stage of the development and it is essential that geothermal developers take care of environmental conditions. Therefore, mitigation is needed to limit impacts on air, water, agricultural land and wildlife habitats. In addition, developers have to consider the needs on the local community such as road improvements, public health and other facilities like schooling and housing (Koenig, 2016).

3.4 Other risks

Apart from resource, technical and environmental risks, there are some other risks that must be considered in geothermal projects:

- Political, law, regulation and permits;
- Stakeholders;
- Development plans;
- Financial, markets and PPA (Power Purchase Agreement);
- Design and tendering;
- Access and supplies; and
- Contracts.

All geothermal projects must comply with law, regulations and permits in the project area. Regulations might change in the middle of the project which can cause a delay. Another issue which has become one of the main focus in geothermal projects is project financing and tariffs. For every geothermal project, favourable power purchase contracts are needed. The high risk in the exploration stage causes distrust of banks to provide loans. Small developers generally try to form joint ventures or equity partnerships, so they can share the risks. In some countries, a loan guarantee program from the government allows several development projects to progress. For the market, developers need to consider market access that can be limited by the lack of infrastructure including transmission and distribution networks. Proper preparation for access and supplies is required.

4. RISK FOR DIENG GEOTHERMAL PROJECTS

4.1 Understanding and assumptions

A geoscientific study, previous drilling in 1975-1998 and operating history since 1998 prove that the Dieng geothermal system has potential. The system is liquid-dominated and is characterized by intense hydrothermal activity which is indicated by large, conspicuous, surface thermal manifestations comprising fumaroles, hot springs, and acidic mud pools and ponds. The Dieng geothermal system is entirely hosted in a thick sequence of volcanic rocks (pyroclastic and lavas), underlaid by andesite complex/microdiorite. Manifestations are distributed in three areas, namely Sileri, Sikidang, and Pakuwaja, and are sustained by steam and gas separated from the top of the boiling geothermal reservoir, interacting with shallow groundwater and rocks. The main area of the developing field is divided into two parts, Sileri in the northwest and Sikidang in its centre and the reservoir temperature ranges from 280 to >320°C. The chemical composition of discharged fluid shows that the chloride content in Sileri is higher than 8000 mg/l and the NCG portion is 0.8% by weight. In Sikidang, the chloride content is lower than 6000 mg/l and the NCG portion is mostly higher than 1.5%, reaching up to 14-17% (PwC, 2013).

Geothermal development in Dieng was firstly carried out by Pertamina from 1975 to 1994. Pertamina drilled 27 wells, 24 of which are located in the Sikidang area. From 1995 to 1998, HCE drilled 20 wells of which 17 wells are in the Sileri area. Fluid from the wells is separated by separators which are installed nearby the wells. The separators are used to separate the 2-phase fluid flow but do not work properly. The separated steam is transported through the steam pipeline to the power plant located in the Sikidang area. The separated brine is reinjected at separator pressure using a pump located in the Sikidang area.

Power plant Unit 1 (60 MW) in Dieng was commissioned by HCE in 1998 but suspended due to Presidential Decree No. 5/98. In 2002, GeoDipa was established and is now the new owner of the Dieng field. GeoDipa began operating Unit 1 supplied by the existing wells, but only producing around 46 MW due to wellbore problems and lack of steam. GeoDipa also planned to construct Unit 2 but it has been delayed due to financial and technical reasons.

According to stage gate, the development of Unit 2 reached the feasibility study stage in 2006. A feasibility study for Unit 2 was first conducted in 2006 and updated in 2013, but the project could not proceed due to legal issues. In 2018, GeoDipa could handle the legal issue and is resuming the project by updating the feasibility study. This will be followed by purchasing drilling long lead items, IPM tender and EPC for SAGS and the power plant.

The plan for the development of Unit 2 is to drill additional wells and build both the FCRS and the power plant. In total, 9 production wells and 4 injection wells are believed to be needed for Unit 2. Some steam is available from older wells but a few new wells have to be drilled. FCRS will be constructed, taking into account the silica scaling problems. The applicable type of FCRS for this project is a combination of a two-phase flow type and central separation type. Two-phase flow will be transported from the production wells and separated in a separator station near Unit 2. The steam from the separators will be transported to the steam turbine, while the separated brine from the separators will be diverted to the reinjection wells after chemical injection for pH control. The pipeline route will be designed, taking into account the steep slope and it will be shorter. There will be two types of pipelines, one for two-phase fluid and one for reinjection fluid. The diameter of the two-phase flow line pipeline will be designed considering corrosion and erosion caused by fluid. A bridge will need to be constructed over a small river on the pipeline route. For the power generating facility a turbine inlet, steam turbine, condenser, gas extraction system, cooling water pipe and a cooling tower need to be installed (Boedihardi et al., 1991; JBIC, 2006; PwC, 2013).

4.2 Dieng Unit 1 risks

Based on the operation of Unit 1, five major issues associated with power enhancement have been identified by Meliala et al. (2015):

- Production well blockages;
- Silica deposition problem in 2-phase facility and brine reinjection system;
- Options to increase Unit 1 steam supply to full load;
- Assessment of steam field surface facilities;
- Constraints on monitoring programme.

In 2018, a risk assessment was carried out to identify and analyse the risks by the different divisions within GeoDipa Dieng. The process was carried out by observing how the identified risks affected the achievement of targets in 2018. The 13 top risks were updated (Appendix I), both quantitatively and qualitatively. The risks have been ranked from the highest risk to the lowest. In total, 8 issues are classified as extremely high risk (Table 4) and 5 as high risk. The highest risk is related to the brine management system which causes scaling, especially silica scaling.

TABLE 4: Top risks in Dieng Unit 1 operations

No.	Risk event	Risk level	Actions / risk treatment
1	Management of silica related to the brine management system is not optimal	**Extremely high**	Addition of silica handling services. Brine line maintenance. Injection well workover.
2	Brine management system is not optimal	**Extremely high**	Procurement of brine transfer pump redundancies, brine line redundancies and pump. Procurement of supporting accessories for brine line redundancies
3	Lack of monitoring causes non-optimum preventive maintenance of power plant	**Extremely high**	Ensure specifications of spare parts on request (during *aanwijzing* process and quality acceptance). Addition of man power for execution of work.
4	Damage to surface equipment (surface facilities)	**Extremely high**	Procurement of material unit for master valve, throttle valve unit, pipe, DCS steamfield, control valve.
5	Interference from the turbine control system	**Extremely high**	Supply of Turbine Control System (TCS) spare cards. TCS reset settings when inspection. Houseload test during inspection.
6	Compensation related to community asset damage and public facilities	**Extremely high**	Review and improvement of operational SOP. Certification of equipment. Preventive maintenance. Change of equipment. Disaster mitigation. Environmental monitoring.
7	Domestic wastewater pollution	**Extremely high**	Preparation of plans for domestic wastewater treatment installation.
8	Overflow from pond and open canal	**Extremely high**	Ensure the pipeline cleaning data is accurate. Coordination with related functions. Provide backup pipes and pumps. Construction of a dam in an open canal before the brine flows into the pond. Deposition of silica sludge occurs in the open canal first before entering the pond.

4.3 Assessment of the Dieng Unit 2 project risks

Before carrying out a project, it is necessary to identify risks that could impact project activities. Risk identification can be used as an early warning system when the project is likely to deviate from the plan. The category of risks that should be identified include resource (Table 5), engineering and technology (Table 6), permit and planning (Table 7), market and financial (Table 8), health and safety (Table 9), and environment (Table 10).

TABLE 5: Resource risks for Unit 2 project

No.	Risk event	Risk level			Actions / risk mitigation
		Feasibility study	Exploitation	Utilization	
R1	Collapse in formation while drilling		Extremely high		Detailed geoscientific studies, well targeting and well design.
R2	Dry wells		Extremely high		Detailed geoscientific studies.
R3	Inadequate steam supply due to scaling and corrosion (production wells, turbine and FCRS)			Extremely high	Comprehensive monitoring program for steam and water quality. Corrosion inhabitation in steam. Improved brine management (e.g. hot water injection, modify pH, inhibitors, retention tank, etc.).

TABLE 6: Engineering and technology risks for Unit 2 project

No.	Risk event	Risk level			Actions / risk mitigation
		Feasibility study	Exploitation	Utilization	
T1	Changes in construction design.		High		Select an experienced design consultant who has a good reputation and track record. Coordination with related parties.
T2	Delay in building a powerhouse.		High		Monitor and impose strict deadline. Ensure all materials arrive at the appointed time. Follow the procurement standard (e.g. FIDIC).
T3	Delay in the engineering and procurement work.		High		Coordination with contractors. Perform progress engineering meetings. Technical training for the employees. Follow the procurement standard (e.g. FIDIC).
T4	Equipment does not meet technical specification.		High		Strict requirements for equipment manufacturers or providers.
T5	The contractor fails to execute the job as required.		High		Conduct periodic monitoring and review.

TABLE 7: Permit and planning risks for Unit 2 project

No.	Risk event	Risk level			Actions / risk mitigation
		Feasibility study	Exploitation	Utilization	
P1	Delay in the implementation of the development stage	High	High	High	Create and implement schedules Ensure selection of experienced contractors Coordination between work functions
P2	Contract dispute	Medium	Medium	Medium	Maintain good communication and coordination with the consortium

The risks for Dieng Unit 2 project have been identified, using the same methodology used by GeoDipa for assessing the risks of Unit 1. The risk assessment cannot be presented in detail in this report but the highlights are presented in Appendix II.

TABLE 8: Market and financial risks for Unit 2 project

No.	Risk event	Risk level			Actions / risk mitigation
		Feasibility study	Exploitation	Utilization	
M1	Project cost overrun	High	High	High	Proper research and development prior to project start. Keep the project on track and ensure that tasks are executed as intended.
M2	Increase in price of equipment, operation and maintenance services	Medium	Medium	Medium	Contractually-guaranteed prices for a fixed period of time.

TABLE 9: Health and safety risks for Unit 2 project

No.	Risk event	Risk level			Actions / risk mitigation
		Feasibility study	Exploitation	Utilization	
H1	Work accident	High	High	High	Compliance of activities to procedures, regulations, and HSE work practice. Sensitization and education about the possibility of hazards during work.

Of the risks described in Tables 5-10, 22 risk events are relevant for the Unit 2 project (Figure 5). Four of these risk events are classified as extremely high risk. These risk events are related to resource and environmental risk and require special attention throughout the project. Fifteen risk events are classified as high risk and three risk events as medium risk. With the risk assessment of Unit 2, GeoDipa will be able to reach acceptance level before spending significant funds on the next development stages, such

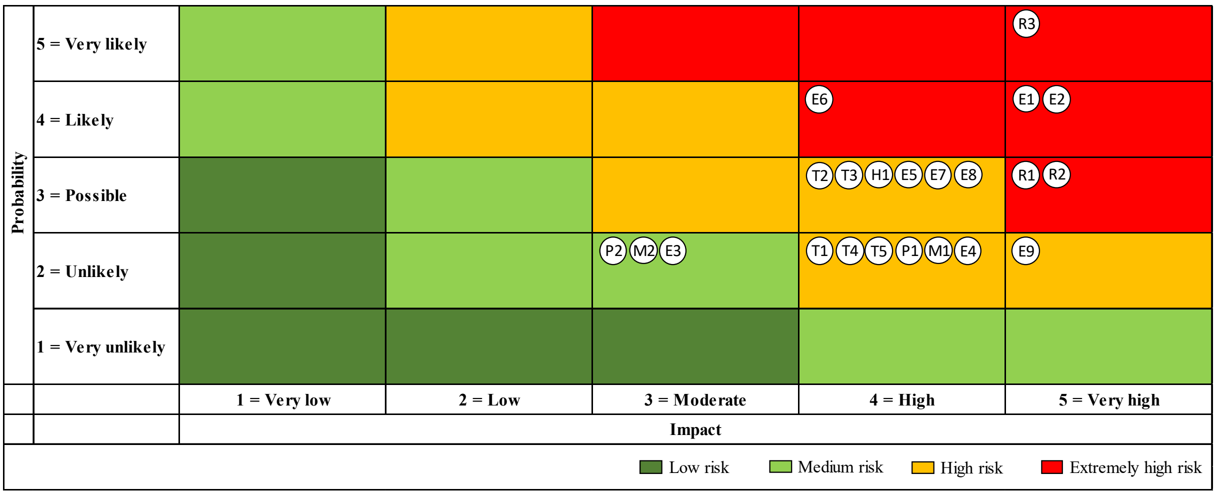


FIGURE 5: Risk profile of the Unit 2 project based on probability and impact assessment (see also Appendix II), R1, R2, R3, E1, E2, E6, are classified as extremely high risk; T2, T3, H1, E5, E7, E8, E9, T1, T4, T5, P1, M1, E4 are classified as high risk, P2, M2, E3 are classified as medium risk; R=Resource, T=Engineering and technology, P=Permit and planning, M=Market and financial, H=Health and safety, E=Environmental

TABLE 10: Environmental risks for Unit 2 project

No.	Risk event	Risk level			Actions / risk mitigation
		Feasibility study	Exploitation	Utilization	
E1	Protests and uprising - Communities and activists are very sensitive to negative issues of geothermal activity.	Extremely high	Extremely high	Extremely high	Provide information and knowledge (socialization) regarding geothermal benefits. Implementation of Focus Group Discussion (FGD) that involves all stakeholders particularly the affected villages.
E2	Noise complaints.		Extremely high	Extremely high	Design focus on noise reduct. Inform local community about activities that will have high noise, e.g. well testing. Minimize the speed of construction traffic.
E3	Surface disturbance during civil works and mobilization.		Medium		Conduct monitoring programs for runoff and drainage, soil stability and landslide.
E4	Ground subsidence, causing damages to buildings, roads etc.			High	Conduct studies on ground measurement. Monitor ground elevation.
E5	Increased seismic activity.		High	High	Design work procedures to minimize risk of injection related seismic events, slow start and slow stop of injection.
E6	Ground water pollution.		Extremely high	Extremely high	Work procedures to minimize brine, condensed water & drill. water released to environment. Monitor plugging up of injection boreholes. Provide spare injection wells.
E7	Oil pollution from contractors.		High		Provide double-skinned oil tank. Monitor the pipelines. Consider electricity for drilling. Installation of oil trap in sensitive areas, e.g. drill pad.
E8	Exposure to toxic gases.	High	High	High	Monitor toxic gases at potential release points around the site. Installation of gas sensor and detector. Use appropriate PPE.
E9	Wayleave access for transmission line is cancelled by the landowner.		High		Ensure the land acquisition is done.

as drilling and construction. Risk assessment for Unit 2 is important to support the feasibility study and decision making as well as to identify missing information or major issues that could cause the abort of the project. Appropriate mitigation is an important task of the feasibility study team.

4.4 Key uncertainties

During the operation of Dieng Unit 1, GeoDipa has encountered problems concerning the steam field operations. The results of Unit 1's risk identification show that the highest ranked risk is found in the technical risk section which will be a consideration for the construction of Unit 2. One of the risks which will be of concern is the formation of scaling. A suboptimal brine management system causes scaling in production wells, the turbine and FCRS.

4.4.1 Scaling in production wells

Scaling and casing failures in production wells occurred during the operation of Unit 1. The failures were caused by mechanical stress, low-quality casing materials and other human factors while the scaling is caused by chemical components dissolved in the fluid. Some of the scales at different depths were investigated by GeoDipa during a workover in 2012 (Table 11). The data shows that the scaling type formed in the production wells consists of sulphide minerals. Sulphide mineral precipitation is controlled by processes that cause cooling such as boiling, mixing or conductive loss. The solubility of sulphide minerals (e.g. galena, sphalerite, chalcopyrite) at reservoir temperature (280-340°C) is relatively high, while it is drastically lower at wellhead temperature. Neutral brine from great depths mixing with cooler fluids at lower depths can cause the formation of sulphide scaling. Boiling also may induce significant precipitation of sulphide minerals. The same scaling phenomena is likely to affect the new production wells which will be drilled for Unit 2 (PwC, 2013).

TABLE 11: Scale fragments in selected wells investigated in 2012

Well	Instrument	Tag depth (m)	Fragment
HCE-7C	Go devil	1441	Sphalerite (ZnS), Galena (PbS), Chalcopyrite ($CuFeS_2$) – Smectite.
HCE-29A	Sample catcher	1062	Amorphous silica.
HCE-9B	Sample catcher	542	Siderite ($FeCO_3$), Geothite ($FeOOH$), Maghemite (Fe_2O_3), Smectite.
DNG-15	Sample catcher	725	Siderite.
DNG-10	Go devil	165	Siderite, Jarocite (KFe3+3(SO4)2(OH)6), Diaspore (AlOOH).
HCE-7B	Go devil	490	Galena, Sphalerite.

Harijoko et al. (2015) conducted an analysis of sulphide scales from two production wells (HCE-7B at 495 m depth and HCE-7C at 1441 m depth) to characterize the sulphide minerals deposited from geothermal water at the boiling point. The analysis from X-ray diffraction revealed that the sulphide minerals formed in the production wells are galena, chalcopyrite, sphalerite and pyrrhotite.

4.4.2 Scaling and corrosion in the turbine

In the early years of the operation of Unit 1, the output was greater than 40 MW but the steam quality was poor. During that operational period, minor silica deposits were discovered in the turbine which caused problems for the operation of the power plant (Figure 6). The main types of minerals found were Fe, SiO_2, and Ca. The silica deposits are attributed to flashing and boiling of water droplets carried with the steam.

FIGURE 6: Corrosion in turbine after cleaning the scaling and corrosion deposits

FIGURE 7: Scaling in reinjection pipe

FIGURE 8: Scaling in canal

4.4.3 Scaling in fluid collection and re-injection system

One of the main problems and a concern in Dieng is scaling in the FCRS. Deposition of mainly silica scaling occurs in the FCRS, separator and brine transportation lines (Figures 7 and 8). The deposition of silica begins in the atmospheric separator and continues in the brine ponds and the reinjection pipelines. Geothermal fluid cause two types of silica deposits. The first type is amorphous silica which is white and rather soft, so it is easy to clean. The other type of silica is a blackish polymer which is very hard and firmly attached to the pipe. Sigfússon and Gunnarsson (2011) explained that silica polymerization is greatly affecting the success of pH modification. Before polymerization is significant, the reaction in the brine runs slowly so that the brine can immediately migrate into the injection formation and the deposition of silica is delayed.

Deposition of silica in the reinjection well causes a decrease in reinjection capacity over time. This is caused by high SiO_2 concentration in brine. The Silica Saturation Index (SSI) is the ratio between the concentration of silica in fluid and its solubility as amorphous silica. When the SSI value is above 1, silica scale is formed. According to a study on silica scaling in Dieng by Utami et al. (2014), the SiO_2 content within the water in the separator and weir box will increase when there is a significant change of pressure and temperature. The SSI would rise from 1.14 to 4.8 and silica scaling would be the consequence.

Geothermal fluid will become oversaturated with SiO_2 after too much flashing, due to temperature drop, enrichment of SiO_2, degassing and pH increase. The amount of scaling in FCRS varies, from a small amount to a large amount that can interfere with geothermal production. However, minor deposits can be handled through normal maintenance. Some locations where silica deposition has been discovered are:

- *Pipeline from well head to steam separator*: minor, brownish deposits chiefly made of silica with subordinate Fe (III) oxy-hydroxides;
- *Steam separators*: minor deposits at brine discharge curve;
- *Pipelines connecting steam separators to atmospheric separator*: minor scaling;
- *Settling pond*: substantial silica deposits (Figure 9), consistent with

FIGURE 9: Silica scaling in pond

the time of permanence of the brine during transfer to the reinjection pumps;
- *Steam pipeline*: minor scaling spotted in moist drainage pipes due to the brine being carried by the steam which can create serious problems in the turbine if not efficiently removed; and
- *Reinjection lines*: significant silica scaling with average length of 2-3 km.

Studies on pond geometry assuming brine input rate of 50 tons/hour and 90°C showed that a residence time of at least 74-315 hours is expected (Table 12) (PwC, 2013).

TABLE 12: Pond volume and residence times

Pond	**Volume (m^3)**	**Brine input rate at 90°C (tons/h)**	**Residence time (h)**
7	6450	50	124
28	6708	50	129
29	16400	50	315
30	3864	50	74
31	4032	50	77

Currently, brine handling is being carried out by cold brine handling system. Another mitigation action is to acidify the pH level. In acid injection, 98% H_2SO_4 is used and it is expected that the polymerization process cannot run properly, thus inhibiting the formation of silica polymers. However, this method causes problems in the inner part of the pump and steam supply to the turbine is disrupted because work is needed to repair the leaky pipe section. This pipe leak is worsened by the limitations of the pump used in the injection system. In addition, acid injection causes sulphate compounds ($BaSO_4$ and $CaSO_4$) to deposit which disrupts the liquid-phase pumping system. High sulphate contents and unusually high acidity are more frequent in the Sikidang area than in the Sileri area. In the main separator, treatment with sulfuric acid is carried out to reduce silica deposits. This causes the formation of silica deposits in brine ponds (JBIC, 2006; PwC, 2013).

4.5 Risk mitigation

During the development phase, GeoDipa needs to address any technical risks, especially the scaling and corrosion problems, in order to achieve efficient plant operation. To achieve optimal production capacity, it is necessary to create a data base compilation containing the following information:

- Data from drilling activities such as depth, drilling history, cutting analyses, casings characteristics, logs performed, etc. A summary of production wells productivity (declining history) is useful to evaluate the influence of scaling on steam production.
- Data from well testing such as compilation of physical data (P, T, flow rate, etc.) and a complete chemical analysis of the produced fluids.
- Data from workover operations such as casing information, scaling samples recovered during workover as cuttings, localized and analysed for chemical and mineralogical composition, casing surveys (caliper logs, cement bond logs, video logs, PT logs) to identify potential depth of blockage, flash point, failure portions of casing, etc.

Routine monitoring, sampling and analysis of the fluid properties in every production and reinjection well, in the surface facilities (two-phase fluid pipelines, separators, chemical injection equipment, brine reinjection pipeline, power plant drain reinjection pipeline and the emergency pond) is useful to optimize future activities to prevent scaling. If concentration of SiO_2 and Cl in brine are high, it is necessary to have more efficient separators in future power plants. It is also essential to monitor the WHP and flow rate of both steam and liquid brine from the well head to the separator to verify if scaling is occurring. Chemical analysis of brine and gases discharged from production well and chemical analysis of scale deposition to identify the chemical species and components can be conducted. If the chemical composition is changing, a new sample must be taken and a complete analysis carried out (PwC, 2013).

For future Unit 2 operation, GeoDipa should increase the productivity of production wells and the separation efficiency of the separator. Sulphide scaling in production wells can be reduced by injection of water, chemical oxidizing agents and inhibitors. In some cases, however, other problems such as corrosion could occur after the application of inhibitors (Ármannsson and Hardardóttir, 2010).

Silica scaling may occur due to continuous pressure drop caused by the separator orifice. The silica deposition process can be controlled by the pressure of the production separator. While SSI is smaller than 1, silica is dissolved and the fluid can be reinjected. After passing the production separator, SSI tends to increase due to the super saturated conditions where the potential for silica deposition is even greater. To avoid these conditions, production and reinjection wells need to be located on the same pad. Another option is to direct the separated brine to the atmospheric separator to separate the fluid phase again in atmospheric conditions before the remaining phase is passed to the pond and left there for about 4-5 hours so the silica is deposited in the pond. After that, the brine can be re-injected into the reinjection well (PwC, 2013; Suwana, 2004).

Some other methods that can be considered to mitigate silica are:

- *Hot water injection.* A high-temperature reinjection system is an effective method to prevent scaling caused by brine with high SiO_2 concentrations. Depending on the silica concentration, the temperature is maintained at or above the amorphous silica solubility. At Dieng geothermal field, this is a possible approach to prevent silica deposition, but other methods are needed additionally. For example, all pipelines must remain pressurized when the pressurized fluids are transferred from the well head separator to reinjection wells. Many geothermal fields have implemented this method (PwC, 2013).

- *pH modification.* A pH modification system is another effective countermeasure to prevent scaling from brine with high SiO_2 concentration. Before applying the pH modification, a study on chemical composition, concentrations and dosage of acids is needed because corrosion may occur in an acidic environment (Topcu et al., 2017). Studies show that scaling and corrosion can be minimized by acidifying brines to pH $\geq$ 4.5 (measured at ambient conditions). By reducing the brine pH to no lower than 4.5, a compromise between scaling and corrosion can be achieved (Gallup, 2011). For a number of geothermal fields, pH modification technology has been applied to control scale deposition in equipment, injection piping, injection wells and injection formations. pH modification was conducted in the hyper-saline brines in Salton Sea, California to mitigate the ferric silicate deposition in surface equipment, pipes and injection wells. The pH modification reduced the scaling from > 30 cm/year to < 1 cm/year without severely corroding surface piping and injection well tubulars (Gallup, 2011). At the Mak-Ban field, Philippines, pH modification has been applied to control scaling without causing significant corrosion for over 10 years in a binary bottoming cycle with a long re-injection pipeline, an injection well and the injected formation (Gallup and Barcelon, 2005). pH modification using HCL or H_2SO_4 has also been conducted in Hellisheidi power plant in Iceland which could greatly reduce loss of injectivity in re-injection wells (Keller, 2018).

- *Inhibitors.* An inhibitor to control silica scaling is one way to avoid scaling on piping or equipment surfaces. The use of dispersants with very low dosage facilitates the cleaning of pipes and equipment. If the dosage is too high, coagulation of silica will occur and cause deposition of soft deposits which rapidly reduces brine flow. Since inhibitors are costly, the use of high dosages is uneconomical (Gallup, 2005; Gallup and Barcelon, 2005, in Gallup, 2009).

- *Cold water injection.* Separated water which has been cooled in the pond before injection is currently used for Unit 1. For the future power plant, this method can also be applied to prevent scaling. In the reinjection process it is necessary to ensure that most of the silica precipitation occurs in the settling pond. The reinjection pump must be installed in a way that amorphous silica deposited at the bottom of the pond will not enter the pump suction (PwC, 2013). Cold water injection has been successfully carried out in trials in the Te Mihi geothermal field in New Zealand (Mroczek et al., 2017).

- *A retention tank* is used to retain separated waters before reinjection. The separated water flows through the retention tank for further polymerization of silica before the condensate is mixed with it. The condensed steam dilutes the concentration of dissolved elements in the separated water because it does not contain dissolved elements except for CO_2 and H_2S. At Nesjavellir and Hellisheidi, Iceland, a retention tank is in use to reduce silica scaling (Gunnarsson et al., 2010; Gunnlaugsson, 2012).

5. CONCLUSIONS AND RECOMMENDATIONS

GeoDipa is currently updating the feasibility study for the Dieng Unit 2 project. Prior to taking a decision, GeoDipa has to classify, identify and mitigate the key project risks. These risks are related to resource, technology and permits. Six risks are classified as extremely high and most of them are related to silica scaling issues and environmental impact. Based on the risk assessment, the project should focus on the key risks outlined in Table 13.

TABLE 13: Key risks and mitigation for Dieng Unit 2 project

Key risks	Mitigation
Collapse of formation while drilling.	Detailed geoscientific studies, well targeting and well design.
Dry wells.	Detailed geoscientific studies.
Inadequate steam supply due to scaling and corrosion (production wells, turbine and FCRS).	Comprehensive monitoring programme for stream and water quality. Corrosion inhabitation in steam. Improved brine management (e.g. hot water injection, pH modification, inhibitors, retention tank, etc.).
Protests and uprising – Communities and activists are very sensitive to the negative issues of geothermal activity.	Provide information and knowledge (socialization) regarding benefits of geothermal production. Implement Focus Group Discussion (FGD) involving stakeholders incl. affected villages.
Noise.	Design focus on noise reduction. Inform local community about activities that will have high noise, e.g. well testing. Minimize the speed of construction traffic.
Ground water pollution.	Work procedures to minimize brine, condensed water and drilling water released to environment. Monitor plugging up of injection boreholes. Provide spare injection wells.

Development of Unit 2 is expected to have a lower risk taking into consideration the experience of 20 years of operation of Unit 1. Nonetheless, a profound analysis of the risks related to silica scaling, corrosion and environmental issues is vital before making the decision on Unit 2. A good example is the result of pH modification for Unit 1, which, together with high temperature injection, effectively protects the FCRS including reinjection wells. To prevent scaling in Dieng geothermal area, separator pressure should be 17.2 bar-a, what corresponds to a separated brine temperature of 205°C and the pH value should be 5 which can be achieved by pH modification (JBIC, 2006).

ACKNOWLEDGEMENTS

I would like to express my gratitude to the United Nations University Geothermal Training Programme and PT Geo Dipa Energi (Persero) for the opportunity to study in the six-month training programme. I would like to thank Dr. Bjarni Pálsson for giving me such a great guidance to finish this report and Mr. Sverrir Thórhallsson for sharing the knowledge that enabled me to finish this report. Special thanks to all members of the UNU-GTP study board and staff for assistance during the programme. I thank the UNU fellows of 2018 and all my colleagues in Indonesia for always supporting me in every situation. Finally, I would like to thank God for granting me life and health during the programme in Iceland.

REFERENCES

Ármannsson, H., and Hardardóttir, V., 2010: Geochemical patterns of scale deposition in saline high temperature geothermal systems. *Proceedings of the 13th International Conference on Water-Rock Interaction*, *Guanajuato, Mexico,* 133-136.

Azimudin, T., 2018: *A to Z pengembangan energi panas bumi di Indonesia (in Bahasa)*. Universitas Gadjah Mada, unpublished lecture notes, 18 pp.

Berrizbeitia, L.D., 2014: *Environmental impacts of geothermal energy generation and utilization.* Volcanoes of the Eastern Sierra Nevada – G190, Indiana University, USA, 12 pp.

Bignall, G., 2013: *Application of geoscience for geothermal resource evaluation and mitigation of development risk*s. GNS Science, NZ, unpubl. presentation, 33 pp.

Boedihardi, M., Suranto., and Sudarman, S., 1991: Evaluation of the Dieng geothermal field; review of development strategy. *Proceedings of the 12th Annual Convention, Indonesian Petroleum Association*, Indonesia, 347-361.

Cooper, R.G., 2016: *The stage-gate system: a road map from idea to launch – an intro & summary.* Gemba Innovation, Denmark, 16 pp.

Datuin, R. and Gazo, F.M., 1989: Material problems of geothermal power plants: a Philippine experience. *Proceedings of the 11th New Zealand Geothermal Workshop, New Zealand*, 275-281.

Elíasson, E.T., Thórhallsson, S. and Steingrímsson, B.S., 2008: Geothermal power plants. *Presented at "Short Course on Geothermal Project Management and Development", organized by UNU-GTP, KenGen and MEMD-DGSM, Entebbe, Uganda,* 15 pp.

Gallup, D.L., 2009: Production engineering in geothermal geology: A review. *Geothermics, 38,* 326-334.

Gallup, D.L., 2011: pH modification scale control technology. *Proceedings of the International Workshop on Mineral Scaling, Manila, Philippines*, 39-46.

Gallup, D.L., and Barcelon, E., 2005: Investigations of organic inhibitors for silica scale control for geothermal brines - II. *Geothermics, 34,* 756-771.

Gehringer, M. and Loksha, V., 2012: *Geothermal handbook planning and financing power generation.* The World Bank, Washington DC, ESMAP, 164 pp.

Gunnarsson, I., Ívarsson, G., Sigfússon, B., Thrastarson, E.Ö., and Gíslason, G., 2010: Reducing silica deposition potential in waste waters from Nesjavellir and Hellisheidi power plants, Iceland. *Proceedings of the World Geothermal Congress, Bali, Indonesia,* 5 pp.

Gunnlaugsson, E., 2012: Scaling in geothermal installation in Iceland. *Presented at "Short Course on Geothermal Development and Geothermal Wells", organized by UNU-GTP and LaGeo, Santa Tecla, El Salvador,* 6 pp.

Gunnlaugsson, E., Ármannsson, H., Thórhallsson, S., and Steingrímsson, B., 2014: Problems in geothermal operation – scaling and corrosion. *Presented at "Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization", organized by UNU-GTP and LaGeo, Santa Tecla, El Salvador,* 18 pp.

Hadi, J., Quinlivan, P., Ussher, G., Alamsyah, O., Pramono, B., and Masri, A., 2010: Resource risk assessment in geothermal greenfield development; An economic implication. *Proceedings of the World Geothermal Congress, Bali, Indonesia*, 5 pp.

Harijoko, A., Hapsari, K., Wibowo, Y.T., Atmaja, R.W., and Nurpratama, M.I., 2015: The sulfide minerals deposit in the geothermal pipes of Dieng geothermal field, Indonesia. *Proceedings of the World Geothermal Congress, Melbourne, Australia*, 5 pp.

Hochwimmer, A. and Kretser, S., 2015: Safety by design processes for the engineering of geothermal facilities. *Proceedings of the World Geothermal Congress, Melbourne, Australia*, 8 pp.

Hunt, T.M., 2000: *Five lectures on environmental effects of geothermal utilization*. UNU-GTP, Iceland, report 1, 110 pp.

IFC, 2013: *Success of geothermal wells: a global study*. International Finance Corporation, Washington, DC, 80 pp.

JBIC, 2006: *Feasibility study for Dieng Nos. 4, 5 and 6 units geothermal power development - final feasibility report*. Japan Bank for International Cooperation for PT Geo Dipa Energi, Indonesia, unpublished internal report, 260 pp.

Keller, M.L., 2018: *H_2S abatement and pH modification techniques for scaling inhibition at Hellisheidi geothermal plant*. Reykjavik University, Iceland, internet website: https://www.or.is/

Koenig, J., 2016: *Lectures on geothermal resources and their development*. UNU-GTP, Iceland, report 7, 60 pp.

Layton, D.W., Anspaugh, L.R., and O'Banion, K.D., 1981: *Health and environmental effects document on geothermal energy.* University of California, California, 61 pp.

Matek, B., 2014: *The manageable risks of conventional hydrothermal geothermal power systems*. Geothermal Energy Association, USA, 34 pp.

Meliala, E., Ridwan, R.H., and Marza, S., 2015: Power enhancement of Dieng geothermal installed capacity. *Proceedings of the World Geothermal Congress, Melbourne, Australia*, 6 pp.

Miller, R.L., 1980: Chemistry and materials in geothermal systems. In: Casper, L.A., and Pinchback, T.R. (editors), Geothermal scaling and corrosion. American Society for Testing and Materials, ASTM STP 717, 3-9.

Mroczek, E., Graham, D., Siega, C., and Bacon, L., 2017: Silica scaling in cooled silica saturated geothermal water: comparison between Wairakei and Ohaaki geothermal fields, New Zealand. *Geothermics, 69,* 145-152.

Okwiri, L.A., 2017: *Risk assessment and risk modelling in geothermal drilling*. Reykjavik University, MSc thesis, UNU-GTP, Iceland, report 2, 62 pp.

Ouko, E.A. and Ómarsdóttir, M., 2015: The geothermal journey – a case example of Iceland and Kenya. *Proceedings of the World Geothermal Congress, Melbourne, Australia*, 8 pp.

Ngugi, P.K., 2014: Risks and risk mitigation in geothermal development. *Presented at "Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization", organized by UNU-GTP and LaGeo, Santa Tecla, El Salvador,* 11 pp.

Pálsson, B., 2017: Feasibility studies for geothermal projects. *Presented at "SDG Short Course II on Feasibility Studies for Geothermal Projects", organized by UNU-GTP and LaGeo, Santa Tecla, El Salvador,* 12 pp.

Poernomo, A., Satar, S., Effendi, P., Kusuma, A., Azimudin, T., and Sudarwo, S., 2015: An overview of Indonesia geothermal development – current status and its challenges. *Proceedings of the World Geothermal Congress, Melbourne, Australia*, 11 pp.

PT Geo Dipa Energi, 2018: *Quarterly report 1 2018* (in Bahasa). PT Geo Dipa Energi (Persero), Indonesia, unpublished internal report, 60 pp.

PwC, 2013: *Final report consultant's service for the development of geothermal area Dieng, unit 2 and 3 and Patuha units 2 and 3*. PricewaterhouseCoopers, for PT Geo Dipa Energi, Indonesia, unpubl. internal report, 429 pp.

Quinlivan, P., Batten, A., Wibowo, M., Hinchliffe, S., Rahayu, D., Doria, I., Yahmadi, A., and Tondang, H.Y.T., 2015: Assessing geothermal tariffs in the face of uncertainty, a probabilistic approach. *Proceedings of the World Geothermal Congress, Melbourne, Australia*, 10 pp.

Richter, B., 2018: *The planning of geothermal projects*. UNU-GTP, Iceland, unpub.lecture notes, 92 pp.

Robertson-Tait, A., Henneberger, R., and Sanyal, S., 2008: Managing geothermal resource risk – experience from the United States. *Presented at "Workshop on Geological Risk Insurance", organized by World Bank Geothermal Energy Development Program, Karlsruhe, Germany,* 10 pp.

SNI, 1998: *Standar Nasional Indonesia - Klasifikasi potensi energi panas bumi di Indonesia (in Bahasa)*. Badan Standardisasi Nasional, Indonesia, 17 pp.

Sanyal, S.K., and Morrow, J.K., 2010: Quantification of geothermal resource risk - a practical perspective. *Geothermal Resources Council, Transactions, 34,* 125-130.

Sarmiento, Z.F., 2011: Risk management for geothermal projects. *Presented at "Short Course on Geothermal Drilling, Resource Development and Power Plants", organized by UNU-GTP and LaGeo, Santa Tecla, El Salvador,* 10 pp.

Sigfússon, B., and Gunnarsson, I., 2011: Scaling prevention experiments in the Hellisheidi power plant. *Proceedings of the 36th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, CA,* 4 pp.

Steingrímsson, B., 2009: Geothermal exploration and development from a hot spring to utilization. *Presented at "Short Course on Surface Exploration for Geothermal Resources", organized by UNU-GTP and LaGeo, Ahuachapan and Santa Tecla, El Salvador,* 8 pp.

Suwana, A., 2004: *Tinjauan ulang data kimia fluida sumur panasbumi Dieng untuk menganggulangi terjadinya deposit silika (in Bahasa)*. PT Geo Dipa Energi, Indonesia, unpubl. internal report, 80 pp.

Thórhallsson, S., 2018: *Common problems faced in geothermal generation and how to deal with them*. UNU-GTP, Iceland, unpublished lecture notes, 68 pp.

Topcu, G., Celik, A., Baba, A., and Demir, M.M., 2017: Design of polymeric antiscalants based on functional vinyl monomers for (Fe, Mg) silicates. *Energy & fuels, 31,* 8489-8496.

Utami, B., Herdianita, N.R., and Atmaja, R.W., 2014: The effect of temperature and pH on the formation of silica scaling of Dieng geothermal field, Central Java, Indonesia. *Proceedings of the 39th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA,* 6 pp.

APPENDIX I: Risks in Dieng power plant Unit 1 operations

No.	Risk event	Risk level	Actions / risk treatment
1	Management of silica related to the brine management system is not optimal.	**Extremely high**	Addition of silica handling services. Brine line maintenance. Injection well workover.
2	Brine management system is not optimal.	**Extremely high**	Procurement of brine transfer pump redundan-cies, brine line redundancies and pump. Procurement of supporting accessories for brine line redundancies.
3	Lack of monitoring causes non-optimum preventive maintenance of power plant	**Extremely high**	Ensure specifications of spare parts on request (during *aanwijzing* process and quality acceptance). Addition of man power for work execution.
4	Damage to surface equipment (surface facilities)	**Extremely high**	Procurement of material unit for master valve, throttle valve unit, pipe, DCS steamfield control valve.
5	Interference from the turbine control system	**Extremely high**	Supply of Turbin Control System (TCS) spare parts. TCS reset settings when inspection. Houseload test during inspection.
6	Compensation related to community asset damage and public facilities	**Extremely high**	Review and improvement of operational SOP. Certification of equipment. Preventive maintenance. Change of equipment. Disaster mitigation. Environmental monitoring.
7	Domestic wastewater pollution	**Extremely high**	Preparation of plans for domestic wastewater treatment installation.
8	Overflow from pond and open canal	**Extremely high**	Ensure accurate assessment of pipeline cleaning data. Coordination with related functions. Provide backup pipes and pumps. Construction of a dam in an open canal in front of inflow to pond. Deposition of silica sludge occurs in the open canal before entering the pond.
9	Work accidents caused by the contractor	**High**	Ensure compliance to the K3LL plan. Application of Contractor Safety Management System (CSMS). Conduct supervision by internal parties of the project.
10	Employee work accidents	**High**	Socialization of SOP (Standard Operating Procedure). Procurement of adequate security and other equipment. Socialization and procurement of Personal Protective Equipment (PPE). Conduct safety meetings before starting work. Provide safety training for workers. Provide safe working conditions. Provide training to increase competence of workers.
11	Exposure to toxic gases	**High**	Conduct activities in accordance with SOP to avoid escalation of toxic gases (H_2S & CO). Use appropriate PPE to avoid the escalation of toxic gases (H_2S & CO).
12	Non-B3 (non-hazardous / non-toxic) waste management is not optimal	**High**	Provide a waste bank. Utilization of organic waste. Purchase a composter machine.
13	The company is not complying with applicable regulations	**High**	Prepare licensing requirements documents. Establish good relations with the government (community relations). Implement community development programs.

APPENDIX II: Top project risks for Dieng 2

Risk category	No.	Risk event	Risk level (Probability × Impact)			Actions / risk mitigation
			Feasibility study	Exploitation	Utilization	
Resource	R1	Collapse of formation during drilling		High (3 × 5)		Detailed geoscientific studie, well targeting and well design.
	R2	Dry wells		High (3 × 5)		Detailed geoscientific studies.
	R3	Inadequate steam supply due to scaling and corrosion (production wells, turbine and FCRS)			Extremely high (5 × 5)	Comprehensice monitoring program for stream and water quality. Corrosion inhabitation in steam. Improved brine management (e.g. hot water injection, pH modification, inhibitors, retention tank, etc.).
Engineering and technology	T1	Changes in construction design		High (2 × 4)		Select an experienced design consultant who has a good reputation and track record. Coordination with related parties.
	T2	Delay in building a powerhouse		High (3 × 4)		Monitor and impose strict deadline. Ensure all materials arrive at the appointed time. Follow the procurement standard (e.g. FIDIC).
	T3	Delay in the engineering and procurement work		High (3 × 4)		Coordination with contractors. Perform progress engineering meetings. Technical training for the employees. Follow the procurement standard (e.g. FIDIC).
	T4	Equipment does not meet technical specification		High (2 × 4)		Strict requirements for equipment manufacturers or providers.
	T5	The contractor fails to execute the job as required		High (2 × 4)		Conduct periodic monitoring and review.
Permit and Planning	P1	Delay in the implementation of the development stage	High (2 × 4)	High (2 × 4)	High (2 × 4)	Create and implement schedules. Ensure selection of experienced contractors. Coordination between work functions.
	P2	Contract dispute	Medium (2 × 3)	Medium (2 × 3)	Medium (2 × 3)	Maintain good communication and coordination with the consortium.
Market and financial	M1	Project cost overrun	High (2 × 4)	High (2 × 4)	High (2 × 4)	Proper research and development before the project starts. Keep the project on track and ensure that tasks are executed as intended.
	M2	Increase in price of equipment, operation and maintenance services	Medium (2 × 3)	Medium (2 × 3)	Medium (2 × 3)	Contractually-guaranteed prices, fixed time period. Secure fixed loans interest from the bank.

Risk category	No.	Risk event	Risk level (Probability × Impact)			Actions / risk mitigation
			Feasibility study	Exploitation	Utilization	
Health and safety	H1	Work accident	High (3 × 4)	High (3 × 4)	High (3 × 4)	Compliance of activities to procedures, regulations and HSE work practice. Sensitization and education on the possibility of hazards during work.
Environmental	E1	Protests and uprising - Communities and activists are very sensitive to the negative issues of geothermal activity.	Extremely high (4 × 5)	Extremely high (4 × 5)	Extremely high (4 × 5)	Provide information and knowledge (socialization) regarding geothermal benefits. Implementation of Focus Group Discussion (FGD) involving all stakeholders particularly affected villages.
	E2	Noise		Extremely high (4 × 5)	Extremely high (4 × 5)	Design focus on noise reduction. Inform local community about activities that will have high noise, e.g. well testing. Minimize the speed of construction traffic.
	E3	Surface disturbance during civil works and mobilization		Medium (2 × 3)		Conduct monitoring programs for runoff and drainage, soil stability and landslide.
	E4	Ground subsidence, causing damages to buildings, roads etc.			High (2 × 4)	Conduct studies on ground measurement Monitor ground elevation
	E5	Increased seismic activity		High (3 × 4)	High (3 × 4)	Design work procedures to minimize risk of injection related seismic event, slow start and slow stop of injection.
	E6	Ground water pollution		Extremely high (4 × 5)	Extremely high (4 × 5)	Work procedures to minimize brine, cond. water and drilling water released to the environment. Monitor plugging up of injection boreholes. Provide spare injection wells.
	E7	Oil pollution from contractors		High (3 × 4)		Provide double-skinned oil tank. Monitor the pipelines. Consider using electricity for drilling. Installation of oil trap in sensit.area, e.g. drill pad
	E8	Exposure to toxic gases	High (3 × 4)	High (3 × 4)	High (3 × 4)	Monitor toxic gases at pot. points around the site. Installation of gas sensor and detector. Use appropriate PPE.
	E9	Wayleave access for transmission line is canceled by the landowner		High (2 × 5)		Ensure the land acquistion is done.