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GEOTHERMAL RESOURCE ASSESSMENT: CASE EXAMPLE, OLKARIA I

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ABSTRACT

Stakeholders are always eager to know the geothermal power potential of newly explored prospects so as to gain confidence in availing more resources for further work. At all levels of exploration whether at surface or deep drilling, there is always some uncertainty on data available and estimation of power potential becomes a big challenge. Stochastic (Monte Carlos Simulation) method is frequently used to estimate power potential of geothermal fields at early stages of exploration where data is scanty and uncertainties quite high. In this paper, this method is introduced and case example of its application to Olkaria I geothermal field presented.

1. INTRODUCTION

After successful exploration of a geothermal prospect, stakeholders are always eager to know its power potential. This comes as early as after completion of surface geo-scientific exploration or even after initial exploration drilling. The earlier estimates of power potential give confidence to the project owners to source for more resources to undertake subsequent stages of development. With high uncertainty and scanty data available during initial stages of exploration, stochastic and risk analysis methods are frequently used to estimate the range and probable distribution of stored heat reserves and hence, exploitable energy base of the newly explored geothermal prospect or fields. These methods have been borrowed from the oil industry where they have been used for a long time to estimate probabilistic hydrocarbon-in-place and oil and gas reserves in sedimentary basins.

2. MONTE CARLO METHOD

Monte Carlo Method is also called Monte Carlo Simulation or Stored Heat Method. The technique involves using random numbers and probability to solve problems. It iteratively evaluates a deterministic model using sets of random numbers as inputs. Deterministic models use a certain number of input parameters in few equations to give a set of outputs. They give the same results no matter how many times the problem is recalculated. Stochastic models on the other hand, use variable (random) inputs and give different results depending on the distribution functions of the input parameters. They are often used when the model is complex, nonlinear, or has more than just a couple uncertain parameters. The simulation can have as many evaluations as determined by available computers and time. The random numbers turn the deterministic model into a stochastic model.

In Monte Carlo Method, the objective is to determine how random variation, lack of knowledge or error affects sensitivity, performance or reliability of the system being modelled. The inputs are randomly generated from probability distributions to simulate the process of sampling from actual population. The distribution chosen for the inputs should closely match the existing data or should best represent the current state of knowledge. Data generated from the simulation can be represented as probability distribution curves or converted to error bars and confidence intervals etc. General steps in Monte Carlo Simulation are:

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

3. APPLICATION TO GEOTHERMAL RESOURCE ASSESSMENT

3.1 Introduction

In the case of geothermal resource assessment, energy reserve is estimated from data generated from geological mapping, geochemical studies, resistivity surveys, infrared surveys, seismic data, magnetics, gravity, ground-water temperatures, heatflow surveys and results of exploratory drilling. These data are valuable in determining the distribution of input parameters for the simulation. Out of these surveys, the following important inputs are determined:

1. Resource area – obtained from geological mapping and geophysical measurements;
2. Resource temperature – obtained from geochemical studies, groundwater temperatures and exploratory drilling; and
3. Thickness of the reservoir – obtained from exploratory drilling and geophysical measurements.

Other parameters such as porosity, rock density, specific heat capacity of fluid and rock are taken from data collected from drilled wells or other fields of similar geological settings or reservoir characteristics and also from handbooks. These data are then used in volumetric stored heat model outlined below.

3.2 Deterministic model for volumetric stored heat

Volumetric stored heat estimates the heat in place for area of interest with the following reasonable assumptions made about:

a) The percentage of that heat that can be expected to be recovered at the surface; and
b) The efficiency of converting that heat to electrical energy.

This calculation takes into account only a volume of rock and water that is reasonably likely to contain adequate permeability and temperature for generation of electricity using prevailing contemporary technology. Hot rock that is deeper and is unlikely to be economically drillable is not included. The estimates of recoverable heat using this method do not imply any guarantee that a given level of power generation can be achieved. To achieve some level of guarantee, wells capable of extracting heat from the rock by commercial production of geothermal fluid must be drilled and tested.
The total heat in place is given by the equation:

$$H = Ah(H_r + H_w) \tag{1}$$

where H = Stored heat (J);
A = Resource Area (m^2); and
h = Reservoir thickness (m).

The subscripts r and w denote rock, and water (fluid).

Heat contained in the rock is given by:

$$H = (T_i - T_f)(1 - \phi)C_r\rho_r \quad (2)$$

where T_i = Average reservoir temperature (°C);
T_f = Base temperature (°C);
C = Specific heat capacity (kJ/kg °C);
ρ = Density (kg/m^3); and
ϕ = Porosity.

Heat contained in the water (fluid) is given by:

$$H = \rho_{wi}\phi(h_{wi} - h_{wf}) \quad (3)$$

where h = Enthalpy (kJ/kg).

The subscripts wi and wf denote water at reservoir temperature and base temperatures respectively.

The final estimate of power potential is then calculated using the following equation:

$$E = \left[\frac{HR_f\eta}{FL}\right] \quad (4)$$

where E = Power plant capacity;
R_f = Recovery factor;
η = Conversion efficiency;
F = Plant capacity factor; and
L = Plant life.

3.3 Simulation of the volumetric stored heat model

Most of the parameters used to calculate the power potential in section 3.2 above are not known with certainty. All we can say is the range of most probable values of each of those parameters and to reflect the uncertainties, input variables such as resource area, reservoir temperature, porosity, specific heat capacity and reservoir thickness should be quantified as separate probability distributions. Each step of simulation samples the independent variables and so, a complete representation of all possible outcomes can be achieved if the number of steps is large. The simulation process retrieves possible values for the independent variables randomly selected from the assigned probability distributions. Each sample set computed at every simulation step represents a possible combination of input parameters. Sampling can be done from an assigned probability distribution using computer generated pseudo-random numbers between 0 and 1. The outcome is entirely random and falls within the limits of an assigned input distribution.

Probability distribution of the input variables is usually based on the scientific judgement using all of the relevant information available and the assumptions of the modeller. The distributions in most cases take the form of normal distribution, uniform (rectangular) distribution and triangular distribution. Normal and triangular distributions are suitable when actual data are limited but known that values in question fall near the centre of the limits. In the absence of any other information, rectangular distribution is a reasonable default model. After a successful simulation, the output gives the probability of exceeding a certain level of power potential.

4. CASE EXAMPLE – RESOURCE ASSESSMENT OF OLKARIA I

4.1 Introduction

The greater Olkaria geothermal field covers an area of more than 80 km^2 and is divided into several sectors (Figure 1) for exploitation purposes. Sectors that are already under exploitation are Olkaria East (Olkaria I), Northeast (Olkaria II), Olkaria West (Olkaria III) and Olkaria Northwest. Olkaria Domes is currently under appraisal drilling.

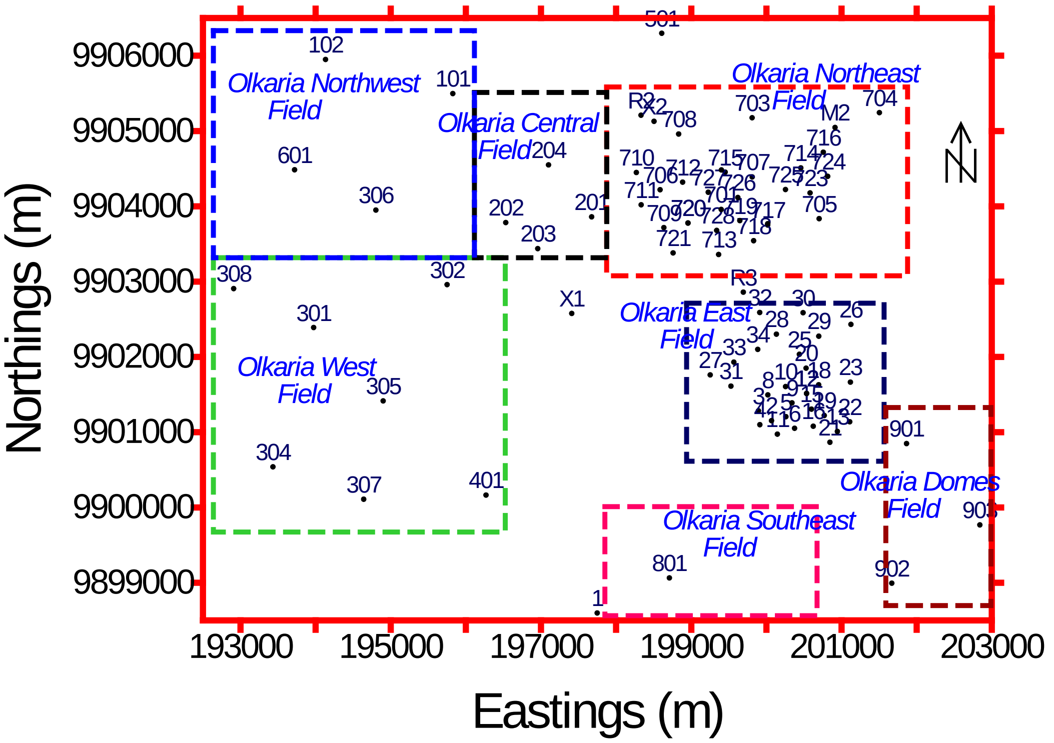

FIGURE 1: Location of production sectors within the greater Olkaria geothermal field

The first 15 MWe turbine in Olkaria I started generation in 1981 and the field has been producing 45 MWe since its full commissioning in 1985 while Olkaria II, which was commissioned in October 2003 is now producing 70 MWe. Olkaria III started production from its phase 1 in the year 2000 and has been producing 12 MWe from a binary power plant, since then. Olkaria I plant has done its design life and now studies are being done to find out if the reservoir can still support further production. One of the preliminary studies that have been done is use of stored heat (Monte Carlo) method to estimate the power that could still be produced.

4.2 Reservoir properties

Olkaria I is a boiling two-phase liquid dominated reservoir capped by a 700 m thick cap rock. The field has 33 wells drilled to depths ranging from 900 m to 2484 m within a 4-km^2 area.

Initial well temperature and pressure profiles in Olkaria I follow boiling point for depth curve from the point where the steam zone intercepts the water reservoir (Figure 2). Steam zone temperatures averages at 240°C and pressures of 33 – 36 bars. At depth, average temperature at 1500 m is 300°C and at 2200 m the temperature is 330°C. Productive aquifers are associated with contact between lavas, porous pyroclastics and fractured trachytes. Wells intercept these permeable aquifers at different depths spanning the whole of the drilled zone.

4.3 Input data for Monte Carlo Simulation

4.3.1 Reservoir area

The reservoir area in Olkaria I is defined by the 20 ohm-m anomaly (Figure 3). The wells are currently drilled in half of the defined area due to inaccessibility of the Ololbutot lava flow (Figure 4), which is a rough and rugged terrain. However, the area under this lava flow has a good potential of being a geothermal reservoir and with the current technology, it can be accessed by directional drilling. From Figure 3, the minimum area would be about 7 km^2 if the higher resistivity zones encroaching into the low resistivity area are taken into account and the maximum would be 8 km^2 if these high resistivity zones were included.

4.3.2 Reservoir thickness

Casing depths for wells already drilled in Olkaria I range from 500 – 600 m. Productive zones from the deep wells occur at various depths spanning the whole of the open hole. If all the wells are to be drilled to 2200 m, the reservoir thickness will therefore, vary from 1600 m to say, 800 m.

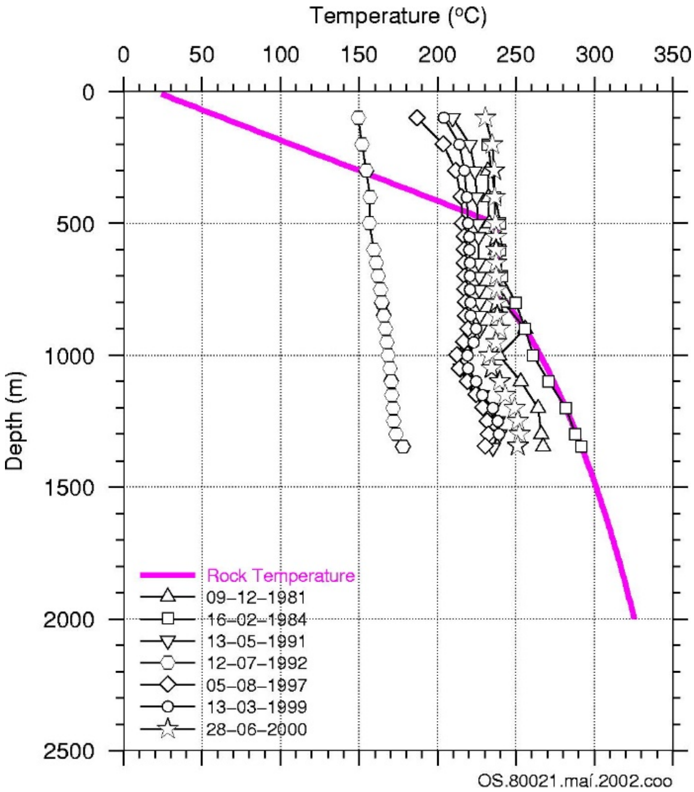

FIGURE 2: Temperatures in well OW-21, a typical Olkaria I profile

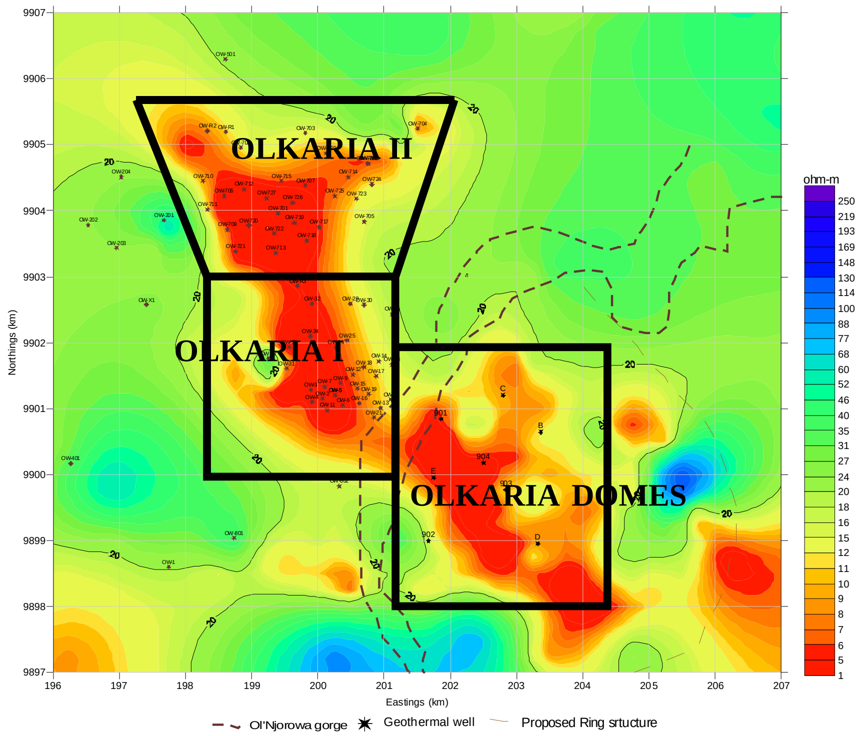

FIGURE 3: Map showing TEM Resistivity at 1000 m a.s.l.

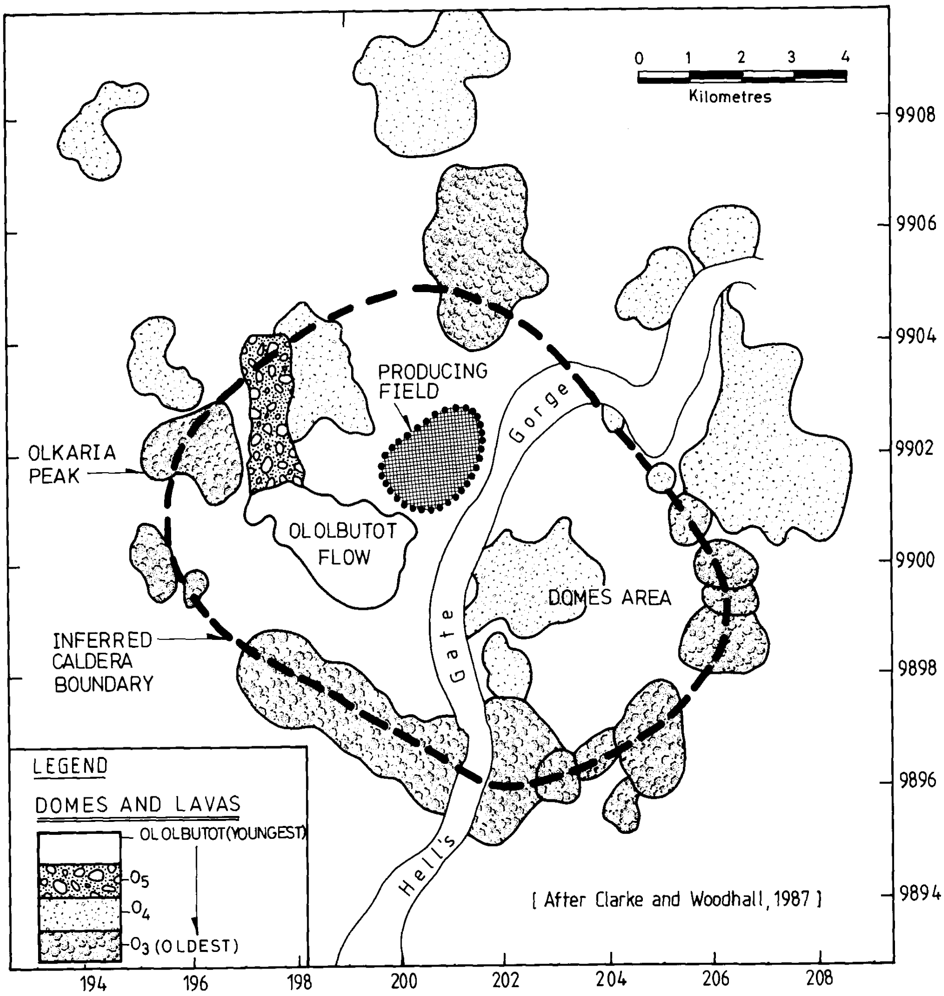

FIGURE 4: Map showing Ololbutot lava flow in relation to the production field (Olkaria I)

4.3.3 Recovery factor

Recovery factor is a function of porosity. In Olkaria I, studies from numerical simulations have come up with a porosity value of 6% (Bödvarsson et al., 1987; Ofwona, 2005). Muffler and Cataldi (1978) have defined a linear relation between porosity and recovery factor. For a porosity of 6%, the Cataldi plot gives a recovery factor of 15%. Bayrante et al. (1992) used a recovery factor of 20% for assessment of Mahanagdong project in Philippines for the same porosity. In this paper, a recovery factor of 20 % is used.

4.3.4 Reservoir fluid temperature

The reservoir fluid temperature is taken as the average of the steam zone temperature (240°C) and bottom hole temperature (330°C). This is about 285°C. Base temperature of 180°C is used because most of the wells that intercept temperatures of this magnitude in Olkaria do not discharge.

4.3.5 Rock density and conversion efficiency

A rock density of 2700 kg/m^3 is used and a conversion efficiency of 12%.

4.4 Stored heat calculation results

Various input parameters to this analysis are summarized in Table 1. Most likely estimates are given as well as estimated probability distributions and minimum and maximum values for different input parameters. These input parameters are used in the Monte Carlo simulation in excel spreadsheet. The simulation runs can be as much as time and computer allows. The more runs, the better. For this case, the runs were 2000. The results show a frequency distribution peak at a power capacity of 100 MWe but with a broad range from 80 to 150 MWe due to the inherent uncertainties of the input variables (Figure 5). Figure 6 shows that there is a 50 % chance of producing more than 120 MWe.

TABLE 1: Best estimates and probability distribution

Input	**Units**	**Best guess**	**Probability distribution**		
			Type	**Min**	**Max**
Area	km^2		Rectangular	7	8
Thickness	m	1,200	Triangular	800	1600
Rock Density	kg/m^3	2,700	Constant		
Rock Spec. Heat	kJ/kg °C	1	Constant		
Porosity	%	6	Triangular	1	12
Temperature	°C	285	Triangular	240	330
Base Temp.	°C	180	Constant		
Fluid Density	kg/m^3	783	Steam Table		
Fluid Spec. Heat	kJ/kg °C	4.2	Steam Table		
Recovery Factor	%	20	Triangular	15	25
Conversion Efficiency	%	12	Triangular	10	15
Plant Life	years	25	Triangular	20	30
Load Factor	%	95	Constant		

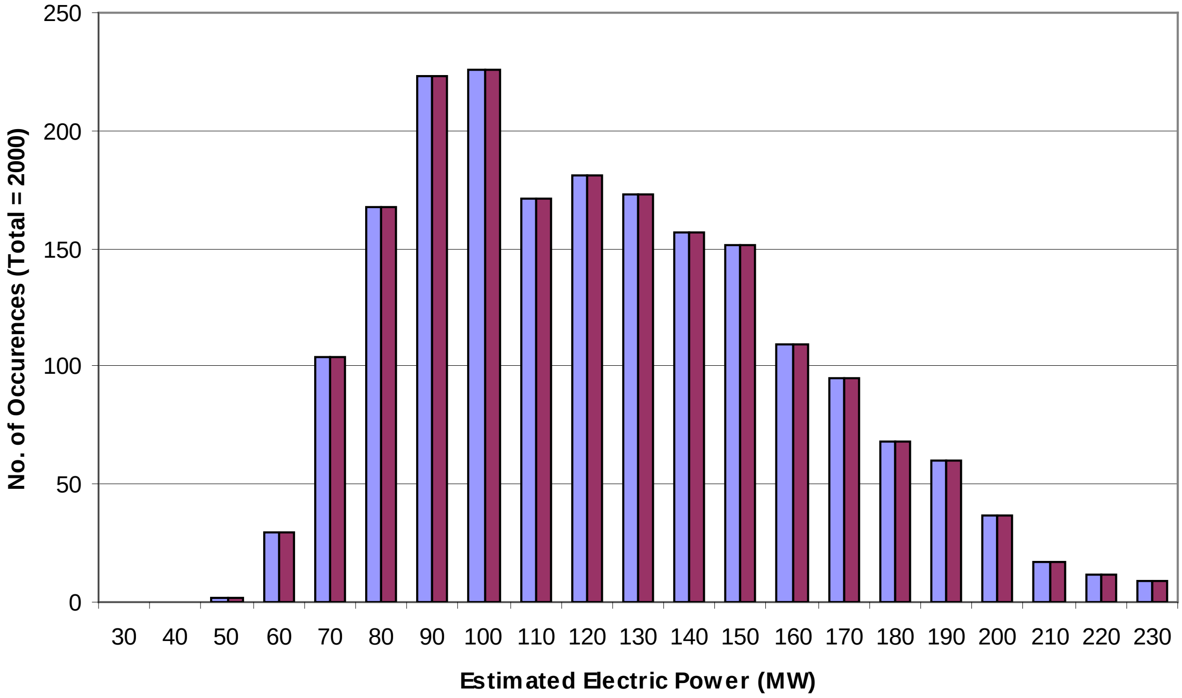

FIGURE 5: Frequency distribution of power capacity

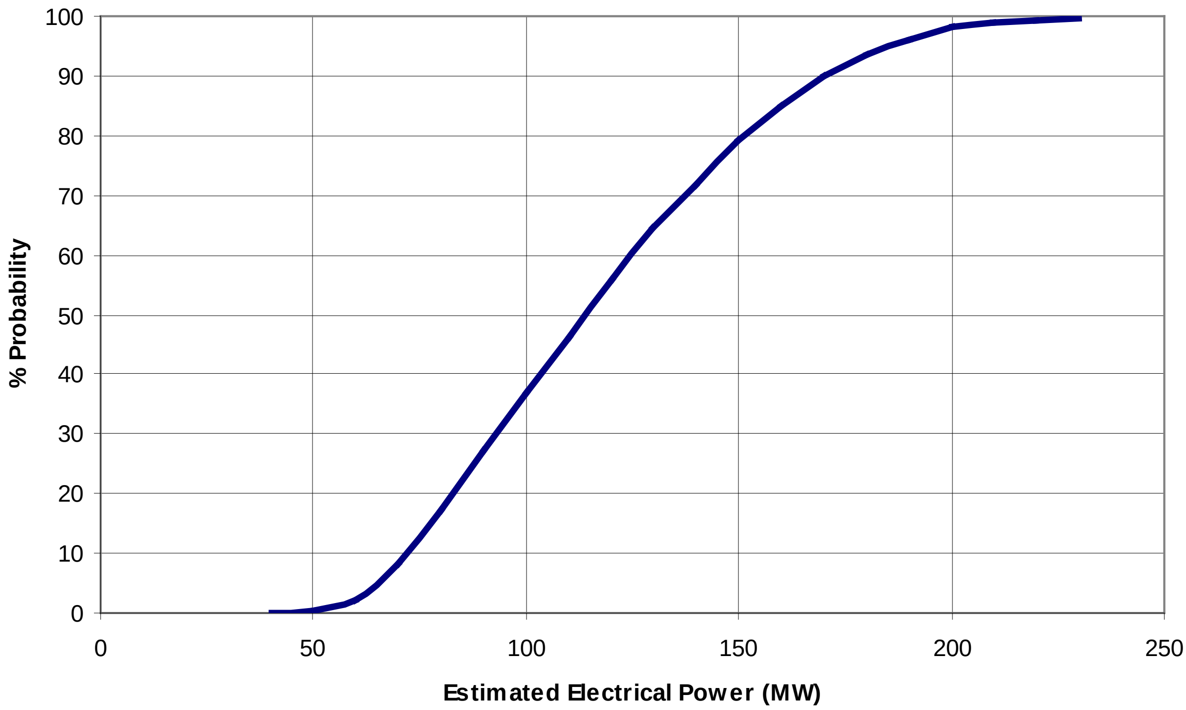

FIGURE 6: Cumulative frequency distribution

5. CONCLUSIONS

Estimation of power potential for Olkaria by Monte Carlo method produces reasonable and realistic estimates. This method has been applied in other geothermal fields around the world and will be appropriate for estimation of power potential in geothermal fields in African Rift region.

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