Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Resource Assessment Review of the Daklan Geothermal Prospect, Benguet, Philippines

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Keywords: Resource Assessment, Monte Carlo Simulation, Daklan Geothermal Prospect

ABSTRACT

Among resource assessment approaches, the "volumetric" also known as "stored heat" method is the most practical approach and generally suitable for estimating the capacity of a geothermal prospect even in its initial stages of exploration and development. The results from this method are usually optimistic because of the use of fixed parameters and at the same time conservative because heat recharge is not considered. Probabilistic analysis is usually coupled with volumetric method to account for the uncertainties encountered in calculation.

Review and analyses of the existing exploration data from Daklan geothermal prospect shows a relatively modest sized geothermal resource. The Monte Carlo simulation shows that the most likely resource area can support is a conservative 30-35 MWe development for 25 years. It should be noted however, that the exploration wells revealed a low permeability reservoir. But because of the high bottomhole temperatures ranging from 240-290^{0}C encountered in the wells drilled, further studies are needed to be done in the area to fully delineate the extent of the geothermal resource and identify permeable targets.

1. INTRODUCTION

The Daklan geothermal prospect, shown in Figure 1, is situated in the municipalities of Bokod and Kabayan in Benguet and the municipality of Kayapa, province of Nueva Vizcaya. The geothermal prospect is defined in a parcel of land bounded by the latitudes 16-35-00 and 16-27-00, and by longitudes 120-45-00 and 120-54-00.

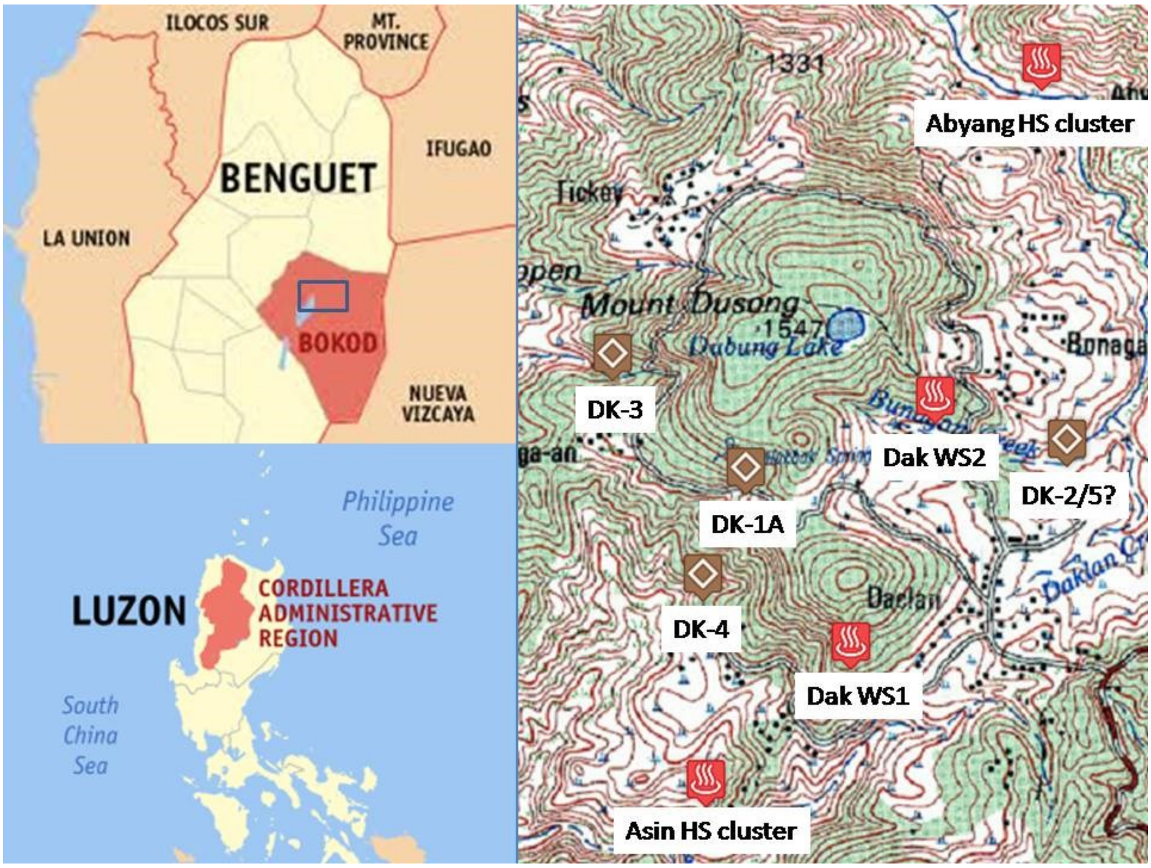


Figure 1: Location map of the Daklan geothermal prospect. Lower left: location of the Cordillera Administrative Region relative to Luzon Island. Upper left: approximate location of the geothermal prospect within Benguet province. Right: topographic location of Daklan geothermal prospect. Adapted from Halcon, 2013.

Geothermal resource assessment comes in several methods, but all aims to define a resource that can be utilized economically. The study of Clothworthy, et. al. (2006) reveals a worldwide trend for financing geothermal projects through stock market listing. However, this process depends on the level of technical data that suggests a good geothermal prospect. It is then important for a projct to be characterized with a high level of certainty. Several authors (Muffler and Cataldi, (1978); AGEA (2010); Sanyal and Sarmiento (2005) and Clothworthy et al (2006)) have presented various categorizations that define geothermal reserve and geothermal resource mainly based on economic utilization.

The area has been studied extensively by the Philippines Bureau of Energy Development (BED), Italy's Electro-Consult (ELC) and PNOC-EDC (now EDC) during the 1980's. This paper is focused on the evaluation of existing data of the Daklan geothermal prospect to estimate its resource capacity with the use of "stored heat (volumetric) method" and "Monte Carlo simulation".

2. OVERVIEW OF THE DAKLAN GEOTHERMAL PROSPECT

2.1 Geology

The Daklan geothermal prospect, along with other prospect areas in the Cordillera Administrative Region belongs to the Luzon Central Cordillera Volcanic Belt. The geothermal prospects in this area are related to the Plio-Quaternary volcanic centers of andesite to dacite composition which are related and connected to the North Cordillera Quartz Diorite Complex straddling the central region of the Northern Luzon.

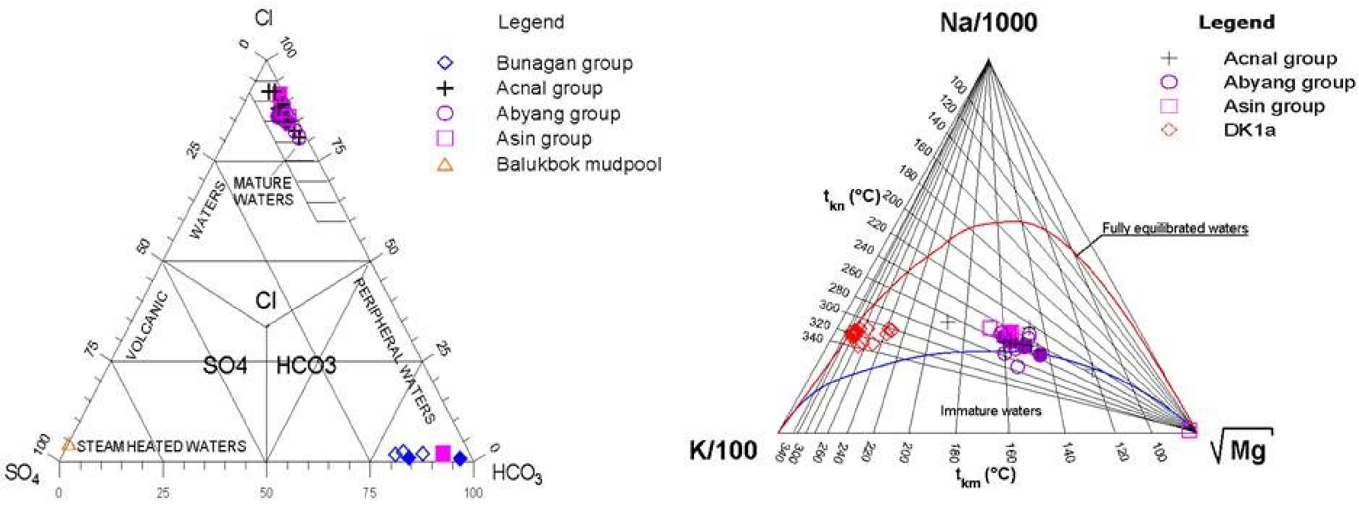
The geology of the Daklan geothermal prospect is represented by the lithologies identified by BED-ELC (1980a) and PNOC-EDC (1982), namely: recent volcanic, hornblende quartz diorite, volcano-sedimentary complex and metamorphosed basement. The volcano-sedimentary complex, believed to be the reservoir, is further subdivided into volcano-sedimentary breccias, a deeply fractured basalt and volcaniclastics, and alut sedimentary unit that overlie the volcanic-sedimentary breccias; this unit is impervious and fine grained.

The area is also surrounded by a volcano-tectonic depression (lower rightpicture in Figure 1) having a surface area of 13 km^2. and is bounded by the Asin creek to the east and to the NW by a semi-circular fault. A NE-SW normal fault defines the geothermal prospect along with a NW-SE trending normal faults that delimits the volcano-tectonic depression. The faults and the volcano-tectonic depression acts as structural control mechanism on the lateral extent of the geothermal reservoir as hot springs occurs along the boundary of the abovementioned structure. It is postulated (PNOC-EDC 1982) and (FEDCO 2011)that lithologic contacts, fractures, joints and faults controls the permeability of the Daklan geothermal field.

Thermal manifestations located in the area are found to be in the form of solfatara, hot springs and warm springs. The occurrence of intensely bubbling mudpool at the peak and 55-80^{0}C hot springs in the periphery of the volcano-tectonic depression indicates an active convection in the reservoir.

2.2 Geochemistry

Spring waters in the Daklan geothermal prospect can be basically classified under three groups based on the Cl-SO_4-HCO_3 ternary diagram shown in Figure 2:



(a) (b)

Figure 2: a) Cl-HCO3-SO4 ternary diagram of the spring waters. b): Na-K-Mg ternary diagram of the thermal waters of Daklan geothermal prospect. Adapted from Halcon (2013).

1) *Neutral Na-Cl waters*, represented by waters located along the boundary of the volcano-tectonic depression. Figure 2 (a) indicates that the spring waters occurring at the Acnal, Asin and Abyang creeks travels through the NW-SE and SW-NE trending faults are neutral sodium chloride waters which are reservoir water representative.

2) Neutral HCO_3 waters represented by waters along the middle of the Daklan dome.

3) Acid SO_4 waters found in the vicinity of the solfatara and bubbling mudpool.

Only two out of the five wells drilled in the area were reported that they have been successfully discharged, due to tight formations (FEDCO 2011). From these wells, DK1a sample, when plotted in Na-K-Mg ternary diagram, plots at the full equilibration region. According to Figure 2 (b), relative reservoir temperature calculations based on the geothermometry calculations for the samples taken from springs and well discharge estimates the reservoir to host geothermal fluids at a temperature of greater than 300 °C.

2.3 Geophysics

The resistivity survey done by both BED-ELC (1980c) and PNOC-EDC in FEDCO (2011)has identified a conductive layer within the volcano-tectonic depression. It has a thickness between 150-500 m and domes below Dusung Lake, showing the likely location of the upflow region. The base of the conductive layer is at 800 to 1200 m below the surface. The dark blue ellipsoid in Figure 3 shows the resistivity anomaly at 800 m below surface. The geophysical surveys have delineated a resistivity anomaly ranging from 4 to 10 km^2 taken from PNOC-EDC (1982) as cited in FEDCO (2011).

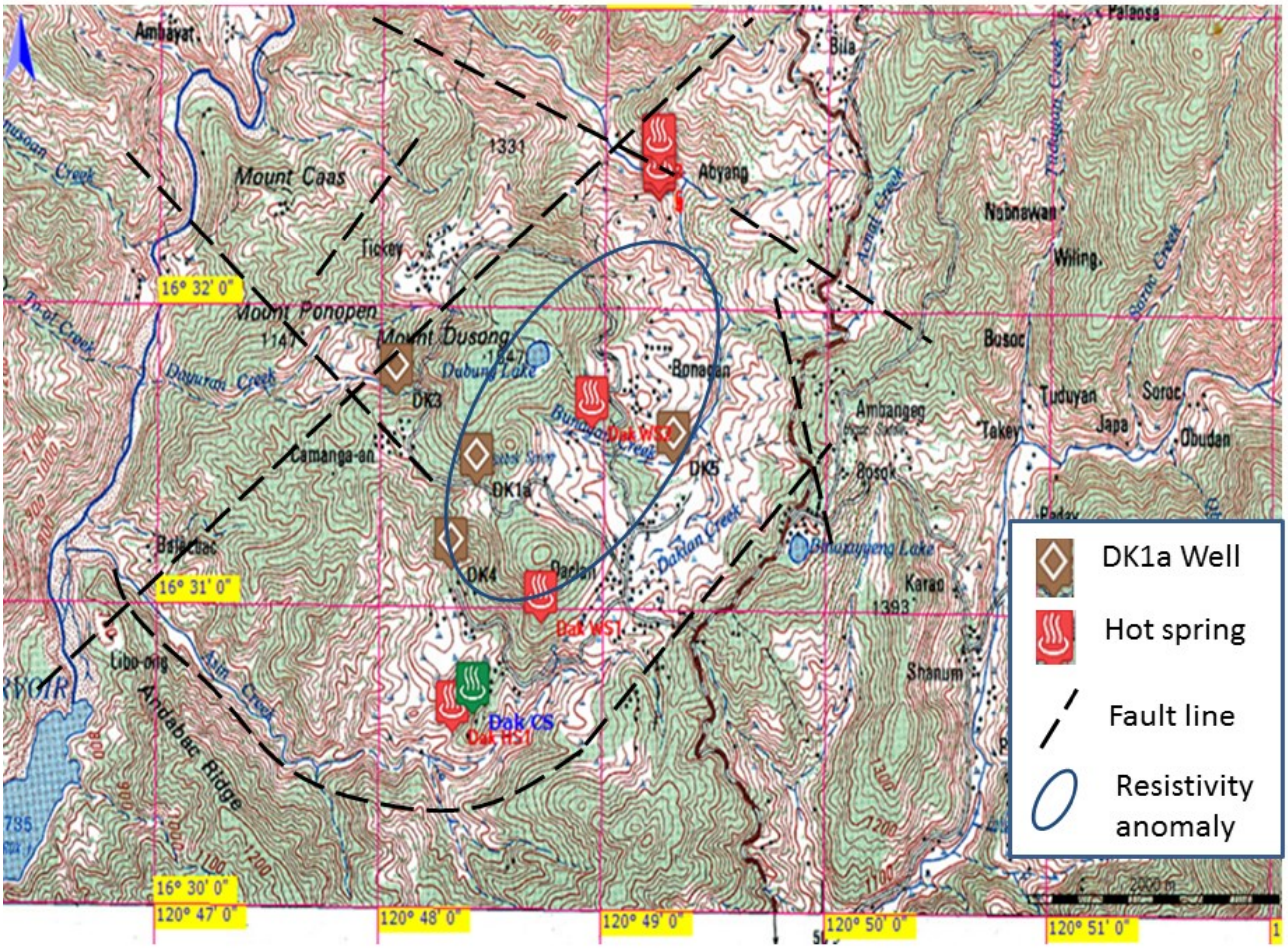


Figure 3: Modified postulated resistivity anomaly adapted from PNOC-EDC (1982) from FEDCO (2011). Blue oval is an approximation of the bottom of the conductive layer

2.4 Drilling activities

Thermal gradient and deep exploratory drilling were conducted in the area. Both have confirmed that the Daklan geothermal prospect hosts a high temperature reservoir. However, it was also confirmed that the area has limited permeability as displayed by the two out of the five deep well that were able to discharge after stimulated by air compression.

DK1a and DK4 have been drilled near the upflow zone. However, it was only DK1a that was able to sustain flow for almost a year, producing from 0.6 to 2 MW (Datuin 1986) and to at least 3 MW (Tolentino 1984). The flowrate recorded for DK1a is 14kg/s and discharge enthalpy of 1285 kJ/kg. According to geothermal resources categories defined by Kaya et. al. (2011), the Daklan geothermal prospect is a medium enthalpy 2-phase liquid dominated field. It was also noted that despite a 293 m fish on DK1a, it was still able to discharge, indicating better permeability in the area. The maximum recorded bottomhole temperature at DK4 is 290^0C and DK1a is 281^0C (Figure 4).

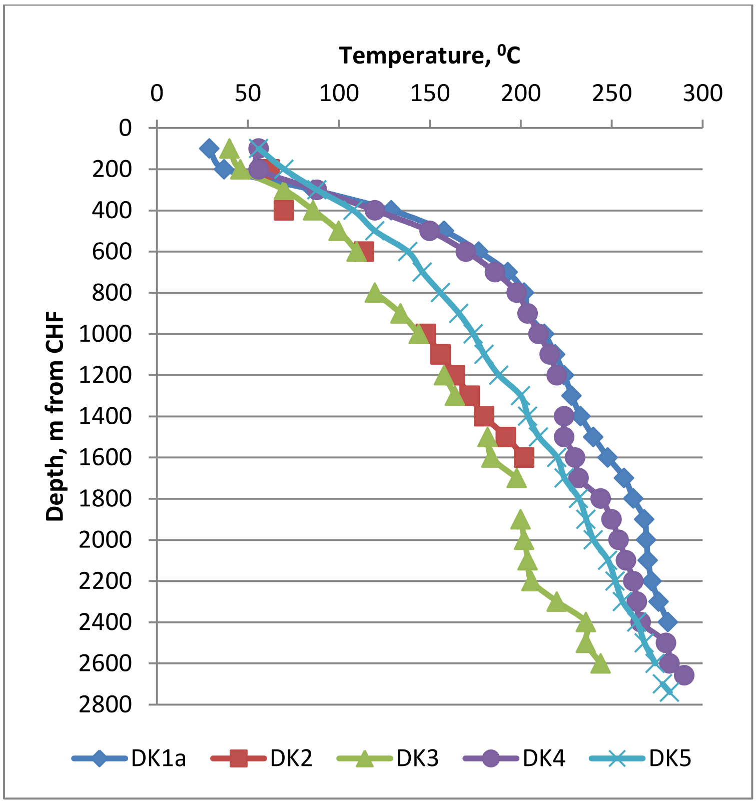


Figure 4: Temperature profile of Daklan deep exploratory wells.

3. CONCEPTUAL MODEL

The result of the studies conducted by BED-ELC (1980d)and PNOC-EDC (1982) revealed a high temperature, medium enthalpy; liquid dominated geothermal resource located in Daklan, Bokod, Benguet. Geological studies show that the geothermal fluid is probably hosted by the andesite-basalt breccia of the volcano-sedimentary complex. Likewise, the location of the thermal manifestations is typical of a high terrain geothermal area. The presence of an actively bubbling mudpool in a high elevation and neutral Cl hot springs in lower elevation is also an indication of an active fluid convection in the area. The Daklan geothermal prospect covers an area of approximately 4 km^2 to 10 km^2. km within the volcano-tectonic depression.

Convective fluid flow in the reservoir is controlled by structures and lithologic contacts. It ascends near DK1a and outflows towards the Abyang and Asin creek, where neutral Cl hot springs are located. The ascending fluid encounters flashing and the separated steam heats-up the local ground that produces the bubbling mudpool in Balukbok.

The existing data, suggests that the Daklan geothermal prospect hosts a small reservoir limited within the volcano-tectonic depression. However, the review of FEDCO (2011) suggests that the resource may still host a resource extension towards the NE based on the existing MT data

Figure 5 shows conceptual model of the Daklan geothermal prospect on a vertical SW-NE slice through the field, based on the analysis of data obtained from temperature profiles from the wells, geochemical, geophysical and geological information.

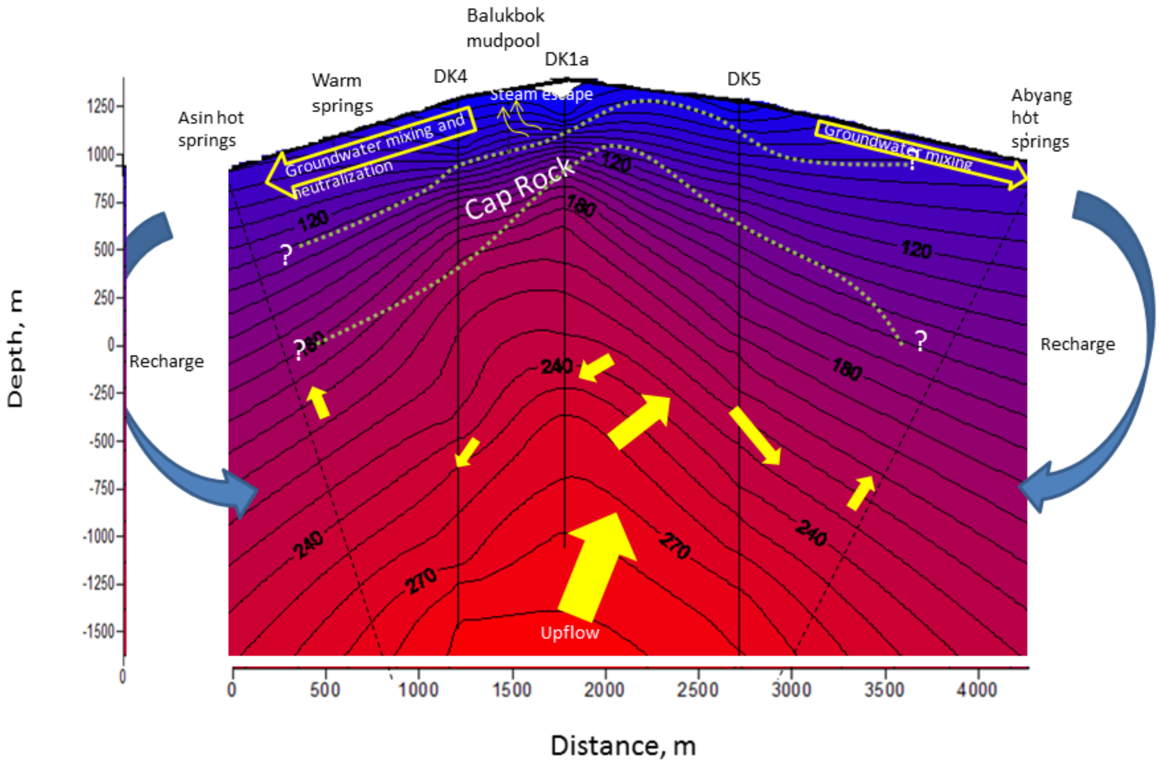


Figure 5: Conceptual model of the Daklan geothermal prospect modified from Halcon (2013).

4. RESOURCE ASSESSMENT

Resource assessment is the estimation of the amount of thermal energy that can be extracted from a geothermal reservoir and used under certain assumed economic, legal, and technological conditions for a period of time (Sarmiento 2011); Arkan and Parlaktuna(2005). The Mckelvey diagram illustrates the economics of the geothermal base, based on the degree of geologic assurance. Here, resource is defined as the useful accessible resource base while reserve is the part that is identified and economical.

Assessment of geothermal resources involves determination of the size and geoscientific characteristics of each resource area to calculate the accessible resource base (*residual and useful thermal energy* stored in the reservoir) and the resource (*recoverable thermal energy*).

The methods used for resource assessment vary depending on the available information at different stages of geothermal development. The accuracy of the methods depends on the available information and their certainty. Whilst several methods are commonly used in the industry for resource assessment (e.g surface thermal flux method, power density method, numerical reservoir modelling), in this study, stored energy and producible heat energy of Daklan geothermal prospect were determined by applying volumetric (stored heat) method.

4.1 Volumetric method

The volumetric method, also known as stored heat method is based on the calculation of thermal energy recoverable within a certain volume of rock.

The stored heat method is normally used initial stages of development, before production (Sanyal and Sarmiento 2005;Zarrouk and Simiyu(2013). Stored heat method uses parameters that can be measured or estimated and the calculation involves the identification of key reservoir parameters, such as reservoir thickness, reservoir thermodynamic conditions, reservoir size and temperature.. The uncertainties in the method are defined by the use of probability distribution to give reasonable estimates (AGEA 2010). The major uncertainties in the stored heat method identified from various sources are the correct estimation of reservoir size, recovery factor and temperature distribution (Zarrouk and Simiyu 2013).

The theoretical maximum quantity of useful heat, *Hth*, which is available for utilization, is given by the equation (O'Sullivan 2013):

$$Hth = Hi - Hf \quad (1)$$

$$Hi = \sum_{j=1}^{n} Aej(i)Vj \quad (2)$$

$$Hf = \sum_{j=1}^{n} Aej(f)Vj \quad (3)$$

where, *Hth, Hi, Hf, Ae* and *V* are quantity of useful heat, initial stored heat in the reservoir, final stored heat in the reservoir, energy content and reservoir volume, respectively. The suffixes j, i and f on the other hand are division of temperature range, initial and final states, respectively.

The energy content, *Ae*, is given by:

$$A_e = (1-\Phi)\, \rho_r c_r\, T + \Phi\, (\rho_l u_l S_l + \rho_v u_v S_v) \tag{4}$$

From $h=u + P/\rho$, equation (4) can also be written in the form of enthalpy (h):

$$Ae = (1-\Phi)\, \rho_r c_r\, T + \Phi\, (\rho_l h_l S_l + \rho_v h_v S_v - P) \tag{5}$$

Where, Φ, ρ, c_r, h, S, P and T are *porosity (%), density (kg/m^3), rock specific heat (J/kg K), enthalpy (kJ/kg), liquid and vapor saturations, saturation pressure (Pa), and temperature (^{0}C)*. Equation 4 is considered to be fundamentally correct way of calculating the energy content, rather than by using enthalpy only (S. J. Zarrouk 2013). It is explained by Zarrouk (2013) that reservoir fluid is considered immobile prior to production, but once production starts, the fluid will have flow energy. Although the difference is relatively small, fundamental laws should be observed for consistency.

Equation (1) can be rewritten as:

$$H_{th} = A.h.\{[(1-\Phi)\, \rho_r.c_r.\, (T_i-T_f)] + \Phi\, (\rho_{vi}.S_v.\, (h_{vi}-h_{lf}) + \rho_{li}.\, S_l.(h_{li}-h_{lf}) - (P_{si}-P_{sf})]\} \tag{6}$$

The power plant capacity (W_e) can then be calculated from:

$$We = \frac{Hth.Rf.nc}{L.F} \tag{7}$$

Where, R_f, η_c, L and F are recovery factor, conversion factor, power plant life (seconds) and power plant factor, respectively.

4.1.1 Calculation Parameters

Reservoir thickness–The thickness of reservoir is measured from the bottom of the conductive layer (800 amsl) up to the depth of the producing well, DK1a, plus an additional 500m. The additional 500m, as discussed by Sarmiento and Steingrimsson(2011), is reasonable as there are still good evidence of permeability still exists at depths 2500-3000 meters as seen in the field of Tongonan Philippines and Larderello, Italy. In this case, Daklan's reservoir thickness ranges from 1600 to 2393 m.

Areal extent – the areal extent of the reservoir is usually taken from the results of resistivity survey because geothermal reservoirs are usually characterized by substantially reduced electrical resistivity relative to their surroundings. They mainly represent conductive layer which is the formation of cap rock that serves to contain the geothermal fluid. The bottom of this conductive layer is usually measured as the area of the reservoir. The areal extent of the Daklan geothermal prospect was measured from Figure 3covered by the base of the conductive layer, which is around 4.0 km^2. Both area and thickness can still be subdivided further by considering the distribution of temperature gradient. The areal extent of the 270°C and 240°C was taken as the most likely and minimum reservoir area while the conductive layer is the maximum area.

Rock porosity – rock porosity is defined as the ratio of volume of pore space to the volume of the system. Unless a geothermal area has been extensively cored or studied, values for porosity is usually assumed. Zarrouk(2013) suggestthe values range from 0.1 to 0.3. However, due to the inherent low permeability zones encountered by the wells drilled in the area, an assumed range of 0.05 as the minimum and 0.1 as the maximum will be used.

Rock density – to estimate the rock density of a Greenfield geothermal area, the correlation made by Vosteen and Schellsmidt(2003) was used, with values ranging from 2688 to 2789 kg/m^3.

Rock specific heat – to estimate the specific heat of the rock, which is temperature dependent, the correlation by Vosteen and Schellsmidt(2003) was used, with values ranging from 925 to 930 J/kg ^{0}C.

Reservoir fluid – Tolentino and Buning(1984) showed that DK1a has an average discharge enthalpy of 1285 kJ/kg. As per geothermal resource classification Kaya et. al. (2011), the Daklan geothermal prospect hosts a medium enthalpy 2-phase, liquid dominated reservoir. For simple computation, liquid saturation was assumed S=1.

Reservoir temperature–the bottom hole temperature taken from DK1a (281^{0}C) and DK4 (290^{0}C) will be considered for the volumetric reserve estimation. The values taken from geothermometry in excess of 300^{0}C will not be considered as this will give large results. Likewise, for the Monte Carlo simulation, the average reservoir temperature will be considered. A cut-off temperature of 180^{0}C is also adapted.

Recovery factor–reserve estimation is especially sensitive to recovery factor and conversion efficiency. The values used usually varies but are also not supported by reasonable justification on its use. Based on the review given in SKM (Lawless 2007) which propose an empirical equation (R_f=2.5 x Φ) for natural convective reservoirs, a recovery factor of 2.5 times porosity was used for this study.

Conversion efficiency–it is the ratio of net electric power generated to the geothermal heat produced (S. J. Zarrouk 2013). From the work of Moon and Zarrouk(2012), conversion efficiency is dependent on the resource temperature/enthalpy.

Plant factor – power plant factor is a combination of plant availability for generation and ratio of actual output to its optimum design for certain production time. For this study a plant factor of 90% is considered as a reasonable assumption.

Plant life–a geothermal project in the Philippines is initially given a 25 year contract, thus a plant life of 25 years is adapted.

4.1.2 Summary and result of volumetric reserve estimation

The volumetric reserves estimation may tend to underestimate, because possible recharge of hot fluids underneath the reservoir is taken into consideration (AGEA 2010, Zarrouk, 2013) and may overestimate based on the parameters to be used. It is especially sensitive with regard to volume and recovery factor, so the identification of these values should be given due consideration. The result of the calculation reveals that the Daklan area can support a 72 MWe development for 25 years.

4.2 Monte Carlo simulation

Monte Carlo simulation technique is used as the probabilistic approach for the assessment of low temperature geothermal field. This method relies on a specified probability distribution of each of the input variables and generates an estimate of the overall uncertainty in the prediction due to all uncertainties in the variables (Kalos and Withlock, (2008). For estimating geothermal production capacity, this method is applied to the parameters of the volumetric stored heat equation where the parameters are allowed to vary over a range of values and within a defined probability distribution function (PDF) (Lawless 2007).

For each uncertain variable, possible values with a probability distribution needs to be defined. The common types of PDF's are:
1) Log normal, 2) Triangular, 3) Uniform and 4) Lognormal.The type of distribution that can be selected is based on the conditions surrounding that variable. The probability distribution functions used in this study are summarized in Table 1.

Table 1: Probability distribution functions used in this study

Parameter	**Probability Distribution**
Reservoir volume	Triangular
Porosity	Lognorm
Rock parameters	Constant
Reservoir temperature	Triangular; maximum temperature: 270^0C; most likely: 260^0C. Based on the reservoir temperature distribution.
Rejection temperature	180^0C
Liquid properties	Function of temperature
Recovery factor	Function of porosity
Conversion efficiency	Function of reservoir property
Load factor	Triangular

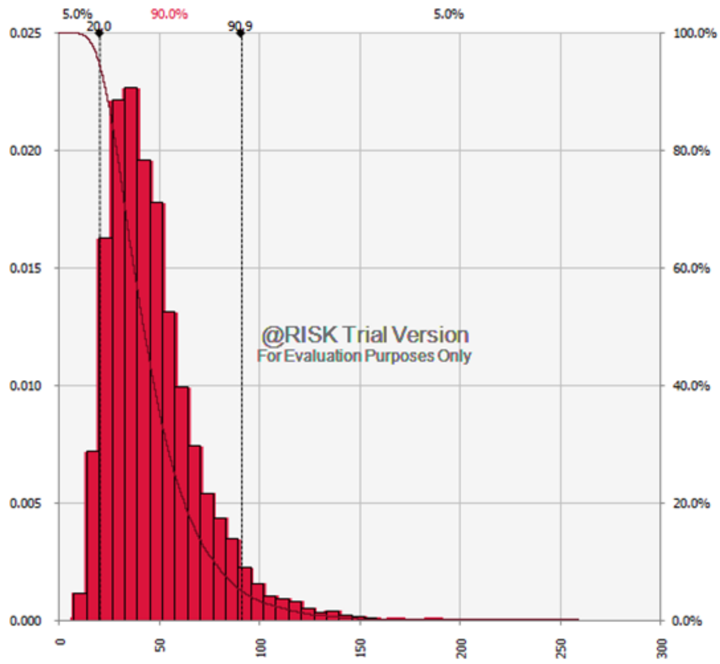
The results of the Monte Carlo simulation are generally presented as a histogram of occurrences of a particular value and as a plot of the cumulative distribution function (CDF). The values are given in the minimum, maximum, mean, mode and median distinctions. The mode is defined as the most likely or the value identified with most frequency in a particular distribution function. The mean is the average of all values while the median is the middle of the highest and lowest values. For this paper, a trial version of the commercially available spreadsheet-based software - @Risk (Palisade Corp. 2013), will be used for the Monte Carlo simulation.

4.2.1 Results of the Monte Carlo simulation

The three categories proposed by Sanyal and Sarmiento (2005) to the cumulative probability of estimated reserve was considered for this study:

- "Proven" – P90 or 90% probability, minimum values
- "Proven + Probable" – lesser value between the results of mode (most likely) or median (P50 or 50%)
- "Proven + Probable + Possible" – P10 or 10% probability, maximum values.

As it can be seen in Figure 7 and Table 2, the Daklan geothermal prospect is a relatively medium sized resource. The field has a proven + probable resource of 20-90 MWe, while it also shows the most likely capacity the field can support for 25 years is a conservative 30 to 35 MWe. On the other hand, while volumetric reserve estimation shows that the Daklan geothermal prospect can support a 72 MWe power plant for 25 years; Monte Carlo simulation reveals that this initial estimate is just one of the probable outputs when other uncertainties are considered. In fact, although histogram shows a maximum 91.2 MWe can be produced, there is less than 10% chance that the resource can support this with the given present exploration data.



Summary Statistics for POWER CAPACITY			
Statistics		Percentile	
Minimum	5.96	5%	20.04
Maximum	211.87	10%	23.55
Mean	47.05	15%	26.46
Std Dev	22.58	20%	28.75
Variance	509.822777	25%	30.99
Skewness	1.49326535	30%	33.40
Kurtosis	6.818027155	35%	35.64
Median	42.33	40%	37.79
Mode	34.96	45%	40.11
Left X	20.04	50%	42.33
Left P	5%	55%	44.82
Right X	90.01	60%	47.62
Right P	95%	65%	50.68
Diff X	69.97	70%	53.99
Diff P	90%	75%	57.69
#Errors	0	80%	62.16
Filter Min	Off	85%	67.98
Filter Max	Off	90%	76.29
#Filtered	0	95%	90.01

Figure 6: Histogram and Cumulative graphs for Power Capacity (left) and its summary statistics (right)

Table 1: Spreadsheet used in the study showing the input variables for the Monte Carlo simulation

INPUT VARIABLES	UNITS	MOST LIKELY	MIN	MAX	MEAN	SD	PROBABILITY DISTRIBUTION	
AREA	m^2	5,500,000.00	4,000,000.00	10,000,000.00			8,867,296.19	tri
THICKNESS	m	1893	1600	2393			2096.1151	tri
POROSITY	%				0.05	0.02	0.0469	lognorm
ROCK DENSITY	kg/m^3	2789					2789.0000	fixed value
ROCK SPECIFIC HEAT	kJ/kg.K	0.975					0.9750	fixed value
TEMPERATURE	^0C	260	240	270			255.2013	tri
FLUID ENTHALPY @ Ti	kJ/kg	1111.1152					1111.1152	=f(temp)
PRESSURE @ Ti	kPa	4337.0977					4337.0977	fixed value
FLUID DENSITY	kg/m^3	791.0524					791.0524	=f(temp)
REJECTION TEMPERATURE	^0C	180					180	fixed value
FLUID ENTHALPY @ Tf	kJ/kg	763.1880					763.1880	=f(temp)
PRESSURE @ Tf	kPa	1002.6346					1002.6346	fixed value
RECOVERY FACTOR	%	0.1172					0.1172	=f(por)
CONVERSION EFFICIENCY	%	0.0961					0.0961	=f(enthalpy)
LOAD FACTOR	%	0.9	0.8	0.95			0.8782	tri
PLANT LIFE	Years	25					7.88E+08	fixed value
	seconds	7.88E+08						

To further analyze the result of the Monte Carlo simulation, sensitivity analyses are done to investigate the impact made by changes in input parameters and assumptions to the overall output of a distribution function (Pannell 2013). The results are better appreciated with visual aids, such as the tornado and spider diagram.

It can be observed in Figure 8 that porosity has the greatest influence in the output of the Monte Carlo simulation. However, since the recovery factor is a function of porosity, from which porosity has a lognorm distribution, thus, indirectly, we can say the reserve estimate is also greatly influenced by recovery factor. @RISK automatically plots the variables with given uncertainty distribution, which in this case, recovery factor values vary with the logarithmic distribution of the porosity.

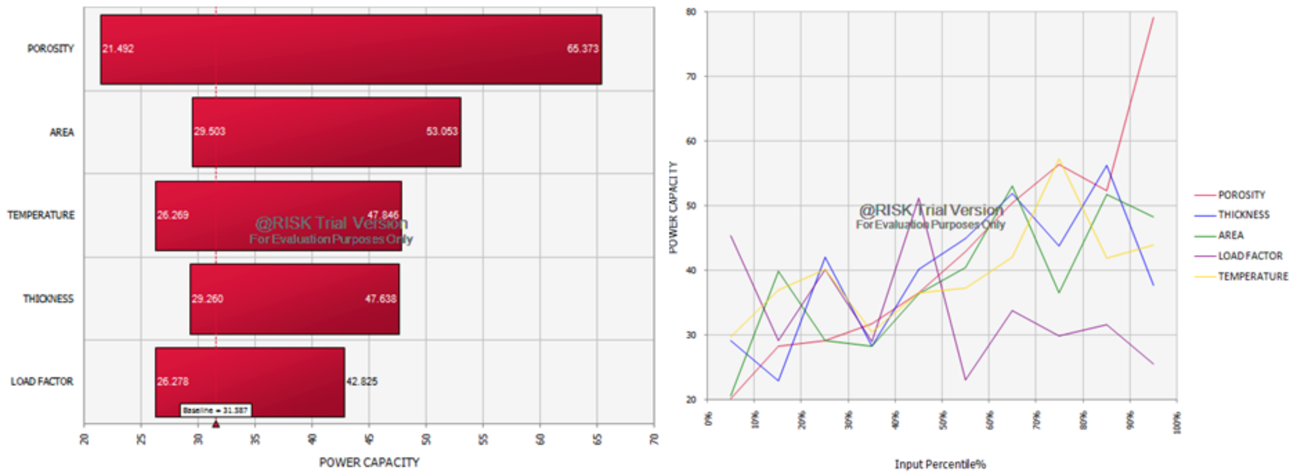


Figure 8: Tornado diagram (left) and Spider diagram (right) showing the inputs ranked by effect on the "mode" output of the Monte Carlo simulation. The effect of porosity is exaggerated as it is a function of recovery factor in the calculation of resource potential, thus recovery factor has the biggest effect on the Monte Carlo simulation done for the resource potential of the Daklan geothermal prospect.

5. CONCLUSIONS

During the early exploration phase, application of volumetric method along with Monte Carlo simulations is a commonly used technique in order to estimate the resource potential of a geothermal area. However in this method, estimates of important reservoir parameters are poorly constrained; hence it yields a rather wide distribution for the probable electrical megawatt capacity. Results can be very optimistic when it uses the best possible set of parameters taken from geoscientific studies. Likewise, it can be labeled as a conservative approach at the same time, because it computes for the stored heat only, ignoring recharge and constant heat supply.

In this study Monte Carlo simulation, Microsoft add-in software @Risk (trial version) was used for computing or iterating outcome scenarios from the assigned parameters with uncertainties. The result is presented in a form of histograms showing the frequency of values and cumulative plots that shows the percentage of the outcome. Depending on the use of a probability distribution function, the outcome of a Monte Carlo simulation varies. According to experiments we tried on the software, the most important factor in reserve estimation is the recovery factor, followed by reservoir volume and reservoir temperature. In this regard, volumetric calculations should always be done with Monte Carlo simulation to get the most acceptable reserve estimate of a geothermal field.

The Monte Carlo simulation done for the Daklan geothermal prospect, suggests that it can support the development of a 30 to 35 MWe power plant for 25 years. This estimate can still be conservative, since it is based on the current available data. Analysis of these data suggests that DK1a was drilled near the upflow zone. Although the discharge was minor, it was able to sustain this discharge even with stuck drill pipes in the well bore. Along with the encountered high bottomhole temperatures of the other wells and a possible resource extension anomaly identified by FEDCO (2011), the Daklan geothermal prospect merits further geoscientific studies in the area.

6. ACKNOWLEDGEMENT

The authors would like to thank the management of Renewable Energy Management Bureau headed by Director Mario C. Marasigan, the Department of Energy and Clean Rock Renewable Energy Resources, Corp. for the support and for allowing the publication of this paper.

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