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ESTIMATING THE GEOTHERMAL POWER POTENTIAL OF THE NW-SABALAN GEOTHERMAL FIELD, IRAN, BY THE VOLUMETRIC METHOD

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ABSTRACT

An important factor in a geothermal assessment is the assessment of the volume of the geothermal system in question. For the volumetric method, we assume, for simplicity, that the volume is a box, with a surface area in the xy plane and thickness z1-z0 along the z-axis. This work presents a comprehensive review of the theoretical background and methodology used in volumetric assessment. The volumetric method using the Monte Carlo simulation was applied to estimate the geothermal power potential of the Sabalan geothermal field given three scenarios of 25, 50 and 100 years duration.

GENERAL INFORMATIONS FROM SABALAN GEOTHERMAL FIELD

Mt. Sabalan lies on the South Caspian plate, which is under-thrust by the Eurasian plate to the north. It is, in turn under-thrust by the Iranian plate, which produces compression in a northwest direction. This is complicated by a dextral rotational movement caused by northward under-thrusting of the nearby Arabian plate beneath the Iranian plate. There is no Wadati- Benioff zone to indicate any present day subduction. The current project area is located within the Moil Valley which, on satellite and aerial photograph imagery, can be seen to be a major structural zone. Exposed at the surface in the valley are altered Pliocene volcanic activity, an unaltered Pleistocene trachydacite dome (Ar-Ar dated at 0.9 Ma) and Quaternary terrace deposits (Bogie et al., 2000).On the basis of the results of the two MT surveys in the years 1997 and 2007, and the presence of hot springs with significant chloride concentrations a three well exploration and three well delineation programmes was undertaken. The topography of the valley limits the location of drill pads to interconnected terraces, requiring that five of the wells be directionally drilled to access and extensively test the resistivity anomaly at depth. The drilling and testing program for the exploration phase was carried out between November 2002 and December 2004. The drilling and testing program for the delineation phase was carried out between May 2008 and August 2009. The six deep exploration and delineation wells that have been drilled well NWS-1was drilled from pad A, NWS-3 was drilled from pad C, NWS-4, NWS-5D was drilled from pad B, NWS-6D and NWS-7D was drilled from pad D. The wells vary in depth from 1901 m to 3197 m MD. Well NWS-1 was drilled vertically while NWS-3, NWS-4, NWS-5D, NWS-6D and NWS-7D are deviated wells. Additionally, one shallow injection well, NWS-2, has been drilled to 600m depth, located on pad A alongside well NWS-1.

THEORY

An important factor in a geothermal assessment is an assessment of the volume of the geothermal system in question using the volumetric method. We assume, for simplicity, that the volume is a box. In this report this box has a surface area A in the xy plane and height (thickness) z1-z0 along the z-axis, where z1 and z0 are the lower and upper limit of the geothermal system, respectively. When the volume of the geothermal system has been assessed the choice has to be made on how to calculate the useable heat that the system contains. For simplicity it can be assumed that the heat capacity and temperature are homogeneous in the xy plane and are only dependent on depth. The heat content of the system can then be calculated by integrating the product of the estimated heat capacity per unit-volume C (z) and the difference between the estimated temperature curve T (z) in the system and the cut-off temperature T0. The cut-off temperature is the temperature of the state from which the heat is integrated. This can be the outdoor temperature, minimum temperature for electric production, absolute zero temperature etc. The choice of T (z) depends on how one calculates the usable energy. We therefore get the heat energy contained in the geothermal system as:

$$Q = A\int_{z_0}^{z_1} C(z)[T(z) - T_0]\,dz \qquad (1)$$

Only a small portion of the total heat in the system is recoverable and therefore we define a recovery factor, R, which is the ratio of the heat which we can recover to the total heat in the system. The recoverable heat is therefore

$$Q_R = RQ \qquad (2)$$

The heat according to equation (1) can be calculated in two ways. The first method is to integrate over the temperature curve and the second method is assuming that the temperature is also homogeneous in the z direction and therefore constant over the whole volume. This constant would be some mean temperature for the volume. The first method is appropriate if it is believed that the temperature curve is nonlinear. But if it is believed that the temperature curve is close to being linear the second method would be more appropriate as the constant temperature would be the average temperature of the system. For simplicity the heat capacity per unit-volume will be taken as homogenous for the whole system and written as

$$C = S_R(1-\varphi)\rho_R + S_w\varphi\rho_w \qquad (3)$$

Where S_R and S_w are the specific heat of rock and water, respectively, ρ_R and ρ_w density of rock and water, respectively, and φ is the porosity of the rock. For the case of a nonlinear temperature curve, which will be assumed from here on, it is convenient to assume that the temperature curve in the system follows a curve shaped like the boiling point curve (James, 1970)

$$T(z) = x.69.56(z + z_{Delta})^{0.2085} \qquad (4)$$

Here x is a ratio factor running from zero to one describing the deviation from the true boiling curve, z_{Delta} is a translation in the z direction in order to fulfil the upper boundary conditions, T_{Z0} at z_0. Then we can write the recoverable heat described in equation (2) as

$$Q_R = RAC\int_{z_0}^{z_1}[T(z) - T_0]\,dz \qquad (5)$$

From the recoverable heat of the geothermal system we can only utilise a small portion for electric production. We therefore define an electric utilization constant η_e which gives us the electric energy

$$Q_e = \eta_e Q_R \qquad (6)$$

And the electric power

$$P = \frac{Q_e}{t} \qquad (7)$$

Where, t is the production time of the electric power in seconds.

MONTE CARLO CALCULATIONS

The variables used in the volumetric method are often shrouded with uncertainty and therefore it is necessary to define a probability distribution for these variables. By choosing one random value for each variable out of that probability distribution, one possible outcome of the volumetric method can be calculated. If this process is then repeated several times a discreet probability distribution for the outcome begins to form. This method of calculation is often named Monte Carlo calculation after the Monte Carlo casino where similar method is used for wealth distribution. To form the discrete distribution for the outcome we divide the interval of possible outcomes into equally long subintervals. The probability that the real outcome is in a particular subinterval is the ratio of possible outcomes that fall in that subinterval to the total number of possible outcomes that have been calculated. With the discrete probability distribution an opportunity emerges to evaluate the probability for the outcome to fall into a particular interval.

EVALUTION OF VARIABLES

To be able to perform the volumetric calculations we must estimate the value or probability distribution for the following variables:

1. Surface area of the geothermal system, A.
2. Thickness of the system, z_1-z_0.
3. Porosity of the rock, φ.
4. Mean physical characteristics of the rock and water in the system, that is the specific heat and density of the rock and water, S_R, S_w, ρ_R and ρ_w.
5. Heat distribution through the container, T (z). This means the deviation ratio from the boiling curve, x, and the boundary condition z_{Delta}.
6. Recovery factor, R.
7. Cut-off temperature, T_0.

These variables will give the heat recoverable from the system. To be able to evaluate the electric production capacity of the reservoir we also need values for the following variables

8. Electric conversion coefficient, ηe.
9. Electric production time, t.

From the interpretation of the MT data and the surface geology we get the volume variables, the area A and lower depth z_1. The system is mainly made of par gneiss. So the range of values for porosity, rock density and the specific heat of the rock of the reservoir are chosen to be the same as for metamorphic rock (Freeze and Cherry, 1979b). The recovery factor is a function of the porosity, as the heat is more difficult to extract from the rock with lower porosity. Low values of porosity are expected for intrusive volcanic rock. For the upper layer the mean porosity used was 0.10 and the corresponding recovery factor used was 25%. For the deeper layers the mean porosity was 0.08 and the recovery factor used was 20%. The conversion efficiency is a function of the resource mean temperature and values between 10 and 11% were used in the calculations.

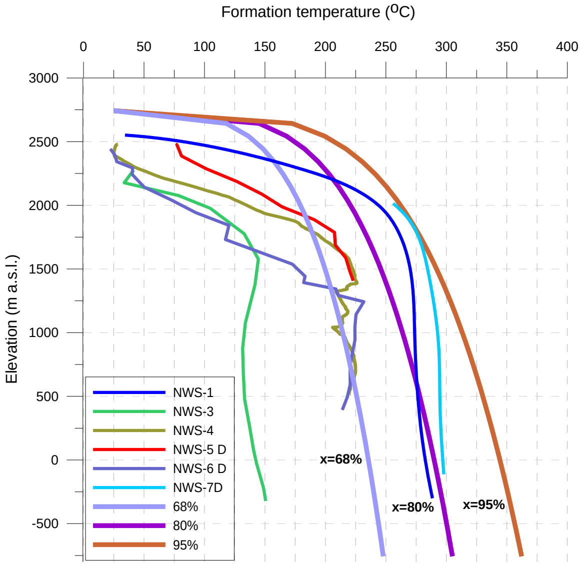

Figure 1: Formation temperature measured and three temperature curves. These curves are with the minimum, most likely and maximum value of the boiling curve ratio.

In figure 1 the temperature measurements in boreholes in the area along with some possible temperature curves T (z) are shown. From this figure we draw a conclusion about the distribution of the boiling curve ratio, x, for our model. The boundary condition Z_{Delta} is calculated from the annual mean surface temperature which is taken to be 25°C. The cut-off temperature is chosen to be 180°C (Wilcox, 2006). To estimate possible electric power production we consider three production time scenarios, 25, 50 and 100 years. A summary of the areas and also the temperatures, porosity and other values used is given in table 1.

RESULTS OF THE CALCULATIONS

An estimate of the electric power, which could be produced from the recoverable heat with cut-off temperature of 180°C from the Sabalan geothermal reservoir, has been calculated according to equation (7) This was done for three production time scenarios. The results are presented as a discreet probability distribution, seen in figure 2, and as a discreet cumulative probability distribution, seen in figure 3. Each figure consists of 100,000 random outcomes. From these random outcomes miscellaneous statistical information can be found. These include the likeliest outcome, 90% confidence interval, mean and median of the outcomes, standard deviation and where the 90% limit for the cumulative

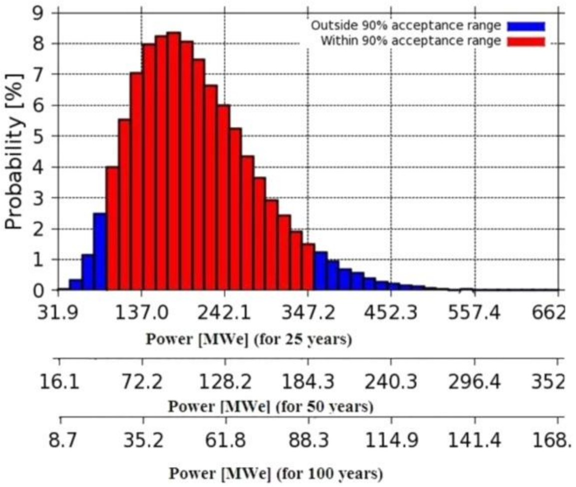

Figure 2: Probability distribution for electric power production. Each pillar is about 15.5 MWe wide for 25 years, about 8 MWe for 50 years and about 4 MWe for 100 years

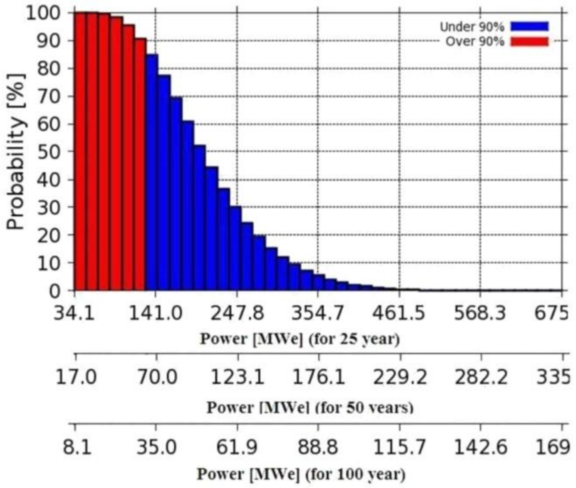

Figure 3: Cumulative probability distribution for electric power production. Each pillar has the same width as given for fig. 2. The height of each pillar represents the probability that the result is in or above the interval of that pillar.

Table 1: Values and distributions of the variables in the volumetric method

Description	Variable	Distribution type	Min. value	Most probable value	Max.value
Upper depth (m)	Z_0	fixed	N/A	0	N/A
Lower depth (m)	Z_1	Triangular dist	2000	2500	3000
Surface area (km^2)	A	Triangular dist	10	19	30
Cut off Temperature (^{o}C)	T_0	fixed	N/A	180	N/A
Porosity (%)	φ	Triangular dist.	4	8	12
Specific heat of rock J/(kgm^3)	S_R	Triangular dist	900	950	980
Density of rock (kg/m^3)	ρ_R	fixed	N/A	2500	N/A
Specific heat of water J/(kgm^3)	S_W	fixed	N/A	4400	N/A
Density of water (kg/m^3)	ρ_W	fixed	N/A	800	N/A
Boiling curve ratio (%)	x	Triangular dist	68	80	95
Recovery factor (%)	R	Triangular dist	15	20	25
Convergence efficiency (%)	ηe	fixed	N/A	11	N/A
Production time (years)	t	fixed	N/A	25, 50, 100	N/A

Table 2: Statistical parameters for the probability distribution for electric power production for the Sabalan geothermal field estimated by the Monte Carlo method.

Statistical size	Values [MWe] (for 25 years)	Values [MWe] (for 50 years)	Values [MWe] (for 100 years)
Most probable value (with 8.4% probability)	170.3 – 185.7	89.9 – 98.1	43.6 – 47.5
90% confidence interval	93.4 – 354.9	40.7 – 180.1	24.2 – 90.2
Mean	205.8	103	51.5
Median	194.8	97.6	48.7
Standard deviation	78.23	39	19.5
90% limit	127.9	63.5	31.6

probability lies. These statistics are presented in table 2 for each of the three production periods. According to the statistics of the probability distribution in figure 2 it is most probable (with 8.4 % probability) that the electrical power production capacity lies between 170 MWe and 186 MWe if the recoverable heat is used for 25 years, between 90 MWe and 98 MWe if it is used for 50 years and between 44 MWe and 47 MWe if it is used for 100 years. Also from the statistics of the distribution in figure 3 it is seen that the volumetric model predicts that with 90 % confidence the power production lies between 93 MWe and 355 MWe for 25 years, between 41 MWe and 180 MWe for 50 years and between 24 MWe and90 MWe for 100 years. It should be emphasized that the great range of values resulting from the Monte Carlo calculations simply reflects the uncertainty in the results obtained by the volumetric assessment method. It is primarily caused by uncertainty in the size, temperature and recovery factor for the Sabalan geothermal reservoir resource. A lower limit for the recovery factor of 15% is used, reflecting uncertainties in porosity and recharge. If reinjection will be applied during utilization to supplement natural recharge a higher lower limit for the recovery factor can be used, raising the lower limit for the production capacity estimate.

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