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GEOTHERMAL RESOURCE ASSESSMENT – CASE EXAMPLE, MENENENGAI PHASE I

Hilary Mwawasi
Geothermal Development Company
P.O. Box 17700 – 20100 NAKURU
KENYA
hmwawasi@gdc.co.ke

ABSTRACT

Resource assessment estimates carried out at various stages of geothermal development facilitate decision making by project stake holders. Due to a desire to have a systematic methodology in reporting exploration, resource and reserve findings the geothermal industry has developed codes aimed at facilitating this process. This paper discusses the volumetric method often used for assessment of resources at the early stages of geothermal development in Kenya by looking at a case example of Menengai phase I.

1. INTRODUCTION

Geothermal development is carried out in stages involving start-up (legal work, concession and permitting), surface exploration, exploration drilling, pre-feasibility, appraisal drilling, feasibility, production drilling/power plant design and construction, resource exploitation and project decommissioning. In the initial stages investment risk is high while capital outlay low, however later stages have higher capital outlay with a lower risk due to acquisition of information from preceding stages that aid in decision making. Resource assessment is the estimation of the amount of thermal energy that can be extracted from the resource and used economically over a period of time. The process is dynamic and often carried out periodically to update previous results based on greater understanding of resource characteristics, improvements in assessment methodologies, extraction and utilization technologies, economic, social and legal factors.

The geothermal industry has developed methodology for reporting geothermal exploration results and the assessment of resource and reserve estimates. Two codes notably exist (Australian and Canadian geothermal reporting code (AGRCC, 2010; Canadian Geothermal Code Committee, 2010) and mirror each other promoting transparency, consistency and confidence. Figure 1 shows a classification of geothermal resources and reserves as adopted in the two codes. Geothermal resources are classified to inferred, indicated and measured while geothermal reserves are categorised into probable and proven (AGRCC, 2010). Geothermal resources are classified based on increasing level of geological knowledge and confidence and directly affect the probability of their occurrence. Geothermal reserves are estimated from geothermal resources after consideration of modifying factors (e.g. production, economic, marketing, environmental, and social, land access rights, legal and regulatory) that affect the likelihood of commercial utilization. The general relationships and pathways between the various categories of geothermal resources and reserves as permitted in the codes are as shown.

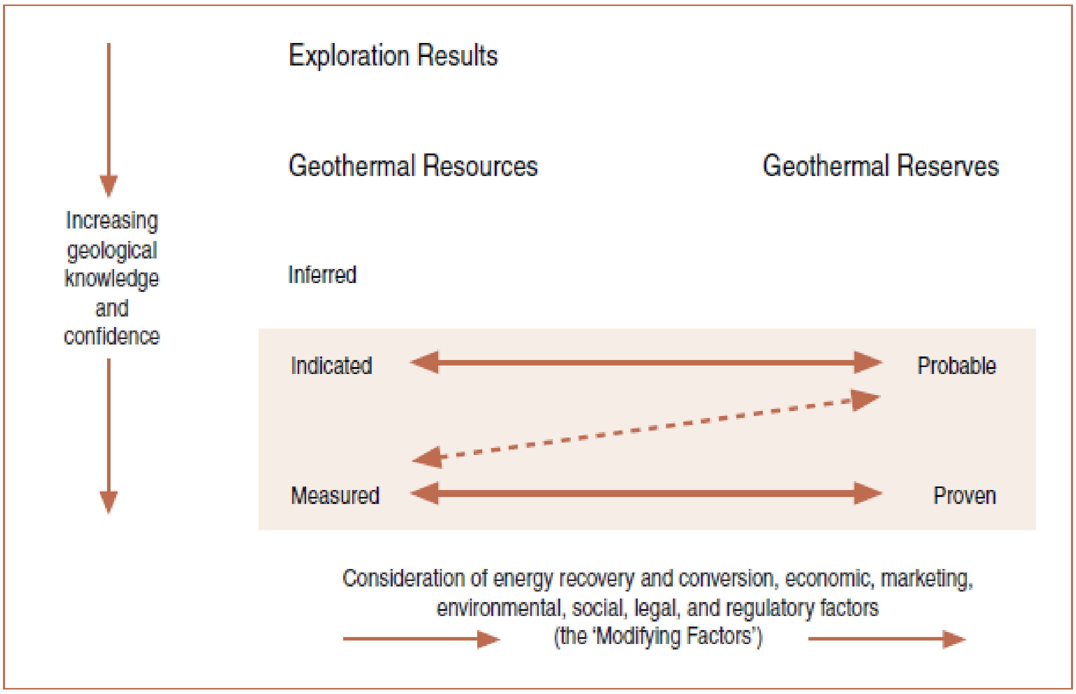

FIGURE 1: Classification of geothermal resources and reserves (AGRCC, 2010)

1.1 Terminology

Geothermal resource: Refers to accumulation of heat in rock and/or fluid in a form presenting prospects for eventual economic extraction.

Inferred geothermal resource: Part of a geothermal resource for which recoverable thermal energy can be estimated with a low level of confidence.

Indicated geothermal resource: Part of a geothermal resource which has been demonstrated to exist through direct measurements that indicate temperature and dimensions so that recoverable thermal energy can be estimated with a reasonable level of confidence.

Measured geothermal resource: Part of a geothermal resource which has been demonstrated to exist through direct measurements that indicate at least reservoir temperature, reservoir volume and well deliverability to enable recoverable thermal energy estimation with a high level of confidence.

Geothermal reserve: Is a portion of indicated or measured geothermal resource that is deemed to be technically and economically recoverable after consideration of both the geothermal resource parameters and modifying factors.

Probable geothermal reserve: Is the economically recoverable part of an indicated or measured geothermal resource in which the recoverable thermal energy estimate is affected by a greater uncertainty in terms of factors affecting the recovery of thermal energy such as well deliverability or longevity

Proven geothermal reserve: Is the economically recoverable part of a measured geothermal resource whose recoverable thermal energy estimate is done from a drilled and tested rock volume within which well deliverability have been determined and production from the field over the project lifetime can be forecast with a high degree of confidence.

Various resource assessment methods exist and include heat flow measurements, areal analogy (power density), volumetric methods, decline curve analysis, lumped parameter models and numerical reservoir simulation (AGEG, 2010). This paper discusses the volumetric method often used for assessment of resources at the early stages of geothermal development in Kenya.

2. VOLUMETRIC METHOD

The volumetric method computes the amount of thermal energy (heat) stored in the rock matrix by coupling the stored heat equation and Monte Carlo Simulation. The rock matrix in which the geothermal reservoir is hosted has void spaces that hold geothermal fluids. The total thermal energy is therefore an aggregate of heat contained by the rock and the geothermal fluid. The stored heat equation shown in equation 1 is used to calculate the thermal energy contained in the rock matrix using a set of input parameters to give an output value of thermal heat. This makes the model a deterministic one where as the geothermal resource under study is often characterized by uncertainty in its reservoir parameters. Typically the individual reservoir parameters present as a probability distribution and when randomly used give different results depending on the distribution function of the input parameters, the previously deterministic model is thus turned into a stochastic model due to the several calculations (iterations) depending on the set of random input parameters used.

$$H = V(T_r - T_a)\{(1-\phi)C_{pr}\rho_r + \phi C_{pf}\rho_f\} \tag{1}$$

Where: H = Stored heat (MWt);
V = Reservoir volume (m^3);
T_r = Reservoir temperature (°C);
T_a = Abandonment temperature (°C);
ϕ = Porosity (-);
C_{pr} = Rock specific heat (kJ/kg °C);
ρ_r = Rock density (kg/m^3);
C_{pf} = Fluid specific heat (kJ/kg °C); and
ρ_f = Fluid density (kg/m^3).

The final power estimate is then calculated using equation:

$$E = \left[\frac{HR_f\eta}{FL}\right] \tag{2}$$

Where: E = Power plant capacity;
R_f = Recovery factor;
η = Heat to electricity conversion efficiency;
F = Load factor; and
L = Plant life.

2.1 Monte Carlo simulation

Monte Carlo simulation also known as the Monte Carlo method is a mathematical technique that enables risk analysis by generating models of possible output values by randomly using a set of input values. It finds application in geothermal by allowing the use of probability distributions of geothermal resource parameters randomly as input to generate probability distribution curves or error bars and confidence levels of results in carrying out resource assessment. Though the method is appealingly simple, it is worth noting that resource parameter values should be based on current knowledge. In Ofwona (2014) emphasis is made on the need of choosing reservoir parameters inputs probability distribution that closely matches existing data collected and reflect current knowledge of the geothermal resource. Further the recovery factor (the portion of the resource that can actually be exploited), reservoir volume (dependent on the areal extent and thickness of the reservoir) and reservoir abandonment temperature are often possible reservoir parameters that have led to overestimates in resource assessment figures in the industry (Grant, 2014). General steps in conducting a Monte Carlo simulation are:

1. Create a parametric deterministic model, $y = f(x_1, x_2, \ldots., x_n)$;
2. Generate a set of random inputs, $x_{i1}, x_{i2}, \ldots., x_{in}$;
3. Evaluate the model and store the results as yi;
4. Repeat steps 2 to 3 for $i = 1$ to q; and
5. Analyse the results using histogram, summary statistics, confidence level etc.

3. CASE EXAMPLE – RESOURCE ASSESSMENT OF MENENGAI PHASE I

The Menengai geothermal field is located approximately 180km northwest of Nairobi and encompasses the Menengai volcano, the Ol' rongai volcanoes, Ol' banita plains and parts of the Solai graben to the northeast, an area measuring approximately 850 km^2 (Mibei and Lagat, 2011) bound by easting's 157000 and 185000 and northings 9966000 and the Equator. Menengai phase I has however been focused within the Menengai crater (Figure 2).

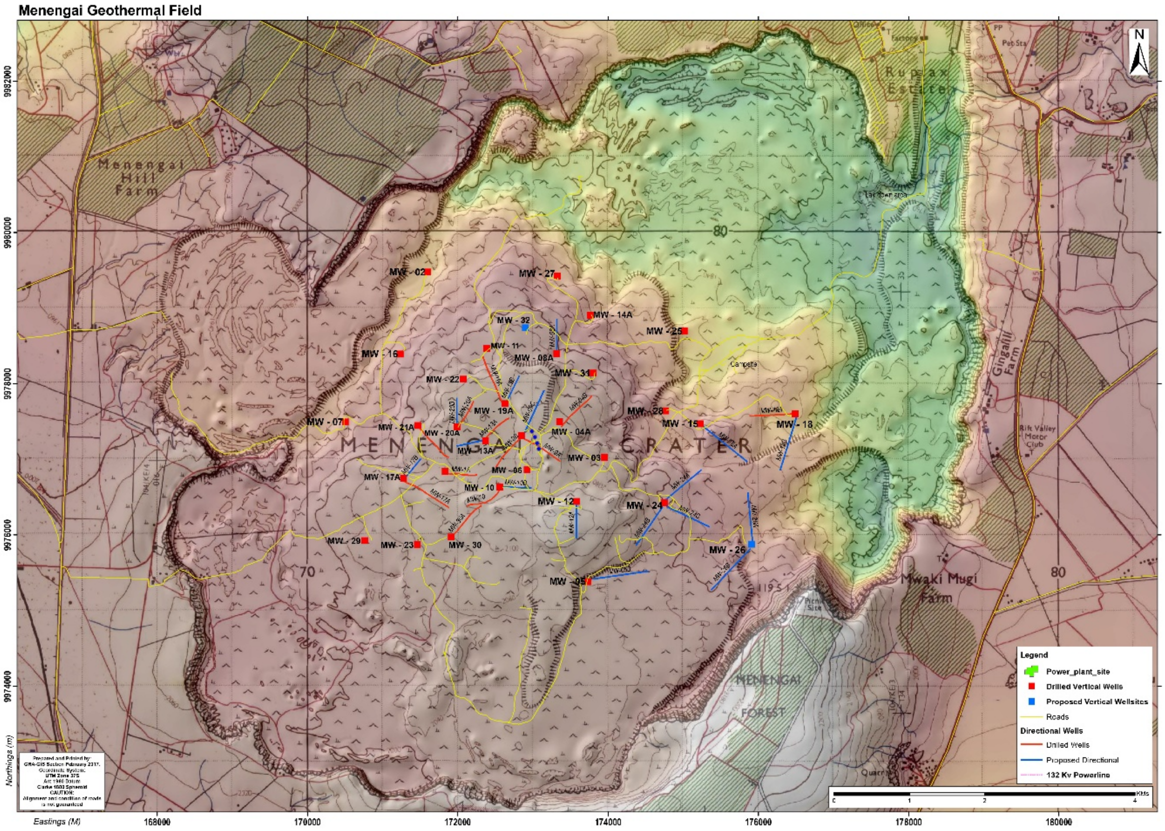

FIGURE 2: Map showing well locations over Menengai geothermal field

3.1 Reservoir properties

Menengai phase I is characterized by a shallow liquid dominated aquifer (occurring around 1200-800 masl) and a deeper vapor dominated aquifer (occurring below ~400 masl). Menengai wells at the summit area are predominantly vapor dominated while those outside seem to be liquid dominated.

3.2 Input data for Monte Carlo simulation

3.2.1 Reservoir area

The reservoir area in Menengai geothermal field as defined by the geophysical anomaly covering an area of approximately 37.9 km^2 over the extent of the caldera as shown in Figure 3. Downhole measurement data has hitherto constrained the reservoir extent based on the 250°C temperature contour at sea level to an area of 10 km^2 (Figure 4).

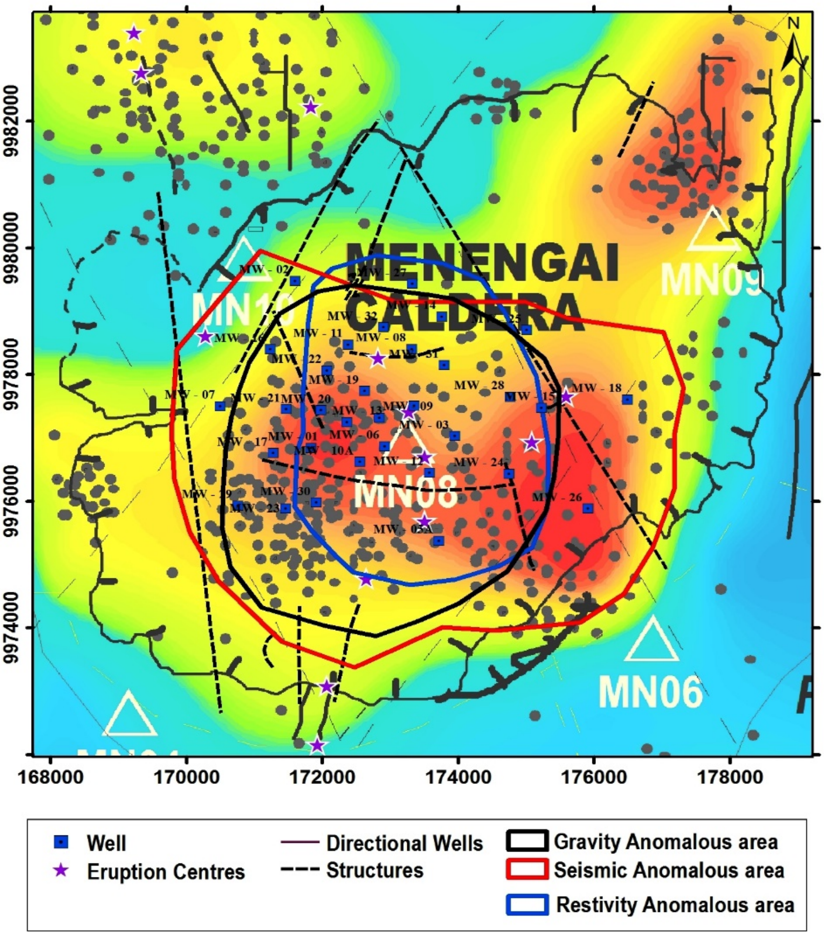

FIGURE 3: Geophysical anomaly map

3.2.2 Reservoir thickness

Reservoir thickness is limited by the presence of a shallow aquifer of lower temperature at a depth of 800 – 900 masl and a deeper high temperature one found at sea level and below. A triangular distribution was considered with most likely value of 700 m.

3.2.3 Rock density

A triangular distribution with a most likely value of 2600 kg/m^3 was used.

3.2.4 Porosity

Porosity values in the order 6% have been used for the Olkaria field (Ofwona, 2008). In Menengai values in the order 6 and 10 % have been used for the deep and shallow reservoir rock matrix respectively

(Kipyego, 2013) a log normal distribution with a most probable value of 7% and standard deviation of 0.01 was used

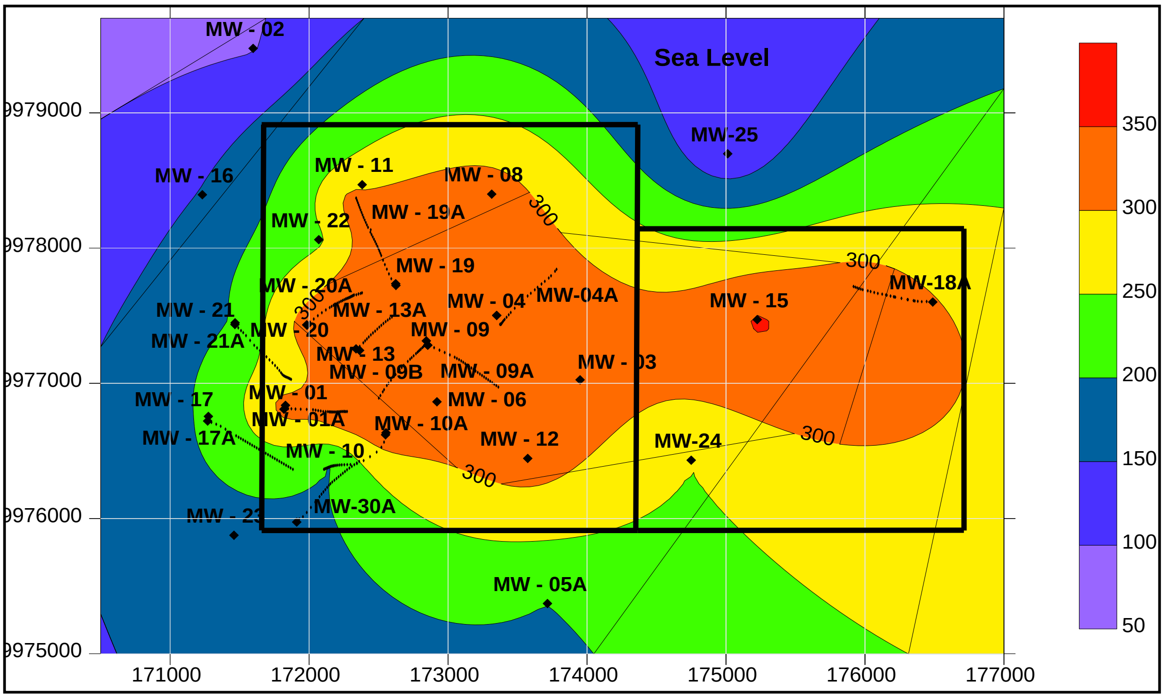

FIGURE 4: Temperature anomaly map

3.2.5 Recovery factor

A linear relationship exists between porosity and recovery factor (Muffler and Cataldi, 1978). For a porosity of 7% the Cataldi plot gives a recovery factor of 17.5%.

3.2.6 Reservoir temperature

A triangular distribution with a most likely value of 310°C was used. An abandonment temperature of 165°C was used considering conventional power generation schemes as the technology of choice.

3.2.7 Conversion efficiency

A conversion efficiency of 15.4% was used.

3.3 Stored heat calculation results

Results from the Monte Carlo Simulation are presented below. Table 1 summarizes the parametric table of the probability distribution of reservoir parameters used. The analysis used an excel spreadsheet tool and over 80,000 iterations were conducted. Results show a frequency distribution peak at a power output of 185 MWe (Figure 5), the probability distribution of results is however in the range from 55 to 445MWe. This is attributed to uncertainties of the input variables. Figure 6 consequently shows that there is a 50% possibility of exploiting more than 190 MWe.

TABLE 1: Input parameters for Monte Carlo simulation

Parameter	**Min.**	**Most likely**	**Max.**	**Distribution type**
Reservoir area (km^2)	10.00	23.95	37.90	Triangular
Reservoir thickness (m)	400	700	1000	Triangular
Rock density (kg/m^3)	2550	2600	2650	Triangular
Porosity (-)	-	0.07	-	Lognormal
Recovery factor (-)	-	0.175	-	Constant
Rock specific heat (kJ/kg°C)	-	1.00	-	Constant
Reservoir average temperature (°C)	290	310	330	Triangular
Reservoir average pressure (MPa)	4.90	6.37	7.85	Triangular
Heat-Electricity conversion efficiency (-)	-	0.154	-	Constant
Plant life (year)	-	25	-	Constant
Load factor (-)	0.90	0.92	0.95	Triangular
Abandonment temperature (°C)	-	165	-	Constant

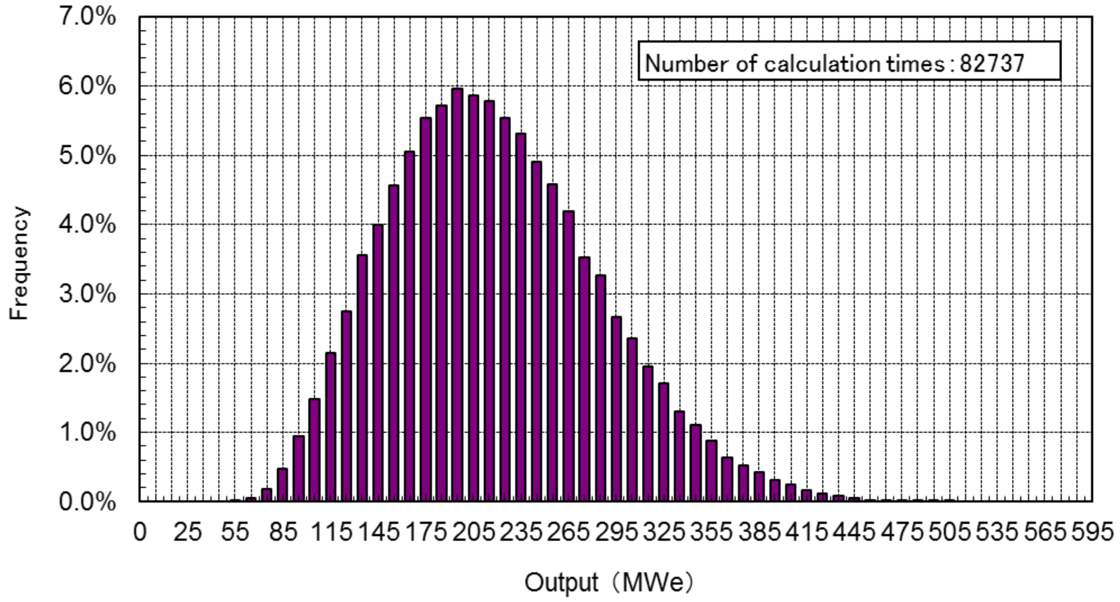

FIGURE 5: Frequency distribution of output power capacity

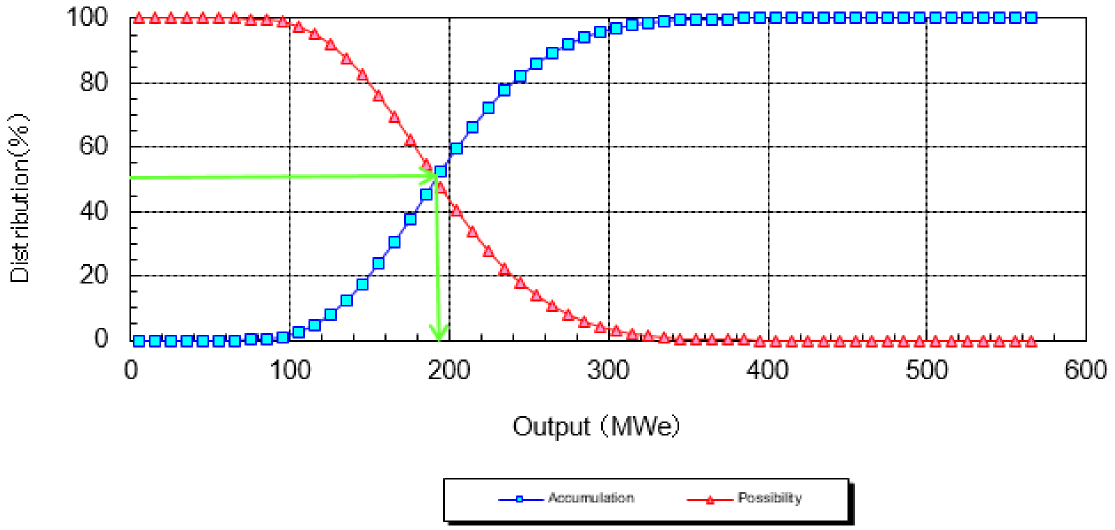

FIGURE 6: Cumulative frequency distribution

4. CONCLUSION

It has been demonstrated that the volumetric method can be used to evaluate a geothermal field with relative ease. The reliability of the estimates however depend on the range of reservoir parameter probability distribution and should therefore reflect closely the resource data collected and current knowledge of the field.

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