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VOLUMETRIC RESOURCE ASSESSMENT

Zosimo F. Sarmiento[1], Benedikt Steingrímsson[2] and Gudni Axelsson[2]

[1]FEDCO – Filtech Energy Drilling Corporation
Tesco Compound, RMT Industrial Complex Tunasan, Muntinlupa City, 1773
PHILIPPINES
sarmiento@fedcophil.com
[2]ISOR – Iceland GeoSurvey, Grensásvegur 9, 108 Reykjavik
ICELAND
gax@isor.is
bs@isor.is

ABSTRACT

Geothermal resource assessment is the estimation of the amount of thermal energy that can be extracted from a geothermal reservoir and used economically for a period of time, usually several decades. Various methods have been developed for this purpose. At early stages of geothermal development, when available data are limited, relatively simple methods are used in assessing the reservoirs. But as more information are gathered on the reservoir parameters and experience is gained in producing energy from the reservoir, sophisticated numerical computer models are used to simulate the geothermal reservoir in the natural state and the response to utilization which eventually will determine the generating potential of the reservoir.

The main focus in this paper is on the volumetric method (stored heat calculations) and the key elements that constitute a thorough evaluation of a geothermal resource. Calculation of the geothermal energy reserves based on the range of values of the various reservoir parameters can be carried out using Monte Carlo simulation. It applies a probabilistic method of evaluating reserves or resources that captures uncertainty. Given the complexity and heterogeneity of the geological formations of most geothermal reservoirs, this method is preferred as opposed to the usual deterministic approach which assumes a single value for each parameter to represent the whole reservoir. Instead of assigning a "fixed" value to a reservoir parameter, numbers within the range of the distribution model are randomly selected and drawn for each cycle of calculation over a thousand iterations.

1. INTRODUCTION

Geothermal resource evaluation (*resource assessment*) is a process of evaluating surface discharge and downhole data, and integrating it with other geoscientific information obtained from geological, geophysical and geochemical measurements. The main focus of geothermal resource evaluation or resource assessment is to confirm that there exists a geothermal resource that could be exploited at a certain capacity for a certain period with well defined fluid characteristics and resource management strategies to ensure production sustainability over a long term period. Resource evaluation serves as a mechanism to verify if the project may be carried out from a technical standpoint by 1) defining the technical characteristics, selecting the best conditions after a technical and economical comparison of various development alternatives and 2) in choosing the type of plant and equipment design that would define their functional characteristics, their cost and implementation schedule and 3) assessing costs and benefits, economic and financial comparisons out of various alternatives as part of an overall project technical and financial feasibility studies.

An assessment of geothermal resources can be made during the reconnaissance and exploratory stage prior to well drilling; typically dealing with the extent and characteristics of the thermal surface discharges and manifestations, geophysical boundary anomaly, and the geological setting and subsurface temperatures inferred from geothermometers. The main feature of this evaluation is the presentation of a conceptual or exploration model that pinpoints the possible heat source and host of the geothermal reservoir. The results of this study serve as the basis for drilling shallow and deep exploratory wells to confirm the existence of a resource.

A discovery well drilled during the exploratory stage provides the basis for refining the preliminary conceptual model. By incorporating the results of drilling and well measurements and testing, reserves estimation needed in establishing the size of the reservoir and numerical modelling used in forecasting the future performance of the field can be conducted. Moreover, when planning to expand the capacity of an operating field, a resource assessment will describe the overall production history to show if additional reserves may be available to supply steam to the power plant.

This paper discusses the main elements of a geothermal resource assessment typically applied at early stages of geothermal development in the Philippines and Iceland. This mainly involves the volumetric method (stored heat calculations) with Monte Carlo simulation technique, which is named after the city of Monte Carlo in Monaco, where the primary attractions are casinos that play games of chance like roulette wheels, slot machines, dice, cards and others. It is a technique that uses a random number generator to produce and extract an uncertain variable within a distribution model for calculation in a given formula or correlation. Monte Carlo simulation became popular with the advent and power of computers; because the simulations are too tedious to do repeatedly.

The numerical simulation modelling is the preferred technique to determine the generating potential of the geothermal reservoir, when the exploration reaches the feasibility stage and through later developments and operation of the geothermal reservoir. The numerical reservoir modelling will be discussed in another paper at this short course.

2. THE GEOTHERMAL RESOURCE

2.1 Location

With a portfolio of various geothermal prospects, investors consider the location of a geothermal prospect as a primary factor in their project selection. Projects for exploration and development are ranked by looking first at the various risks associated with the resource characteristics or quality of fluids, size, geological risks or hazards and location with respect to the load centre or market. Given the same resource risks and characteristics, prospects that are close to the load centres and transmission grid are more likely to be chosen by investors for exploration and development. It also favours a project if the government prioritizes the development of infrastructures in the area where the resource is located. Prospects located in national parks and requiring special legislations before permits are issued for development are more likely to be at the end of the wish list of investors.

2.2 Stage 1 Surface Exploration Program

A geothermal surface exploration program is usually implemented in three phases starting from (1) a due diligence work which is carried out by thoroughly reviewing available information related to previous investigations of hot springs, fumaroles, silica mounds, solfataras and alteration zones as well as air-photo analyses and remote sensing studies, (2) field reconnaissance surveys including primarily the acquisition of geology and geochemistry data with a glimpse of what is expected on the environmental aspects of the area and 3) detailed exploration surveys consisting of geological mapping, geochemical sampling and geophysical measurements that can be used to delineate a potential geothermal reservoir and assist in the designation of possible exploration drilling targets (Richter et al., 2010).

In the Philippines, due diligence work is carried out through the regional identification of a prospect by identifying regional targets based on the association of most high temperature geothermal fields in the Philippines with the Philippine Fault; an active, left-lateral, strike slip fault dotted with Pliocene-Quaternary volcanoes, that forms a discontinuous belt from Northern Luzon to Mindanao. The Philippines has about 71 known surface thermal manifestations associated with decadent volcanism (Alcaraz et al., 1976). These are distributed in 25 volcanic centres as hot spouts, mud pools, clear boiling pools, geysers, and hot or warm altered grounds.

The results of a due diligence study rank the various geothermal prospects that have shown potential for exploration and development by carefully looking into the intensity and significance of the different thermal manifestations observed in the area. Immensely hot and widespread occurrences of thermal manifestations indicate a greater potential for a high temperature and large size reservoir. Acidic fluids are less preferred than the more benign fluids in view of the constraints imposed on handling the corrosion effects on casings and pipelines as well as the associated reservoir management problems during exploitation. The ranking of the field based on such geologic and geochemical parameters are then produced for selection and prioritization in each of the company's future project portfolios. This technique resulted in achieving a very high success ratio in the Philippines, by being able to discover high temperatures fields with exception of some areas that are lacking in permeability and those that have exhibited acid and magmatic fluids.

The field reconnaissance surveys will confirm what has been reported and seen from the areal photos and satellite images. Geologists and geochemists collect both rock and fluid samples, map out major surface manifestations, and then document all the observations that are significant to all the thermal areas for further investigations. The report should show the probable areal boundaries by which the detailed geological, geochemical and geophysical surveys will be conducted. It is on the basis of the results of the reconnaissance surveys that a budget is prepared to cover the expected cost of the detailed exploration surveys.

Following the identification of a more potentially resourceful area, detailed surface geological mapping, geochemical sampling and geophysical measurements are conducted. The results of the multi-disciplinary works are then integrated to draw out a hydrological model of the system, where the postulated upflow and outflow areas are described.

Previously the Philippines and Iceland have been very successful in using resistivity measurements (Schlumberger and later TEM) in discovering some of the operating geothermal fields in the countries today. But it can't be denied that more exploratory wells had to be drilled subsequently than today before the main sweet spots in those fields were identified. Recent application of Magnetotellurics (MT), which are found to have been able to predict more precisely the more drillable productive sections of the reservoir in Iceland and many other geothermal countries of the world, still have to make its mark in the Philippines, given the complex geological setting of the remaining areas that are being offered for concessions. Previously 1d interpretation of the data was carried out but with increased computer capacities joint three dimensional interpretation of TEM and MT data is routinely carried revealing more details in the resistivity structure of the geothermal reservoir than is possible with one dimensional interpretation.

With the construction of a conceptual or exploration model of the field from the results of the detailed surface exploration techniques, a pre-feasibility report is also prepared which similarly touches on preliminary cost estimation, financial analyses, market studies and environmental impact review.

2.3 Stage 2 Exploration Drilling Program

In view of the large drilling cost (of 3-5 million dollars per well) and the associated risk in hitting a good production well, it is at this stage when the need for a well-defined financial risk management strategy and instruments becomes extremely important. In the oil and gas industry, farm-in agreements are usually resorted to where additional investors or consortiums partners are invited to share in the cost of drilling. Financial institutions and other companies are willing to advance the cost of drilling in favour of a carbon trade mechanism.

The local geothermal industry in the Philippines and Iceland apply similar development strategy. The Philippines has explored 22 distinct high temperature resources, to an advanced stage and the exploration in Iceland includes detailed surface exploration and drilling of some 10 geothermal areas. Their development history has a general trend. Upon the integration of the multi-disciplinary exploration data from geology, geochemistry and geophysics for a selected area, a preliminary conceptual model is proposed. Drilling of 2-3 deep exploration wells ensues to validate the hydrological model and to confirm the existence of a geothermal system. Potential targets are identified within the closure of a resistivity or electrical sounding anomaly based on their chances of striking the upflow zones, penetrating permeable structures at depths. The first well is usually targeted towards the main upflow zone, where the chance of drilling a discovery well is high. The other two wells are drilled to probe for the lateral extension of the area; usually to block a well field equivalent to at least 5 km^2, sufficient enough for committing to a 50-100 MW generation potential. Once the existence of a geothermal system is confirmed after preliminary drilling, a resource assessment follows to determine the resource power potential. If the quality of the fluids is such that it could be used for commercial production, a volumetric estimate of the reserves is used for initially committing the size of the power station. The development of Mindanao I in the Philippines typified this approach where the results of the first two exploratory wells were used as a basis for building the 2 x 52 MW power station (Figure 1).

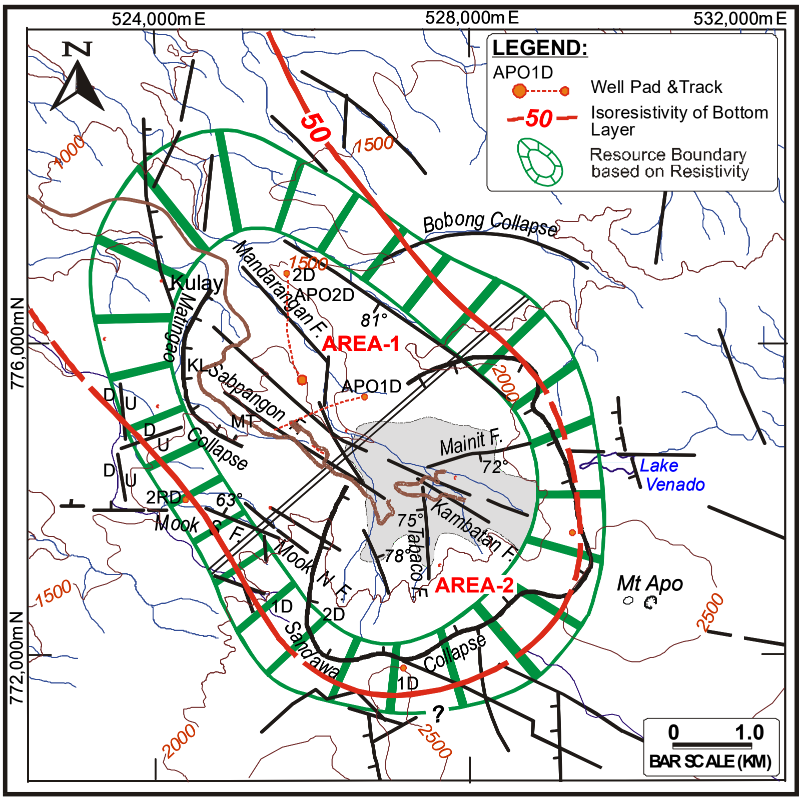

FIGURE 1: Exploratory well location map showing provisional resource boundary for Mindanao geothermal field. (Modified from Delfin et al, 1992)

Targeting the first well is the most difficult decision to make in a new project as its results may affect the final outcome of the project, especially if the results are not encouraging. If this happens, the decision to pursue drilling of the second well hinges fully on whether additional targets differed significantly and/or is entirely different on the first target. The third well is usually drilled only after the second well gives promise or provides a new perspective on the understanding of the prospect. Otherwise, it is cancelled.

2.4 Geology of the Exploration Wells

The subsurface geologic data indicates the equilibrium temperatures of minerals penetrated by the well from the top of the reservoir down to the bottom of the well. Obvious from the results are the alteration minerals commonly found in geothermal systems associated with a high temperature resource. Typical of these minerals are the elite, smectite and epidote. When these temperatures are compared with measured downhole temperatures, the relationship of the alteration minerals with respect to the equilibrium state and maturity of the system is established. If the alteration minerals indicate temperatures much higher than measured temperatures, a relict geothermal system or waning geothermal resource exists. Cooling of the fluids might have also taken place. Mineral assemblages like alunite are usually associated with acidic fluids and therefore their detection during drilling gives warning that the zone by which it was detected may have to be isolated. Other clay minerals are used during drilling to predict temperatures at depth like those of kaolinite, smectite and illite to be in the range of temperatures < 230°C; smectite, illite and quartz with fewer amounts of calcite and chlorite to be in the range of temperature >230°C; epidote, albite, calcite and anhydrite to indicate moderate temperatures of 200-300°C and potassic minerals near hot fluids to be indicative of >300°C of magmatic and high salinity fluids.

3. THERMAL ENERGY CALCULATION

The volumetric method refers to the calculation of thermal energy in- the rock and the fluid which could be extracted based on specified reservoir volume, reservoir temperature, and reference or final temperature. This method is patterned from the work applied by the USGS to the Assessment of Geothermal Resources of the United States (Muffler, 1978). In their work, the final or reference temperature is based on the ambient temperature, following the exhaust pressures of the turbines (for electrical generation). Many, however, choose a reference temperature equivalent to the minimum or abandonment temperature of the geothermal fluids for the intended utilization of the geothermal reservoir. For space heating the abandonment temperature is typically 30-40°C but for electricity generation the reference temperature is usually ~180°C (the separation temperature) for conventional power plants but as low as 130°C for binary plants. . It is important to keep in mind, however, that the efficiency used for the particular energy generation process be based on the same reference temperature, whatever reference temperature is selected.

The equation used in calculating the thermal energy for a liquid dominated reservoir is as follows:

$$Q_T = Q_r + Q_w \tag{1}$$

where

$$Q_r = A \cdot h \cdot [\rho_r \cdot C_r \cdot (1 - \emptyset) \cdot (T_i - T_f)] \tag{2}$$

and

$$Q_w = A \cdot h \cdot [\rho_w \cdot C_w \cdot \emptyset \cdot (T_i - T_f)] \tag{3}$$

The question to be raised is: What if the reservoir has a two-phase zone existing at the top of the liquid zone? Theoretically, it is prudent to calculate the heat component of both the liquid and the two-phase or steam dominated zone of the reservoir. However, a comparison made by Sanyal and Sarmiento (2007) indicates that if merely water were to be produced from the reservoir, only 3.9 percent is contained in the fluids; whereas, if merely steam were to be produced from the reservoir, only 9.6 percent is contained in the fluids. If both water and steam were produced from the reservoir, the heat content in the fluids is somewhere between 3.9 and 9.6 percent. Conclusively, all the fluids are in the rock and it doesn't matter whether one distinguishes the stored heat in water and steam independently.

This approach is illustrated by the following set of equations to separately account for the liquid and steam components in the reservoir:

$$Q_T = Q_r + Q_s + Q_w \tag{4}$$

where

$$Q_r = A \cdot h \cdot [\rho_r \cdot C_r \cdot (1 - \emptyset) \cdot (T_i - T_f)] \tag{2}$$

$$Q_s = A \cdot h \cdot [\rho_{si} \cdot \emptyset \cdot (1 - S_w) \cdot (H_{si} - H_{wf})] \tag{5}$$

$$Q_w = A \cdot h \cdot [\rho_{wi} \cdot \emptyset \cdot S_w \cdot (H_{wi} - H_{wf})] \tag{6}$$

and the parameters are as follows:

Q_T = Total thermal energy (kJ);
Q_r = Heat in rock (kJ);
Q_s = Heat in steam (kJ);
Q_w = Heat in water (kJ);
A = Area of the reservoir (m^2);
h = Average thickness of the reservoir (m);
Cr = Specific heat of rock at reservoir condition (kJ/kg°K);
C_l = Specific heat of liquid at reservoir condition (kJ/kg°K);
C_s = Specific heat of steam at reservoir condition (kJ/kg°K).
Ø = Porosity;
T_i = Average temperature of the reservoir (°C);
T_f = Final or abandonment temperature (°C);
S_w = Water saturation;
ρ_{si} = Steam density at reservoir temperature (kg/m^3);
ρ_{wi} = Water density at reservoir temperature (kg/m^3);
H_{si}, H_{wi} = steam and water enthalpies at reservoir temperature (kJ/kg); and
H_{wf} = Final water enthalpy at abandonment temperature (kJ/kg).

4. POWER PLANT SIZING

The above calculations only provide for the total thermal energy in place in the reservoir. To size the power plant that could be supported by the resource, the following equation is further introduced.

$$P = \frac{(Q_T \cdot R_f \cdot C_e)}{P_f \cdot t} \tag{7}$$

where P = Power potential (MW_e);
R_f = Recovery factor;
C_e = Conversion efficiency;
P_f = Plant factor; and
t = Time in years (economic life):

4.1 Recovery factor

Recovery factor refers to the fraction of the stored heat in the reservoir that could be extracted to the surface. It is dependent on the fraction of the reservoir that is considered permeable and on the efficiency by which heat could be swept from these permeable channels.

4.2 Conversion efficiency

The conversion efficiency takes into account the conversion of the recoverable thermal energy into electricity. More accurately the conversion can be estimated in two stages, first the conversion of the thermal energy into mechanical energy and later the conversion of the mechanical energy into electrical energy. This is not considered necessary, in view of all the uncertainties involved in the volumetric assessment method, so applying a single thermal-mechanical-electrical efficiency is considered sufficiently accurate.

4.3 Economic life

The economic life of the project is the period it takes the whole investment to be recovered within its target internal rate of return. This is usually 25-30 years.

4.4 Plant factor

The plant factor refers to the plant availability throughout the year taking into consideration the period when the plant is scheduled for maintenance, or whether the plant is operated as a base-load or peaking plant. The good performance of many geothermal plants around the world places the availability factor to be from 90-97%.

5. GUIDELINES FOR THE DETERMINATION OF RESERVOIR PARAMETERS

Recent developments in the geothermal industry require the establishment of guidelines on how reserves estimation is to be approached and reported in corporate annual reporting or financial statements. Sanyal and Sarmiento (2005) had proposed three categories for booking of reserves: proven, probable and possible; which are more appropriately estimated by volumetric methods. The reserves could be expressed in kW-h and/or barrels of fuel oil equivalent (BFOE). Conversion into MW unit should only be done when sizing up a power station for a period of time. Recently, Clothworthy et al. (2006), proposed to develop an agreed methodology for defining the reserves in order to increase market confidence in the industry and deter developers and consultants from quoting any figures they choose. The same categories of reserves are indicated except that the word inferred was used instead of the possible reserves. Lawless et al. (2010) is similarly proposing guidelines on methodologies and other consideration when preparing reserves estimation in response to the requirement of investment companies, especially, those listed in the stock exchanges.

5.1 Definitions

The need for an industry standard is now imminent following the above developments, to create consistency in declaring the estimated reserves for a given project. Sanyal and Sarmiento (2005) uses the result of Monte Carlo simulation to determine the proven, probable and possible or inferred reserves based on the resulting percentiles obtained from the cumulative frequency or the probability density function. The percentile value indicates the value of probability that the quantities of reserves to be recovered will actually equal or exceed. The above and all other definitions in this paper conform with SPE (2001), where the *proven* reserves will have a P90 (90 percentile) probability, P50 for the *proven*

+ *probable* reserves and P10 for the *proven* + *probable* + *possible* reserves. The histogram of geothermal reserves calculated by Monte Carlo simulation is often highly skewed; hence, the *proven* + *probable* is better represented by the *most likely* or the *mode* instead of the P50.

5.2 Resource

Resource is the energy which can be extracted economically and legally at some specified time in the future (less than a hundred years).

5.3 Reserves

Reserves are defined as quantities of thermal energy that are anticipated to be recovered from known reservoirs from a given date forward. A reserve is the part of the resources, which can be extracted economically and legally at present and that is known and characterized by drilling or by geochemical, geophysical and geological evidence (Muffler and Cataldi, 1978; Dickson and Fanelli, 2002).

5.4 Proven

Proven reserves are quantities of heat that can be estimated with reasonable certainty based on geoscientific and engineering data to be commercially recoverable from the present to the future, from known reservoirs under current economic conditions and operating methods and government regulation. The definition by Clotworthy et al (2006) and Lawless et al. (2010) give more specific descriptions, stating that a proven reserve is the portion of the resource sampled by wells that demonstrate reservoir conditions and substantial deliverability of fluids from the reservoir.

5.5 Probable

Probable reserves are unproven reserves which are most likely recoverable, but are less reliably defined than the proven reserves but with sufficient indicators of reservoir temperatures from nearby wells or from geothermometers on natural surface discharges to characterize resource temperature and chemistry.

5.6 Possible

Possible reserves have slighter chance of recovery than the probable reserves but have sound basis from surface exploration, such as springs, fumaroles, resistivity anomalies, etc., to declare that a reservoir may exist. Clotworthy et al. (2006) adopted the *inferred* resources from what could cover possible reserves based on McKelvey box as adopted by SPE (2001). Based on their graphic illustration, the probable reserve encompasses what could be categorized as only possible reserves in the Philippines (Figure 2). From *probable* to *possible* there is an increasing geoscientific and economic uncertainty whereas *inferred* connotes further geoscientific uncertainty only.

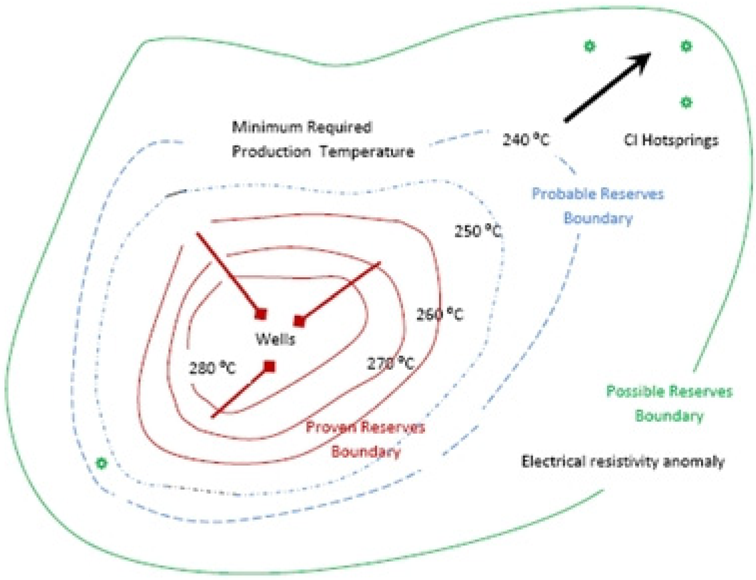

FIGURE 2: Illustration of the boundaries used in differentiating the three categories of reserves

The following guidelines or set of criteria are followed in the resource assessment and reserves estimation in the Philippines.

6. UNCERTAINTY DISTRIBUTION

The accuracy of the methods used in geothermal reserves estimation depends on the type, amount, and quality of geoscientific and engineering data, which are also dependent on the stage of development and maturity of a given field. Generally, the accuracy increases as the field is drilled with more wells and more production data become available. Volumetric estimation is most commonly applied during the early stage of field development to justify drilling and commitment for a specified power plant size. This method is better applied during the early stage than numerical modelling which requires significant number of wells and production history to be considered reliable. To be used for companies' annual reporting and to enhance corporate assets for valuation, booking of geothermal reserves could be performed during the maturity of the field (Sanyal and Sarmiento, 2005). However, because of the limited data and uncertainty on the assumptions on reservoir parameters, some degree of cautiousness and conservatism are also inputted. This approach which takes into account the risk factor in the decision making can be quantified with reasonable approximation using Monte Carlo Simulation.

Unlike a *deterministic* approach, where a single value representing a best guess value is used, the *probabilisti*c method of calculation is considered to account for the uncertainty on many variables in geothermal reserves estimation. As seen from Table 1, a range of possible reserves estimates could be obtained depending on the assumptions included in the calculation. In general, the proven reserves refer to the minimum, the probable reserves as the most likely or intermediate, and the possible or inferred reserves as the maximum. The Monte Carlo simulation performs the calculation and determines the estimate based frequency distribution of the random variables, which are dependent on the number of times a value is extracted from the uncertainty models of the input parameters.

The area and the thickness of the reservoir are usually assigned the triangular distribution because these parameters are obtained directly from drilling and well measurements. There is a good approximation of the resource area based on the temperature contours and electrical resistivity measurements; while drilling depths and indication of permeability and temperature are directly measured from the well. The deepest wells in Iceland are drilled to 3 km depth and even though the best permeability is found at 1 to 2 km depth good permeability has been encounter down to 2.5 km. There has been good evidence from wells currently drilled that permeability still exists at depths below 3,400 meters in the Philippines, (Golla et al, 2006) and down to 4000 meters in Larderello (Capetti and Cepatelli, 2005; Capetti, 2006) which could justify an addition of 500 meters beyond currently drilling depth range of 2500-3000 meters. The successful drilling in Tanawon located at the southernmost edge of Bacman proves a point that geothermal resource may really extend within or beyond the fence delineated by a geophysical anomaly, i.e., Schlumberger resistivity anomaly. The distribution model for these two parameters could be skewed appropriately depending on one's knowledge of the area.

Earlier volumetric estimation in the Philippines defined the lateral and vertical resource boundaries on the basis of the ability of many wells to flow unaided at minimum required temperature of 260°C. However, recent findings from the country's maturing geothermal fields indicate that this minimum temperature limit could be lowered to 240°C. Wells were recently observed to sustain commercial flow rate at this temperature, after the field had been produced sufficiently to cause boiling and expansion of two-phase zones in the reservoir. In New Zealand, wells are drilled to intersect temperatures of 180°C at shallower levels of the reservoir as the fluid has the ability to flow to the surface (Lawless, 2007b).

The porosity is usually assigned a log normal distribution following the observations of Cronquist (2001) quoting Arps and Roberts (1958) and Kaufmann (1963) giving that, in a given geologic setting, a log normal distribution is a reasonable approximation to the frequency distribution of field size, i.e., to the ultimate recoveries of oil or gas and other geological or engineering parameters like porosity, permeability, irreducible water saturation and net pay thickness. The mean and the standard deviation are however needed to be defined. All other parameters like fluid densities and specific heat are dependent on temperatures (Table 2).

The correlation between the recovery factor and porosity is shown in Figure 3, while the conversion efficiency and reservoir temperature correlation is shown in Figure 4.

TABLE 1: Guidelines followed in determining the various parameters for reserves estimation

Parameter	Proven	Probable	Possible/Inferred
Area	Defined by drilled wells with at least 500 meters beyond the drainage of the outermost wells bounded by an extrapolated production temperature of 240°C. Enclosed by good permeability and demonstrated commercial production from wells. Acidic blocks excluded until demonstrability for utilization is achieved.	Defined by wells with temperature contours that would extrapolate to 240°C to the edge of the field. Acidic or reinjection blocks earlier delineated could be included. Areas currently inaccessible because of limited rig capacity and restriction imposed within the boundaries of national parks. Areas with wells which could be enhanced by stimulation like acidizing and hydro-fracturing, by work-over of wells, other treatments or procedures which have been proven to be successful in the future. Areas with extensive surface manifestations where geothermometers indicate consistent or constant? temperatures >250°C.	Areas include those not yet drilled but enclosed by geophysical measurements like Schlumberger/TEM electrical resistivity and magneto-telluric surveys. Defined by areas with thermal surface manifestations, outflow zones, high postulated temperatures based on geothermometers
Thickness	Depth between the 180°C and the maximum drillable depth of the rig that has demonstrated commercial production. Maximum depth should have at least 240°C to warrant commercial output of the well.	Defined by demonstrated productivity in nearby areas or adjacent wells. Depth beyond the deepest well drilled in the area +500 meters provided projected temperatures reached at least 240°C at the bottom	Defined by demonstrated productivity in nearby areas or adjacent wells
Reservoir Temperature	Taken from direct measurement in production wells, supplemented by enthalpy and chemical geothermometers. Reservoir temperature should be at least 240°C to allow the well to self discharge	Extrapolated from temperature gradients and temperature distribution across the field or results of geothermometers using water, steam and gas from hot springs and fumaroles	Results of geothermometers using water, steam and gas from hot springs and fumaroles. Resistivity anomaly where high resistivity anomaly is seen blow conductive cap, indicating chlorite-epidote alteration at depth.
Base Temperature	Similar to the abandonment temperature, usually @ 180°C or at ambient temperature		

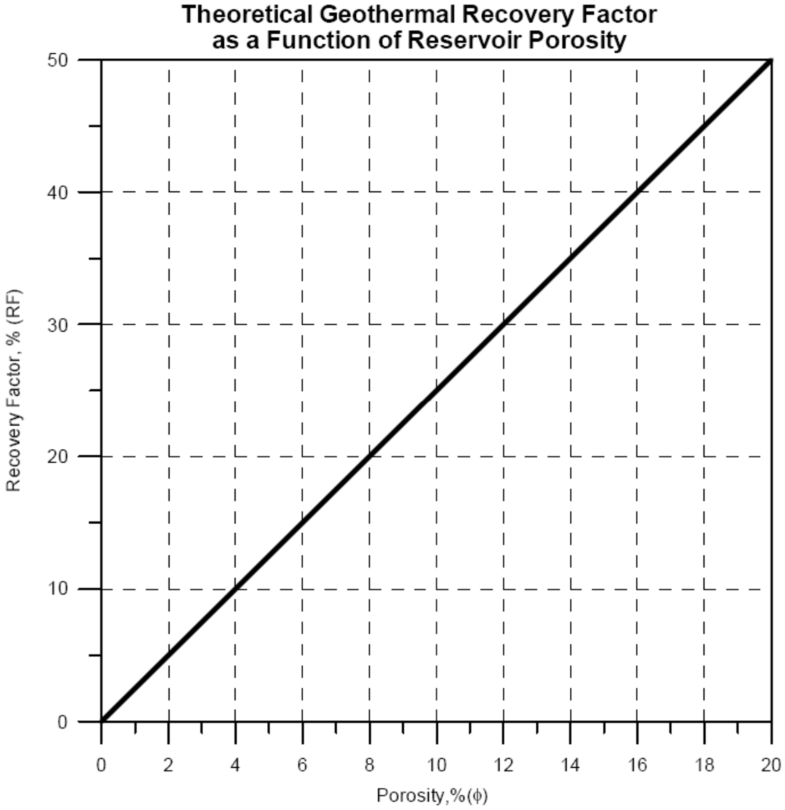

FIGURE 3: Correlation between recovery factor and porosity (After Muffler, 1978)

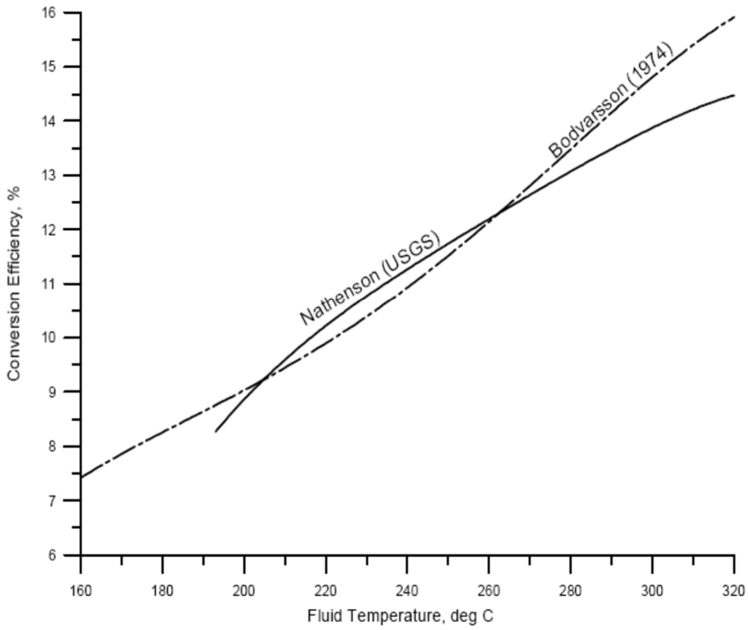

FIGURE 4: Correlation between thermal conversion efficiency and reservoir temperatures (From Nathenson, 1975 and Bodvarsson, 1974)

It has been practice to slice the reservoir into several layers to capture the variation in temperature, porosity, permeability and productivity. This full representation of the various properties of the entire field does not make the whole process more precise than when treating it as a single block in a Monte Carlo simulation, and is not necessary because all of the values in a given range for every parameter are inputted in the calculation.

7. THE MONTE CARLO SIMULATION SOFTWARE

The reserves estimation is done using commercial software that provides for a probabilistic approach of calculating uncertainty in the occurrence of events or unknown variables. The most common commercial software are Crystal Ball (2007) and @Risk which are used in assessing risks in investment, pharmaceuticals, petroleum reserves and mining evaluation. Monte Carlo simulation can also be programmed using an Excel or Lotus spreadsheet but the use of commercial software allow the user to take advantage of all the features required in a statistical analyses as follows:

- Graphs of input parameters and output, frequency, cumulative frequency, linear plot etc.;
- Statistics: minimum, mean, median, mode, maximum, standard deviation and others;
- Sensitivity test.

To obtain a good representation of the distribution sampling is done through 1000 iterations with continuous calculation.

7.1 The input cells

The Monte Carlo Simulation program is embedded in MS Excel spreadsheet and, like other programs, various cells that have links to the main output or target reserves need to be filled-up. A typical worksheet for volumetric reserves estimation is shown in Table 2.

TABLE 2: Typical worksheet and input parameters for Monte Carlo Simulation

VOLUMETRIC STORED HEAT RESERVE ESTIMATES								
Hengill Geothermal Field								
INPUT VARIABLES (USER DEFINED/DERIVED)	UNITS	MOST LIKELY	MIN	MAX	MEAN	SD	PROBABILITY DISTRIBUTION	
Liquid phase volume								
AREA	km²	100	80	120			107.5	triang
THICKNESS (liquid zone+500m	m	1500	1000	2000			1451.0	triang
ROCK DENSITY	kg/m³	3000	3000	3000			3000.0	triang
POROSITY					0.1	0.02	0.1	lognorm
RECOVERY FACTOR		0.230703591					0.2	=f(por)
ROCK SPECIFIC HEAT	kj/kg °C	0.85	0.85	0.9			0.9	triang
TEMPERATURE	°C	280	240	320			283.8	triang
FLUID DENSITY	kg/m³	748.67					748.7	=f(temp)
CONVERSION EFFICIENCY		0.13	0.127	0.141			0.1	=f(temp), tri
FLUID SPECIFIC HEAT	kj/kg °C	5.34					5.3	=f(temp)
PLANT LIFE	years	50					50.0	single value
LOAD FACTOR		0.95	0.9	1.0			0.9	triang
REJECTION TEMPERATURE	°C	180					180.0	single value
OUTPUT VARIABLE								
POWER CAPACITY								
	MWe (liquid)	886.6						
	MWe (total)	886.6						

7.2 Output

To obtain the required output, the user has to specify the targeted input and output to print and plot. In reserves estimation, the most important output of the program is related to the frequency plot of the thermal energy or its equivalent power plant size capacity.

The thermal energy or the plant capacity is usually plotted using the relative frequency histogram and the cumulative frequency distribution. The relative frequency of a value or a group of numbers (intervals or bins) is calculated as a fraction or percentage of the total number of data points (the sum of the frequencies). The relative frequencies of all the numbers or bins are then plotted, as in Figure 5, to show the relative frequency distribution.

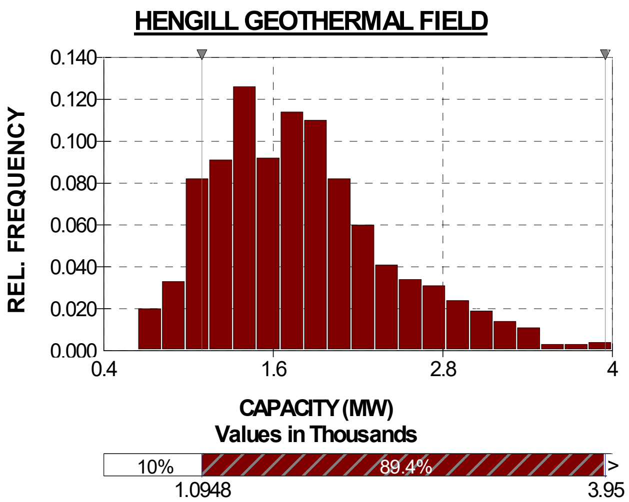

FIGURE 5: Relative frequency plot of the volumetric reserves estimation of the Hengill field (after Sarmiento and Bjornsson, 2007)

On the other hand, the cumulative frequency distribution is similar to a probability density function. It is plotted by cumulating the frequency or adding incrementally the relative frequency of each number

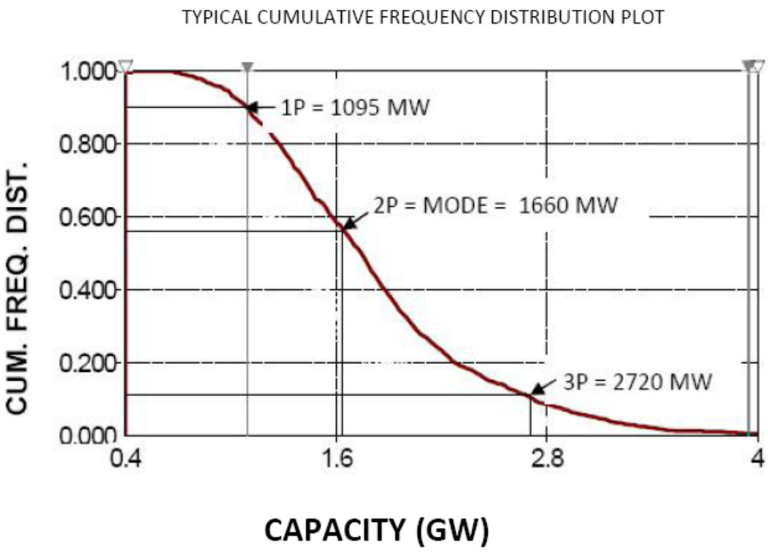

FIGURE 6: Illustration of a typical cumulative frequency plot of the volumetric reserves estimation.

or bins. Figure 6 is plotted by cumulating the frequency distribution from maximum value of the random variable to the minimum random variable. The vertical axis is then interpreted as representing the cumulative frequencies greater than or equal to given values of the random variable. The same plot could be represented in a reverse order, from minimum to maximum, but the vertical axis would then be interpreted as the cumulative frequency equal or less than the given values of the random variable. The cumulative frequency greater than or equal to the maximum value is always 1 and the cumulative frequency greater than or equal the minimum value is always 0. In Figure 6, the probability that the output is greater than or equal to 1,095 MW is 90 percent (*Proven* reserves); the probability that the capacity is greater than or equal to 1,660 MW is 55 percent (*Proven* + *Probable* Reserves, Mode or Most Likely); and the probability that the output is greater than or equal to 2720 MW is 10 percent (*Proven* + *Probable* + *Possible* or Maximum Reserves). These results imply that the field could initially support a 1,095 MW power plant for 25 years; possible expansion to 1660 MW will be subject to further delineation drilling and availability of field performance data. The risk that the field could not sustain 1,095 MW is equal to or less than 10 percent.

8. CONCLUSION

Geothermal resource assessment is the estimation of the amount of thermal energy that can be extracted from a geothermal reservoir and used economically for a period of time, usually several decades. The key elements vital to the successful evaluation of a geothermal resource consist of a thorough review of the exploration results, well discharge tests and application of the appropriate reserves estimation and numerical simulation techniques. The size and the quality of the reservoir fluids define the various options to be followed in planning for full commercial development of the field. The well chemistry takes special emphasis on scaling potential, acidity, high salinity and gas content of the reservoir.

Several methods have been developed for resource assessment. The methods used vary according to the availability of data on the reservoir, its inner structure, the natural state and reservoir response to utilization. Different methods are therefore applied at different stages of the development. At early stages of geothermal development when available data are limited relatively simple methods are used assessing the reservoirs but as the more information is gain on the reservoir parameters and experienced is gain in producing energy from the reservoir sophisticated numerical computer models are used to simulated the geothermal reservoir in the natural state and the response to utilization which eventually will determine its generating potential of the reservoir.

The preferred method in reservoir assessment in the early phases of geothermal development is the volumetric method. The volumetric method refers to the calculation of thermal energy in- the rock and the fluid which could be extracted based on specified reservoir volume, reservoir temperature, and reference or final temperature. Through the aid of a computer program using Monte Carlo simulation, a probabilistic approach of estimating geothermal reserves becomes less demanding. Some guidelines in the selection of the various reservoir parameters are needed to have consistency in the estimation. By this method, the risks associated with overestimating the size of a geothermal field could be quantified. Moreover, future expansion in the field could be planned in advance while drilling gets underway to confirm the available reserves.

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