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COMPUTER PROGRAMME FOR RESOURCE ASSESSMENT AND RISK EVALUATION USING MONTE CARLO SIMULATION

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ABSTRACT

The calculation of the geothermal energy reserves based on the range of values of the various reservoir parameters could be carried out using the Monte Carlo simulation. It applies a probabilistic method of evaluating reserves or resources that captures uncertainty. Given the complexity and heterogeneity of the geologic formations of most geothermal reservoirs, this method is preferred over 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. A Monte Carlo simulation handles this complex scenario which allows extraction of each uncertain variable. The results are then analyzed in terms of the probability of occurrence of the reserves and/or equivalent power output in the range of values over the resulting population. The probability distribution function (pdf) quantifies the upside potential and downward risk in sizing up the field power potential, and gives indication on the probable range of proven, probable and possible reserves.

1. INTRODUCTION

The Monte Carlo simulation is a numerical modelling technique, 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 uncertain variables within a distribution model for calculation in a given formula or correlation. The Monte Carlo simulation became popular with the advent and power of computers; which is too tedious to do repeatedly many times over.

The random behaviour in a game of chance is how Monte Carlo selects the occurrence of an unknown variable in one calculation, and repeated over and over again until the specified iteration cycle is completed. In playing a die, 1, 2, 3, 4, 5 or 6 could come out, but we don’t know which one would be in each roll. The same is true for the various parameters used in calculating the geothermal reserves e.g., area, thickness, porosity, reservoir temperature, recovery factors etc., which vary to a certain range of values but uncertain to a particular sequence in the calculation. To produce the desired results, unknown variables for each reservoir property are fitted into a chosen model distribution e.g., normal, triangular, uniform and log normal, based on the conditions or criteria established by the one most likely to have a better knowledge of the area being evaluated. The simulation then proceeds by extracting numbers representing the unknown variable and used as input into the cells in the spreadsheet until the whole process is completed.

2. THERMAL ENERGY CALCULATION

The volumetric method refers to the calculation of thermal energy in-place of the rock and the fluid which could be extracted based on a specified reservoir volume and reservoir temperature and reference or final temperature. This method is patterned from the works applied by the USGS on 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. 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 30-40°C but for electricity generation the reference temperature is usually assigned at 180°C for conventional power plants but as low as 130°C if binary plant is to be in place.

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

$$Q_T = Q_r + Q_w \qquad \textit{Equation (1)}$$

where:

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

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

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, comparison made by Sanyal and Sarmiento (2007) indicates that if only water is to be produced from the reservoir, only 3.9 percent is contained in the fluids; whereas, if only steam is to be produced from the reservoir, only 9.6 percent is contained in the fluids. If both water and steam where produced from the reservoir, the heat content in the fluids is somewhere between 3.9 and 9.6 percent. All the fluids are in the rock and it doesn't matter whether one distinguishes the stored heat in both water and steam independently.

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

$$Q_T = Q_r + Q_s + Q_w \qquad \textit{Equation (4)}$$

where:

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

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

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

and the following parameters as follows:

Q_T = total thermal energy, kJ/kg
Q_r = heat in rock, kJ/kg
Q_s = heat in steam, kJ/kg
Q_w = heat in water, kJ/kg
A = area of the reservoir, m^2
H = average thickness of the reservoir, m
C_r = specific heat of rock at reservoir condition, kJ/kgK
C_l = specific heat of liquid at reservoir condition, kJ/kgK
C_s = specific heat of steam at reservoir condition, kJ/kgK
$\emptyset$ = porosity
Ti = average temperature of the reservoir, °C
Tc = final or abandonment temperature, °C
S_w = water saturation
ρ_{si}, ρ_{wi} = steam and water density at reservoir temperature, kg/m^3
H_{si}, H_{wi} = steam and water enthalpy at reservoir temperature, kJ/kg
H_{wf} = final or water enthalpy at base temperature, kJ/kg

3. 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.

$$P = \frac{(Q_t \cdot R_f \cdot C_e)}{P_f \cdot t} \qquad \textit{Equation (7)}$$

Where:

P = power potential, MWe
R_f = recovery factor
C_e = conversion efficiency
P_f = plant factor
t = time in years (economic life)

4. 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 to be used for 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 kilowatt-hours 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 (2007) 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.

4.1 Definitions

The need for an industry standard is now imminent following the developments in the industry, where there is consistency in the reporting so that the same terms would have the same meaning when someone reports or declares the estimated reserves for a given project. Sanyal and Sarmiento (2005) used the result of the 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 estimates. 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.

4.1.1 Resourc

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

4.1.2 Reserves

Reserves are defined as quantities of thermal energy which are anticipated to be recovered from known reservoirs from a given date forward. Reserve is that part if the resources which could be extracted economically and legally at present and that are known and characterized by drilling or by geochemical, geophysical and geological evidence (Muffler and Cataldi, 1978; *Dickson and Fanelli*, 2002). It has to be noted that an estimate of reserves by volumetric method is not a guarantee to achieving a resulting level of generation unless it is demonstrated in the field that wells are able to produce at acceptable output. Geothermal resource as differentiated from reserves refers to all the heat underground.

4.1.3 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 (2007) give more specific descriptions as the portion of the resource sampled by wells that demonstrate reservoir conditions and deliverability of fluids over a volume of reservoir such that no substantive surprises can be expected by drilling in that volume.

4.1.4 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.

4.1.5 Possible

Possible reserves are those that have less likely chance of recovery than the probable reserves but with sound basis to declare with surface exploration results that a reservoir may exist based on surface manifestations e.g., natural thermal springs and fumaroles and geoscientific indications e.g. resistivity anomalies. 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 1). The term ***probable*** and ***possible*** signifies increasing geoscientific and economic uncertainty whereas ***inferred*** connotes only increasing geoscientific uncertainty.

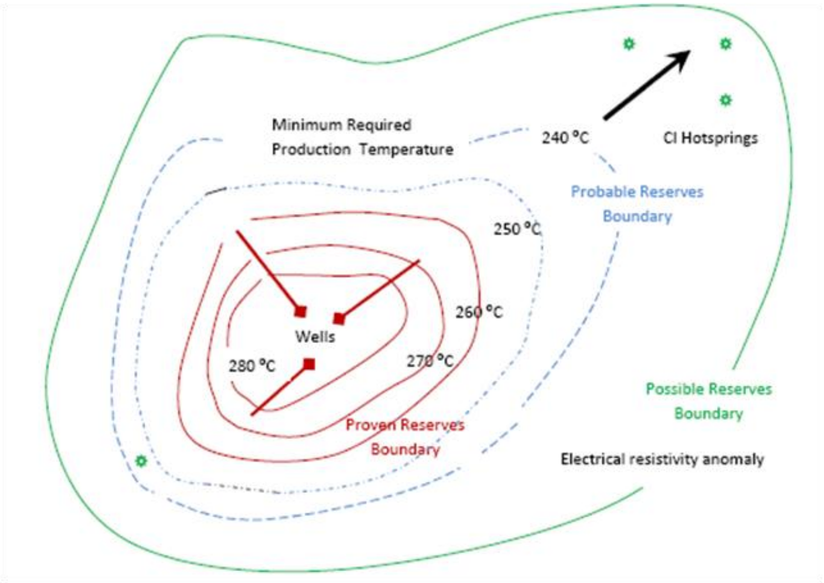


FIGURE 1: Illustration of the boundaries used in differentiating the three categories of reserves.

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

5. 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 becomes 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 this stage than numerical modelling which requires a 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 of 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 the Monte Carlo Simulation.

Unlike a ***deterministic*** approach, where a single value representing a best guess value is used, the ***probabilistic*** 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. The proven reserves refer to the minimum, the probable reserves as the most likely, and the possible or inferred reserves as the maximum.

TABLE1: 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 consistently temperatures >250°C.	Areas include those not yet drilled but enclosed by geophysical measurements like Schlumberger 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		

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. There has been good evidence from wells currently drilled that permeability still exists at depths from 3,400 meters in the Philippines, (Golla et al, 2006) and up 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 since they are still able to flow to the surface (Lawless, 2007b).

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.

The ***porosity*** **(ø)** value is usually assigned a log normal distribution following the observations of Cronquist (2001) quoting Arps and Roberts (1958) and Kaufmann (1963) 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 geologic or engineering parameters like porosity, permeability, irreducible water saturation and net pay thickness. A minimum porosity value of 6% is usually used in the Philippines with up to 10 % in some cases where the wells are found to be good producers. 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.

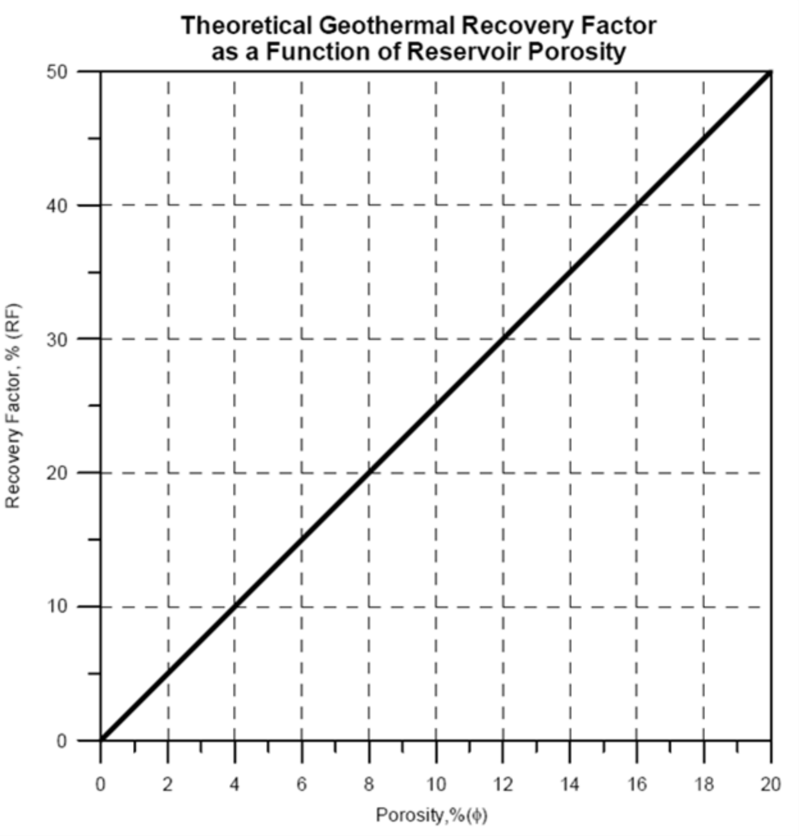


FIGURE 2: Correlation between recovery factor and porosity (After Muffler, 1978)

The correlation between the recovery factor and porosity is shown in Figure 2 while the conversion efficiency and reservoir temperature correlation is shown in Figure 3.

It has been a practice that the reservoir is sliced 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. This is not necessary because all of the values in a given range for every parameter are inputted in the calculation.

The ***conversion efficiency*** takes into account the conversion of the recoverable thermal energy into electricity

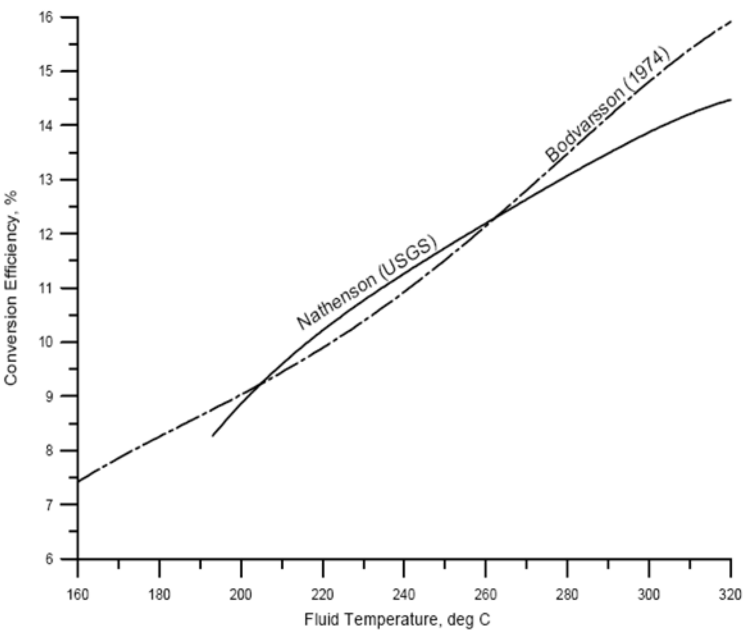


FIGURE 3: Correlation between thermal conversion efficiency and reservoir temperatures (From Nathenson, 1975 and Bodvarsson, 1974).

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 percent.

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.

6. THE MONTE CARLO SIMULATION SOFTWARE

The Monte Carlo simulation performs the calculation on the generation level or reserves estimates by extracting each of the uncertain parameters (random value) within the span of the minimum, most likely and maximum (triangular distribution). The random sampling and calculations are done for 1000 to 10,000 iterations and each result is sent to the bin to be compiled for the frequency distribution. Knowing the range of minimum, most likely and maximum values from the various input parameters, we could thus evaluate the risk and the probability of occurrence when a decision is made on the generation level.

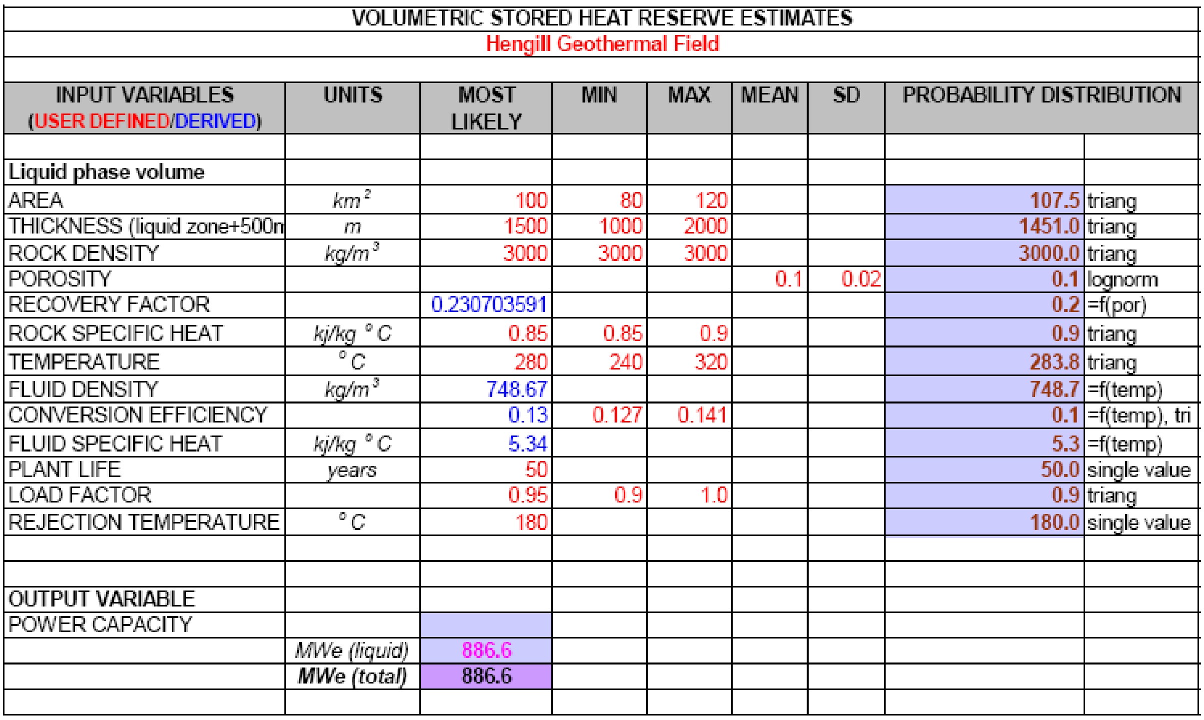
The reserves estimation is done using commercial software that provides for a probabilistic approach of calculating uncertainty in the occurrence of events or unknown variables. The most common commercial software are Crystal Ball (2007) and @Risk which are used in assessing risks in investment, pharmaceuticals,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

6.1 The input cells

The Monte Carlo Simulation program is embedded in an MS Excel spreadsheet and, like other programs, various cells that have links to the main output or target reserves need to be filled-up. Typical worksheet for volumetric reserves estimation is shown in Table 2 and was obtained using @Risk by Palisade Corporation.

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						

6.2 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 in Figure 4 to show the relative frequency distribution.

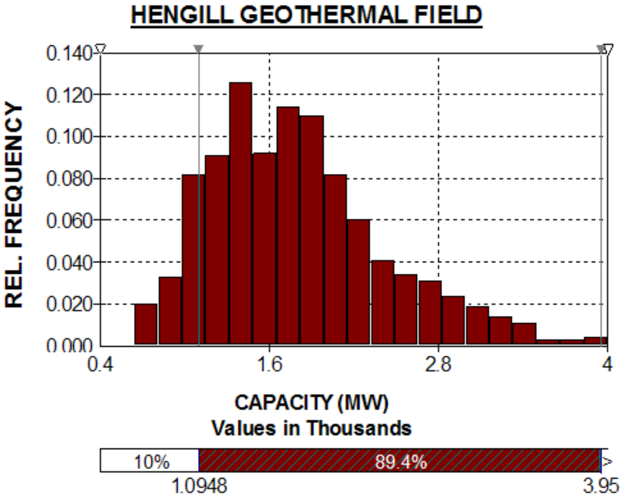


FIGURE 4: Relative frequency plot of the volumetric reserves estimation of the Hengill field (After Sarmiento and Bjornsson, 2007)

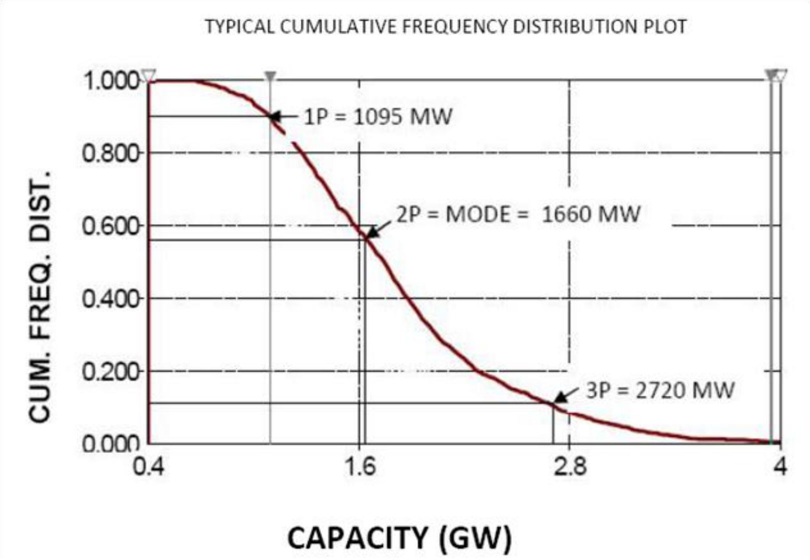


FIGURE 5: Illustration of a typical cumulative frequency plot of the volumetric reserves estimation.

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 or bins. Figure 5 is plotted by cumulating the frequency distribution from the 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 the given values of the random variable. The same plot could be represented in a reverse order, from minimum to maximum, but that 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 zero. In Figure 5, 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 2,720 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.

7. CONCLUSION

Through the aid of a computer program using The Monte Carlo simulation, a probabilistic approach of estimating geothermal reserves becomes handy. 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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