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Resource Assessment of Balçova Geothermal Field

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ABSTRACT

One of the most applicable methods of low-temperature geothermal resource assessment is volumetric method. While applying volumetric method, the values of uncertain parameters should be determined. An add-in software program to Microsoft EXCEL, @RISK, is used as a tool to define the uncertainties of the parameters in volumetric equation. In this study, Monte Carlo simulation technique is used as the probabilistic approach for the assessment of low temperature Balçova geothermal field.

Although Balçova geothermal field is being utilized for several direct heat applications, there exists limited data for resource assessment calculations. Assessment studies using triangular and uniform distribution type functions for each parameter gave the mean values of recoverable heat energy of the field as 25.1 MWt and 27.6 MWt, respectively. As optimistic values (90%), those values were found as 43.6 MWt and 54.3 MWt. While calculating these numbers, a project life of 25 years with a load factor of 50% is used.

1. INTRODUCTION

Geothermal energy is heat energy originating deep in the earth's molten interior. The temperature in the earth's interior is as high as 7000 °C, decreasing to 650 – 1200 °C at depths of 80km-100km (Wright,1998). Through the deep circulation of groundwater and the intrusion of molten magma into the earth's crust to depths of only 1km-5km, heat is brought closer to the earth's surface. The hot molten rock heats the surrounding groundwater, which is forced to the surface in certain areas in the form of hot steam or water, e.g. hot springs and geysers. The heat energy close to, or at, the earth's surface can be utilized as a source of energy, namely geothermal energy.

The total geothermal resource is vast. An estimated 100PW (1 x 10 17 W) of heat energy is brought to the earth's surface each year (World Energy Council, 1994). However, geothermal energy can only be utilized in regions where it is suitably concentrated. These regions correspond to areas of earthquake and volcanic activity, which occur at the junctions of the tectonic plates that make up the earth's crust. It is at these junctions that heat energy is conducted most rapidly from the earth's interior to the surface, often manifesting itself as hot springs or geysers.

Resource assessment can be defined as the broad-based estimation of future supplies of minerals and fuels. This assessment requires not only the estimation of the amount of a given material in a specified part of the Earth's crust, but also the fraction of that material that might be recovered and used under certain assumed economic, legal, and technological conditions.

Furthermore, resource assessment includes not only the quantities that could be produced under present economic conditions, but also the quantities not yet discovered or that might be produced with improved technology or under different economic conditions.

Geothermal resources consist primarily of *thermal energy*, and thus geothermal resource assessment is the estimation of the thermal energy in the ground, referenced to mean annual temperature, coupled with an estimation of the amount of this energy that might be extracted economically and legally at some reasonable future time. Geothermal resource estimation also includes estimates of the amount of *byproducts* that might be produced and used economically along with the thermal energy. These byproducts can be metals or salts dissolved in saline geothermal fluids or gases such as methane dissolved in geopressured fluids.

Assessment of geothermal resources involves determination of the location, size, and geologic characteristics of each resource area to calculate the accessible resource base (*thermal energy* stored in the reservoir) and the resource (*thermal energy* recoverable at the wellhead).

Methodologies used for geothermal resource assessment were reviewed by Muffler and Cataldi (1977; 1978) and divided into four main categories: *Surface thermal flux method, Volume method, Planar fracture method and Magmatic heat budget method*, among which the volume method is the most suitable for many low-temperature reservoirs.

In this study, stored energy and producible heat energy of a low temperature geothermal reservoir of Turkey, Balçova, were determined by applying volume method. An add-in software to Microsoft EXCEL, @RISK, was used to carry out Monte Carlo simulation studies.

2. VOLUME METHOD

The *volume method* involves the calculation of the thermal energy contained in a given volume of rock and water and then the estimation of how much of this energy might be recoverable. The *thermal energy* in the ground can readily be calculated as the product of the volume of a geothermal reservoir, the *mean temperature*, the *porosity*, and the *specific heats* of rock and water. Alternatively, one can calculate the thermal energy approximately as the product of just volume, temperature, and an assumed volumetric specific heat (White, 1965; Renner et al, 1975). Calculation of the amount of recoverable thermal energy is more complex, however, and requires knowledge of reservoir properties such as *permeability*. In most cases, the recovery factor can be specified only approximately (Nathenson, 1975).

For the estimation of the thermal energy at *low temperature* geothermal fields, the *volume method* was used. The stored heat is computed by using the following volumetric equation

(Muffler and Cataldi,1977, 1978);

$$H_{Total} = H_R + H_f \\ = (1-\phi)c_R\rho_R V(T_R - T_A) + \phi c_F \rho_F V(T_F - T_U) \quad (1)$$

where;

H = heat energy, kJ

ϕ= porosity, fraction

c = specific heat, kJ/kg-°C

ρ = density, kg/m3

V = hot rock volume, m3

T = temperature, °C

and subscripts R, F and U stand for rock, fluid and utilized, respectively.

H_{Total} can actually be referred as the *accessible resource base* of the low temperature reservoir under study.

In case of a direct heat application from a low-temperature geothermal reservoir, the accessible resource base (kJ) can be converted to recoverable heat energy (kWt) by using the following equation;

$$H_{Recoverable} = \frac{H_{Total} \times RF \times Y}{LF \times t} \quad (2)$$

where;

$H_{Recoverable}$ = Recoverable heat energy, kWt

H_{Total} = Accessible resource base, kJ

RF = Recovery factor for the given reservoir, fraction

Y = Transformation yield. It takes into account the efficiency of transferring heat energy from geothermal fluid to a secondary fluid, fraction

LF = Load factor. Most of the direct heat applications (space heating, greenhouse heating etc.) of geothermal energy are not continuous throughout the year. This factor takes into account the fraction of the total time in which the heating application is in operation, fraction

t = Total project life, sec

Some of the variables of the volumetric equations (Equation 1 and 2) exhibit uncertainties. Those variables are aerial extension, reservoir temperature, formation thickness, porosity, formation rock and fluid density, specific heat of rock and formation fluid in Equation 1 and accessible resource base, recovery factor and transformation yield in Equation 2.

Monte Carlo simulation is a powerful tool to simulate the systems having variables with uncertainty. An add-in software for Microsoft EXCEL, @ RISK, is capable of running Monte Carlo simulations and will be used throughout this study.

The Monte Carlo simulation and @Risk Software program will be explained in the following sections.

2.1 Monte Carlo Simulation

Numerical methods that are known as *Monte Carlo* methods can be loosely described as statistical simulation methods, where statistical simulation is defined in quite general terms to be any method that utilizes sequences of random numbers to perform the simulation. *Monte Carlo* methods have been used for centuries, but only in the past several decades has the technique gained the status of a full-fledged numerical method capable of addressing the most complex applications. The name *Monte Carlo* was given because of the similarity of statistical simulation to games of chance, and because the capital of Monaco was a centre for gambling and similar pursuits. *Monte Carlo* is now used routinely in many diverse fields including oil well exploration.

Statistical simulation methods may be contrasted to conventional numerical discretization methods, which typically are applied to ordinary or partial differential equations that describe some underlying physical or mathematical system. In many applications of *Monte Carlo*, the physical process is simulated directly, and there is no need to even write down the differential equations that describe the behavior of the system. The only requirement is that the physical (or mathematical) system be described by *probability density functions* (pdf's). For now, we will assume that the behavior of a system can be described by pdf's. Once the pdf's are known, the *Monte Carlo simulation* can proceed by random sampling from the pdf's. Many simulations are then performed (multiple trials or histories) and the desired result is taken as an average over the number of observations (which may be a single observation or perhaps millions of observations). In many practical applications, one can predict the statistical error (the *variance*) in this average result, and hence an estimate of the number of *Monte Carlo* trials that are needed to achieve a given error.

Assuming that the evolution of the physical system can be described by probability density functions (pdf's), then the *Monte Carlo* simulation can proceed by sampling from these pdf's, which necessitates a fast and effective way to generate random numbers uniformly distributed on the interval [0,1]. The outcomes of these random samplings, or trials, must be accumulated in an appropriate manner to produce the desired result, but the essential characteristic of *Monte Carlo* is the use of random sampling techniques to arrive at a solution of the physical problem. In contrast, a conventional numerical solution approach would start with the mathematical model of the physical system, discretizing the differential equations and then solving a set of algebraic equations for the unknown state of the system.

The essential component of a *Monte Carlo simulation* is the modeling of the physical process by one or more *probability density functions* (pdf's). By describing the process as a *pdf*, which may have its origins in experimental data or in a theoretical model describing the physics of the process, one can sample an *outcome* from the pdf, thus simulating the actual physical process. While applying these density functions, some statistical terms such as mean, variance, etc. are utilized.

For each uncertain variable (one that has a range of possible values), one may define the possible values with a *probability distribution*. The type of distribution that can be selected is based on the conditions surrounding that variable. The common distribution types can be seen in Figure 1.

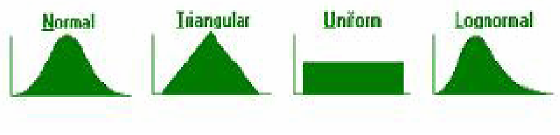


Figure 1: Distribution types.

To add this sort of functions to an EXCEL spreadsheet, it is needed to know the equation that represents this distribution. @RISK can automatically calculate these equations or even fit a distribution to any historical data that one might have.

2.2 @ RISK

In most of the cases, the decisions are based on whatever the data available on hand. But how often the available data is full and the information is complete? In the subject of this study the aerial and vertical change of rock properties such as porosity, formation rock density should be known. Due to limited data source on these properties, it's easy to make wrong decision if all possible scenarios are not taken into account. Making the best decisions means performing risk analysis.

@RISK is an add-in to Microsoft EXCEL, which can add risk analysis to your existing models. @RISK uses a technique known as *Monte Carlo simulation* to show all possible outcomes. Running an analysis with @RISK involves three simple steps:

1. Define Uncertainty for Input Variables

The first step of running an analysis with @RISK is to define all the variables that are uncertain in the model. The nature of the uncertainty of a given variable is described with probability distributions, which give both the range of values that the variable could take (minimum to maximum), and the likelihood of occurrence of each value within the range. In @RISK, uncertain variables and cell values are entered as probability distribution functions for example: RiskNormal (10;100), RiskUniform (20;30), or RiskTriangular(100;135;145). The numbers in normal and uniform type distributions in brackets indicate the minimum and maximum values of the variable that it could take while the numbers in triangular type distribution indicate minimum, most likely and maximum values of the variable, respectively.

Thus the first step is defining all uncertain variables as inputs and assigning distribution functions for them (Figure 2).

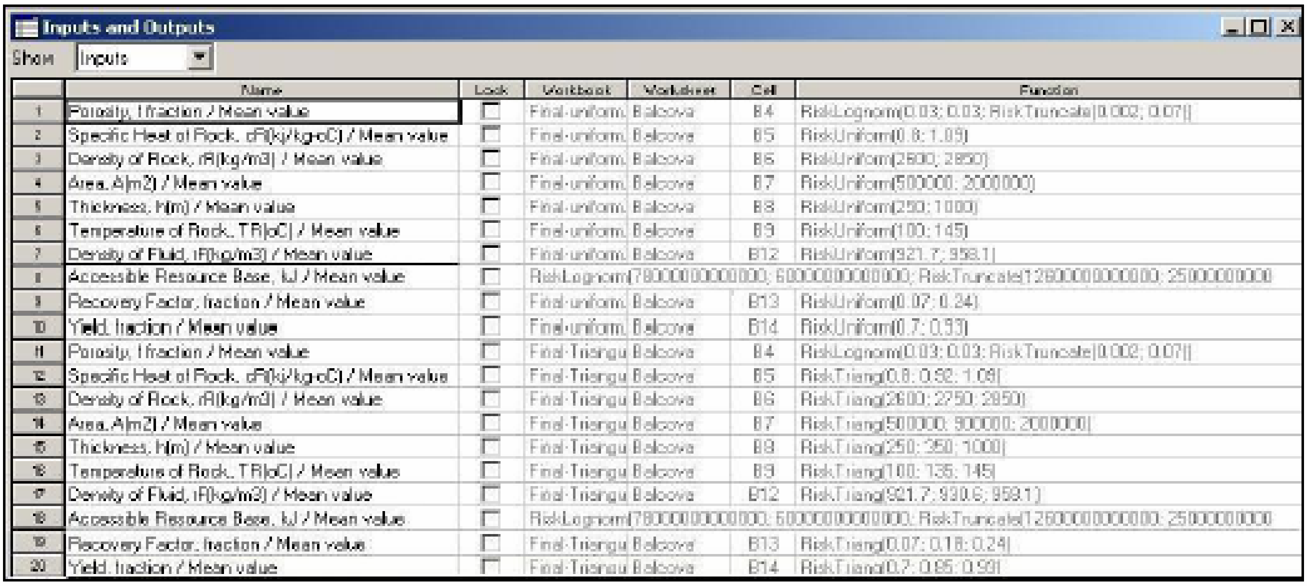
These "distribution" functions can be placed in worksheet cells and formulas just like any other EXCEL function. (Figure 3).

2. Define Output Variables

Next, output cells in which the values of the variables that are interested in will be recorded are defined. For the current study, these variables are accessible resource base and recoverable heat energy (Figure 4).

3. Simulate

Simulate is the option of @RISK which recalculates the spreadsheet model hundreds or thousands of times (Figure 5). The number of different scenarios that can be looked at is limited by 10000 iterations. @RISK samples random values for each iteration from the @RISK functions that were entered and records the resulting outcome. The overall result is a look at a whole range of possible outcomes, including the probabilities that will occur. Almost instantly, it is possible to see what critical situations to seek out or avoid.


Inputs and Outputs
Show Inputs

	Name	Lock	Workbook	Worksheet	Cell	Function
1	Porosity, f fraction / Mean value		Final-uniform	Balcova	B4	RiskLognorm(0.03; 0.03; RiskTruncate(0.002; 0.07))
2	Specific Heat of Rock, cR(kj/kg-oC) / Mean value		Final-uniform	Balcova	B5	RiskUniform(0.8; 1.09)
3	Density of Rock, rR(kg/m3) / Mean value		Final-uniform	Balcova	B6	RiskUniform(2600; 2850)
4	Area, A(m2) / Mean value		Final-uniform	Balcova	B7	RiskUniform(500000; 2000000)
5	Thickness, h(m) / Mean value		Final-uniform	Balcova	B8	RiskUniform(250; 1000)
6	Temperature of Rock, TR(oC) / Mean value		Final-uniform	Balcova	B9	RiskUniform(100; 145)
7	Density of Fluid, rF(kg/m3) / Mean value		Final-uniform	Balcova	B12	RiskUniform(921.7; 958.1)
8	Accessible Resource Base, kJ / Mean value		RiskLognorm(780000000000000; 600000000000000; RiskTruncate(126000000000000; 2500000000000			
9	Recovery Factor, fraction / Mean value		Final-uniform	Balcova	B13	RiskUniform(0.07; 0.24)
10	Yield, fraction / Mean value		Final-uniform	Balcova	B14	RiskUniform(0.7; 0.93)
11	Porosity, f fraction / Mean value		Final-Triangu	Balcova	B4	RiskLognorm(0.03; 0.03; RiskTruncate(0.002; 0.07))
12	Specific Heat of Rock, cR(kj/kg-oC) / Mean value		Final-Triangu	Balcova	B5	RiskTriang(0.8; 0.92; 1.09)
13	Density of Rock, rR(kg/m3) / Mean value		Final-Triangu	Balcova	B6	RiskTriang(2600; 2750; 2850)
14	Area, A(m2) / Mean value		Final-Triangu	Balcova	B7	RiskTriang(500000; 900000; 2000000)
15	Thickness, h(m) / Mean value		Final-Triangu	Balcova	B8	RiskTriang(250; 350; 1000)
16	Temperature of Rock, TR(oC) / Mean value		Final-Triangu	Balcova	B9	RiskTriang(100; 135; 145)
17	Density of Fluid, rF(kg/m3) / Mean value		Final-Triangu	Balcova	B12	RiskTriang(921.7; 930.6; 958.1)
18	Accessible Resource Base, kJ / Mean value		RiskLognorm(780000000000000; 600000000000000; RiskTruncate(126000000000000; 2500000000000			
19	Recovery Factor, fraction / Mean value		Final-Triangu	Balcova	B13	RiskTriang(0.07; 0.18; 0.24)
20	Yield, fraction / Mean value		Final-Triangu	Balcova	B14	RiskTriang(0.7; 0.85; 0.93)

Figure 2: Defining the input variables and their uncertainties in @RISK.

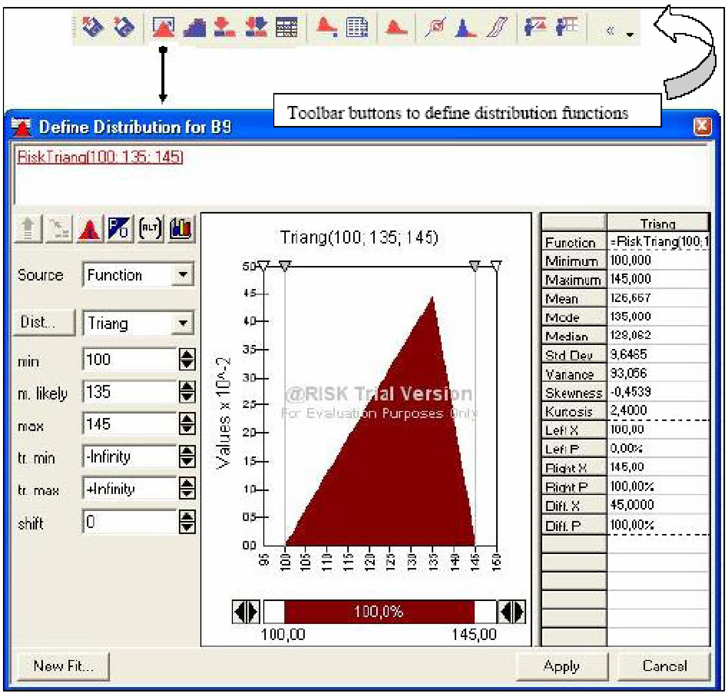


Figure 3: Defining the distribution function for a variable.

Figure 4: Defining output cells in @RISK.

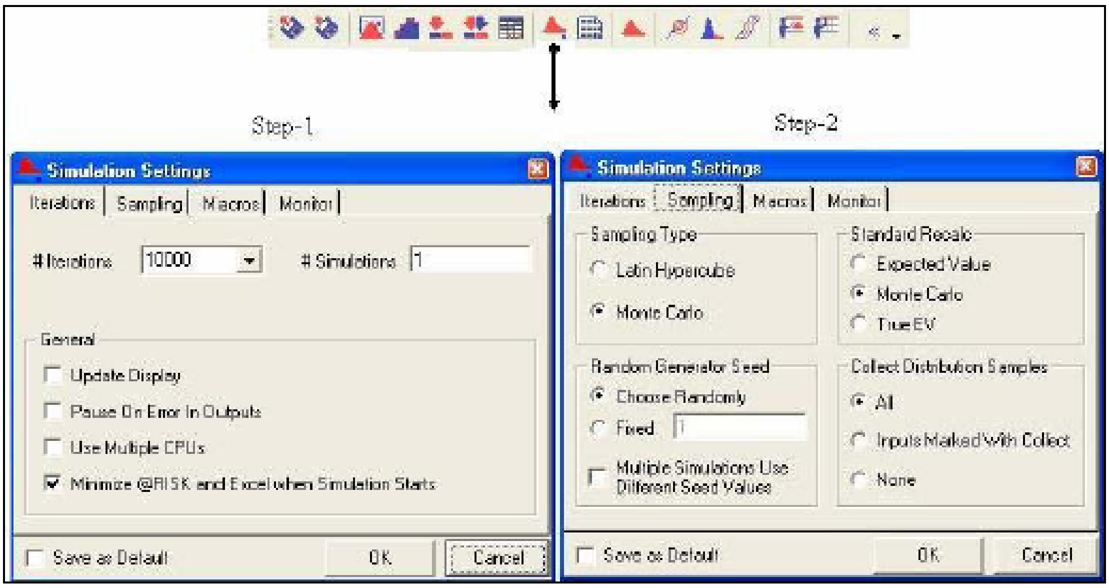


Figure 5: Steps of Simulation in @RISK.

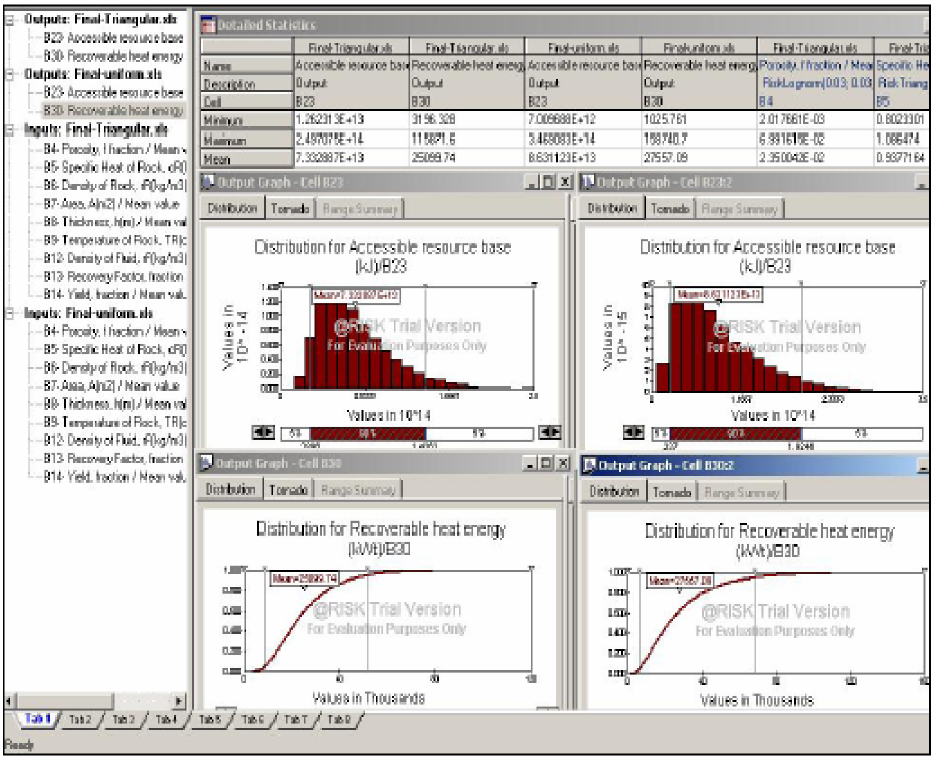


Figure 6: Graphical options of @RISK.

The power of *Monte Carlo simulation* lies in the distributions of possible outcomes it creates. Simply by running a simulation, @RISK takes the spreadsheet model from representing just one possible outcome to representing thousands of possible outcomes.

Thus, @RISK makes it possible to see all possible outcomes in a given situation and tells how likely they are to occur. What this means for a decision maker is that he/she finally has, if not perfect information, the most complete picture possible.

@RISK provides a wide range of graphing options for interpreting and presenting the results. It creates histograms, cumulative curves, area and line graphs (Figure 6). Using overlay graphs to compare several results on one graph. It can even create summary graphs that display risk over a range of time or across outputs.

@RISK also gives a full statistical report of simulations, as well as access to all the data generated. Plus it is possible to generate a one-page, pre-formatted and ready to print Quick Report. Quick Reports include *cumulative graphs*, *regression charts* for sensitivity analysis, *histograms*, and summary statistics.

In addition to this, the availability of data in EXCEL gives the opportunity to present data in the format other than @RISK has.

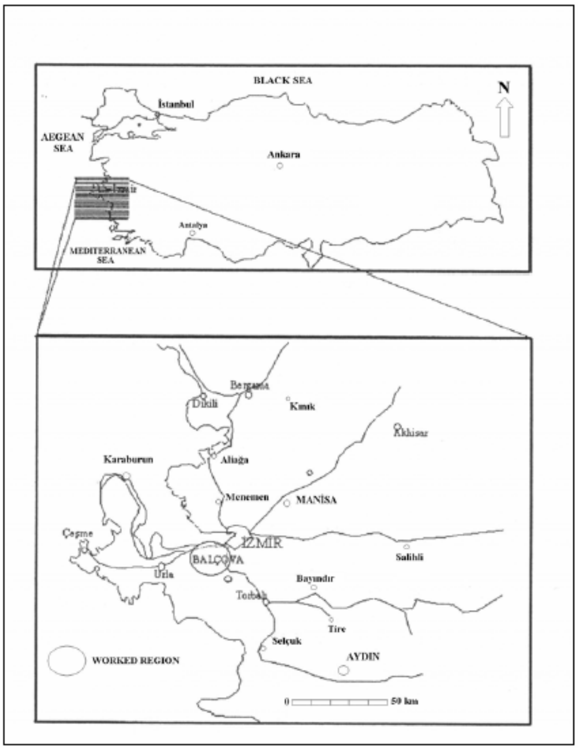


Figure 7: Location map of Balçova geothermal field (Aksoy and Filiz, 2001).

3. BALÇOVA GEOTHERMAL FIELD

Balçova geothermal field is the first field of Turkey utilized for direct heat application of geothermal energy. It is located 11 km southwest of the city of İzmir in western Anatolia (38.2º latitude, 27.0º longitude) (Figure 7).

The geology of the field is rather complicated, however it is known that the deeper parts of the system are composed of an impermeable and a thick unit called İzmir flysch. The upper Cretaceous aged İzmir flysch is a member of the İzmir-Ankara Suture Zone and consists of mainly sandstones, siltstones, shales and carbonates, including exotic blocks of some magmatic units such as; serpentinites, diabases, rhyolites, and granodiorites. İzmir flysch outcrops on a NNE-SSW trending horst and the field lies at the northern slope of the mountain nearby İzmir Bay. The young sediments that fill İzmir Bay cover the field at further north (Öngür, 2001).

İzmir Bay and İzmir Fault occurred together with graben systems in Western Anatolia due to extensional tectonics during the Late Tertiary. Balçova geothermal system lies on Agamennon Fault, which is an extension of İzmir Fault. In addition to E-W trending Agamennon Fault, the field is dissected by several faults parallel to Agamennon fault. Except Agamennon, all other faults are buried in the alluvium but their existence was observed in the drillings.

Mineral Research and Exploration General Directorate of Turkey (MTA) did the first geothermal drilling studies in the region at 1963. Resistivity, thermal probing, and self-potential surveys conducted (the first time a geothermal area received systematic, scientific delineation in Turkey). 3 wells were drilled including the first geothermal exploratory well in Turkey. First well (S-1) resulted with a mixture of hot water and steam at 124 ºC at a depth of 40 m. S-2 and S-3/A were drilled to 100 m and 140 m, with downhole temperatures of 102 ºC, and 101 ºC, respectively. S-3/A did not flow. From 1981 to 1983, 16 wells, including 7 thermal gradient and 9 production wells (100-150 m), were drilled. They encountered temperatures of 50 ºC to 126 ºC with flow rates of 4-20 kg/s. In 1982, system of geothermally heated hotels, curing center, swimming pools, and hot water began operation. 9 wells produce 4500000 kcal/h for surrounding hotels, buildings, and greenhouses. A district heating system with a total capacity of 2.2 MWt began operation in 1983 for heating offices, hospital and dormitories of Dokuz Eylül University (~30000 m²). Heating for Turkey's largest indoor swimming pool, which has capacity of 1600000 kcal/h, began operation in February 1987. In 1989, 2 new wells (B-10 and B-11) were drilled to 125 m that encountered temperatures of 109 ºC and 114 ºC and flow rates of 5 kg/s and 3 kg/s. Geothermal heating of a 11000 m² curing center became operational with a capacity of 1200000 kcal/h on September in 1989. Heating system for an additional 110000 m² (1100 dwellings) plus hot water for the Hospital of Faculty of Medicine at Dokuz Eylül University was installed on February in 1992. Additional system with capacity of 6900000 kcal/h (9.3 MWt) began running on November in 1992. The most important stage was realized by starting the operation of the Balçova Geothermal Center Heating System in 1996 (Battocletti, 1999).

3.1 Data Collection from Balçova geothermal Field for Equation 1

Figure 8 presents porosity values obtained from neutron logs taken in Balçova field. The most frequent porosity is found to be 1% with a frequency of 166 among 401 samples; therefore it was assigned as the most likely value of porosity. The maximum and minimum porosity values were taken as 7% and 0.2%, respectively (Satman et al, 2001).

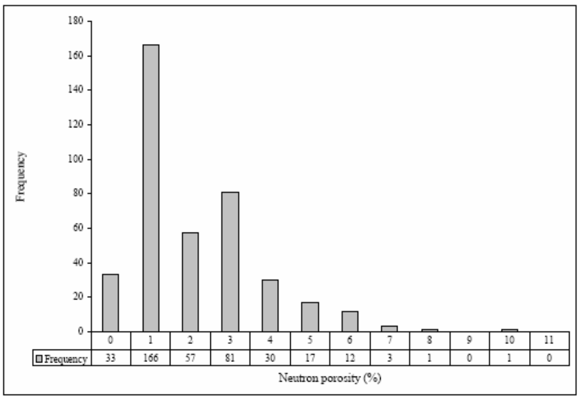


Figure 8: Histogram showing the neutron porosity values from Wells BG-4, BG-8, BG-9 and BG-10 (Satman et al, 2001).

Analysis of Table 1 indicated the minimum, most likely and maximum values of specific heat of rock as 0.80 kJ/kg-°C for Granite, 0.92 kJ/kg-°C for Sandstone and 1.09 kJ/kg-°C for Serpentine, respectively.

Table 1: Specific Heat of Rocks (http://www.engineeringtoolbox.com/24_154.html).

Product	Specific Heat Capacity, kJ/kg-°C
Calcite 32- 212 F	0.84
Clay	0.92
Dolomite Rock	0.92
Granite	0.80
Limestone	0.84
Marble	0.88
Sandstone	0.92
Serpentine	1.09

Normalized rock densities obtained from density logs are presented in Figure 9. Analysis of Figure 9 indicated the minimum, maximum and most likely values of rock density as 2600 kg/m^3, 2850 kg/m^3 and 2750 kg/m^3, respectively.

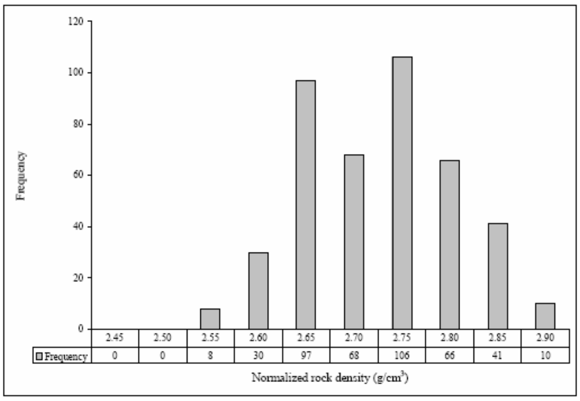


Figure 9: Histogram showing the normalized rock density values from Wells BG-4, BG-8, BG-9 and BG-10 (Satman et al, 2001).

The temperature profiles from shallow and deep wells of Balçova field (Figure 10) were used to determine the ranges of rock temperature and thickness of formation. The well BD-5 is the deepest well at which the temperature profile was taken. This profile shows a maximum temperature of about 115 °C in the depth interval of 700-820 m and then a reversal in deeper sections with a constant temperature profile of 100 °C. This behavior indicates a lateral movement of geothermal fluid in the interval of 700-820 m, but at the deeper sections constant temperature behavior also shows the existence of permeable zones. Therefore the deepest point of the reservoir can be taken as high as 1000 m. The other deep wellbores (BD-1; BD-7) show thicknesses of 250 m and above. Therefore the thickness data are taken as 250, 350 and 1000 m for minimum, most likely and maximum values, respectively.

Figure 10 is also used to determine the possible values of temperature to be used in triangular distribution. The highest recorded temperature is about 145 °C (BD-1), and the minimum is taken as 100 °C while the most likely is 135 °C all deduced from Figure 10.

The density of fluid data for triangular distribution correspond to the density of pure water obtained from steam tables for the temperatures 100, 135 and 145 °C as 958.1, 930.6 and 921.7 kg/m^3, respectively (Mayhew and Rogers, 1977). Triangular distribution values for reservoir area are obtained from Satman et al. (2001).

The remaining variables of Equation 1 (utilized temperature, specific heat of fluid) are taken as constant values. Utilized temperature is assigned to the return temperature of the primary loop of the heat exchanger. The specific heat of fluid is taken as 4.18 kJ/kg-°C, which is the specific heat capacity for pure water. Table 2 lists the values of variables of Equation 1.

3.2 Data Collection from Balçova geothermal Field for Equation 2

In this equation the most critical parameter is recovery factor, which represents the produced percentage of accessible resource. White and Williams (1975), Muffler and Cataldi (1978), and Sorey et al. (1982) discussed this parameter in their studies and they accepted this parameter in the range of 18-25% for the water-dominated systems. On the other hand Nathenson and Muffler (1975) used a value of 24% for recovery factor in their study while modeling hot water systems. World Energy Council, WEC, (1978) used a value of 7% for recovery factor. This is a fairly low value and it is thought that it represents only the heat energy that water has. For this reason a triangular distribution is formed and for the minimum, most likely and the maximum values, 7%, 18% and 24% are chosen, respectively.

The range for transformation yield was defined between 0.7 and 0.93 with a value of 0.85 as most likely.

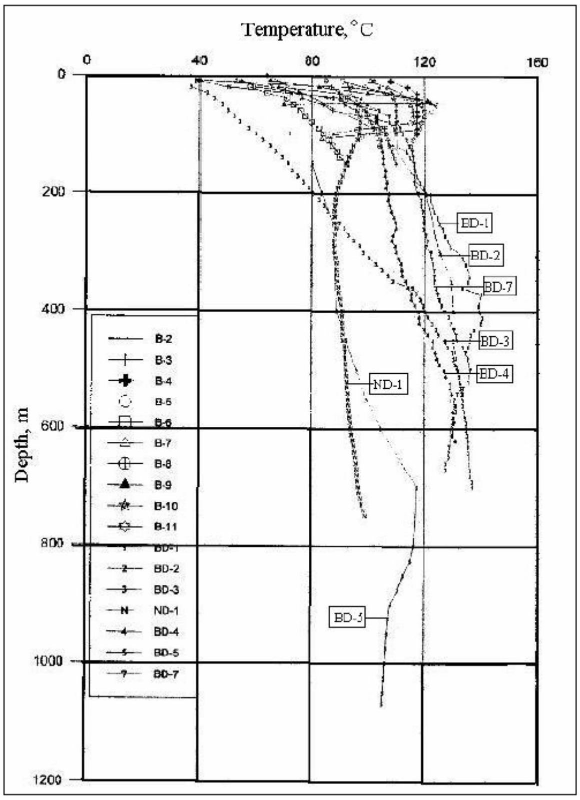


Figure 10: Temperature profiles of shallow and deep wells (adapted from Satman et al. 2001).

Table 2: Values of the variables in Equation 1 with Triangular Distribution.

İzmir Balçova Geothermal Region				
Accessible Resource Base				
Parameters	Most Likely	Type of Distribution	Min.	Max.
Porosity, ϕ (fraction)	-	Lognormal	0.002	0.07
Specific Heat of Rock, c_R	0.92	Triangular	0.80	1.09
Density of Rock, ρ_R	2750	Triangular	2600	2850
Area, A (m^2)	9.00 E+05	Triangular	5.00 E+05	2.00 E+06
Thickness, h	350	Triangular	250	1000
Temperature of Rock, T_R	135	Triangular	100	145
Density of Fluid, ρ_F	930.6	Triangular	921.7	958.1
Utilized Temperature, T_U (^{o}C)	80	Constant	-	-
Specific Heat of Fluid, c_F	4.18	Constant	-	-

H_{Total} can actually be referred as the *accessible resource base* of the low-temperature reservoir under study. For the minimum, most likely and the maximum values, 1.26E+13, 5.53E+13 and 2.50E+14 are obtained respectively for *accessible resource base* from the output of Equation 1 after running @RISK.

The remaining variables of Equation 2 (total project life and load factor) are taken as constant values. The value of 7.88 x 10^8 seconds for total life represents 25 years production time and the value of 50% for load factor represents 183 days production in a year for a comfort temperature of 18 °C (Figure 11).

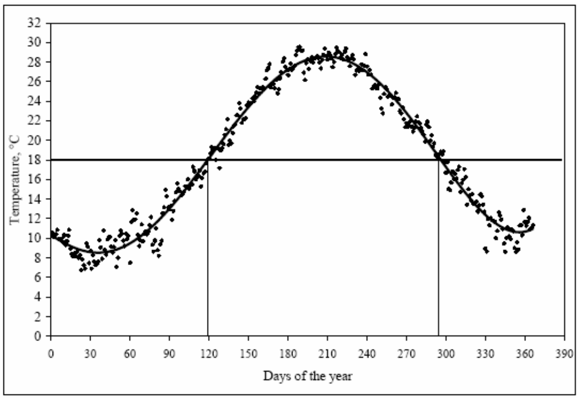


Figure 11: Daily temperature change in İzmir.

Table 3: Values of the variables in Equation 2 with Triangular Distribution.

İzmir Balçova Geothermal Region				
Recoverable Heat Energy				
Parameters	**Most Likely**	**Type of Distribution**	**Min.**	**Max.**
Accessible Resource Base, (kJ)	5.53 E+13	Lognormal	1.26E +13	2.50 E+14
Recovery Factor, (fraction)	0.18	Triangular	0.07	0.24
Yield, (fraction)	0.85	Triangular	0.7	0.93
Total Life, (sec)	7.88 E+08	Constant	-	-
Yearly Production, (fraction)	0.50	Constant	-	-

Table 3 lists the mean, minimum and maximum values of the variables of Equation 2 as the result of simulation study of @RISK.

4. RESULTS AND DISCUSSIONS

The accessible resource base and recoverable heat energy of Balçova low temperature geothermal field of Turkey are estimated by probabilistic approach. Monte-Carlo simulation method is used through an add-in software (@RISK) to Microsoft EXCEL. While applying simulation, the number of iterations was chosen as 10000, which is the maximum number that can be applied in @RISK. Then the @RISK software program assigns random numbers to each variable based on the type of distribution and limits.

The following figures represent the results of this study in detail.

Figure 12 gives the histogram of the output of accessible resource base from @RISK. According to the summary statistics of @RISK the mean value for accessible resource base of Balçova field is 7.33 E+13 kJ. On the other hand, the most likely accessible resource base was found to be 5.53 E+13 kJ (Figure 12). The most likely resource base has the probability of 37%.

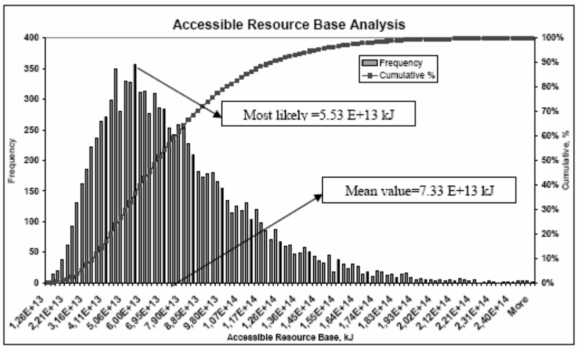


Figure 12: Histogram and Cumulative Graphs for Accessible Resource Base.

Figures 13 gives the histogram of the output of recoverable heat energy from @RISK. According to the summary statistics of @RISK the mean value for recoverable heat energy of Balçova field is 2.51 E+04 kW_t. On the other hand, the most likely recoverable heat energy was found to be 2.12 E+04 kW_t (Figure 13). The most likely resource base has the probability of 47%.

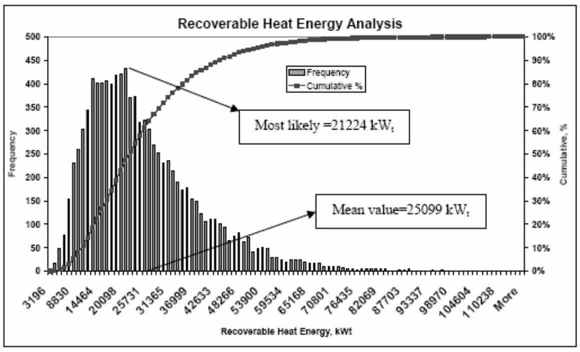


Figure 13: Histogram and Cumulative Graphs for Recoverable Heat Energy.

Analysis of the results of @RISK shows that Balçova geothermal field has recoverable heat energy of 43.6 MW_t at the optimistic approach (90% probability), 10.8 MW_t at the pessimistic approach (10% probability). Mean value was found to be 25.1 MW_t (Figure 14).

These values can also be reported as the number of dwellings that can be heated with the available heat energy. According to ORME Geothermal Company Inc. (Satman et al., 2001), a house with an area of 100 m^2 in Balçova needs 0.004 MWt in order to raise its temperature to 22 °C when the outside temperature is 8.6 °C. The number of dwellings are found to be 2700, 6275 and 10900 for pessimistic, mean and optimistic values of heat energy, respectively.

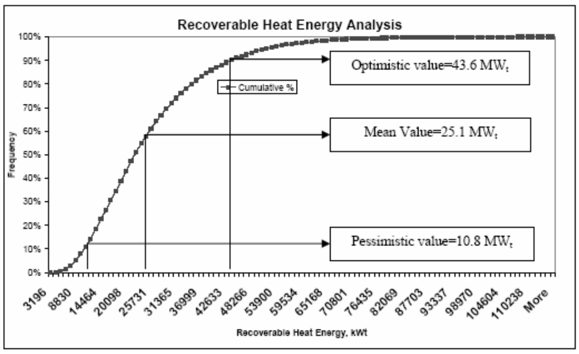


Figure 14: Cumulative Analysis of Recoverable Heat Energy.

4.1 Iteration analysis

The effect of the number of iterations on the results of simulation, 100, 500, 1000, 5000 and 10000 are separately applied to the variables in simulation. The results of the Recoverable Heat Energy with different iteration numbers are plotted in Figure 15. It is clear from Figure 15 that 500 and higher number of iterations give very close results.

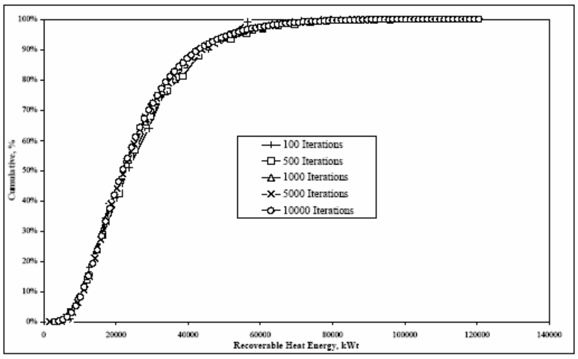


Figure 15: Different Numbers of Iterations for Recoverable Heat Energy.

4.2 Sensitivity analysis

The Sensitivity analysis performed on the output variables and their associated inputs uses either a multivariate stepwise regression analysis or a rank order correlation analysis.

In the regression analysis, the coefficients calculated for each input variable measure the sensitivity of the output to that particular input distribution. The overall fit of the regression analysis is measured by the reported fit or R-squared of the model. The lower the fit the less stable the reported sensitivity statistics. If the fit is too low, a similar simulation with the same model could give a different ordering of input sensitivities.

The sensitivity analysis using rank correlations is based on the calculation of a correlation coefficient between the selected output variable and the samples for each of the input distributions. The higher the correlation between the input and the output, the more significant the input is in determining the output's value.

The sensitivity analysis for accessible resource base and recoverable heat energy are given in Tables 4 and 5.

The most important factors for the calculation of accessible resource base are the thickness and the area, thus in other words the volume of rock. The temperature of the rock is also effective while porosity and density of rock do not have significant effects.

Recovery factor is in third rank for recoverable heat energy, following thickness and area of the reservoir.

Table 4: Sensitivity Analysis for Accessible Resource base Parameters.

Rank	Name	Regression	Correlation
#1	Thickness, h (m)	0.642	0.654
#2	Area, A(m^2)	0.572	0.571
#3	Temperature of Rock, T_R (°C)	0.418	0.431
#4	Specific Heat of Rock, c_R (kJ/kg-°C)	0.120	0.115
#5	Density of Rock, ρ_R (kg/m^3)	0.038	0.019
#6	Porosity, ϕ fraction	0.021	0.015

Table 5: Sensitivity Analysis for Recoverable Heat Energy Parameters.

Rank	Name	Regression	Correlation
#1	Thickness, h (m)	0.570	0.582
#2	Area, A (m^2)	0.510	0.513
#3	Recovery Factor, fraction	0.394	0.404
#4	Temperature of Rock, T_R (°C)	0.372	0.390
#5	Specific Heat of Rock, c_R (kJ/kg-°C)	0.109	0.100
#6	Yield, fraction	0.108	0.110
#7	Density of Rock, ρ_R (kg/m^3)	0.037	0.013
#8	Porosity, ϕ fraction	0.016	0.023

CONCLUSIONS

The following conclusions can be drawn from the results of the current study,

1. Balçova geothermal field has recoverable heat energy content of 58.6 MW_t as an optimistic value (90% probability) and 33.5 MW_t as mean value when triangular type distribution is used for the input variables.

2. No significant difference is observed in the output of @RISK when 500 and higher number of iterations is applied.

3. Sensitivity analysis showed that the most important input parameters are thickness and area of the reservoir rock for both accessible resource base and recoverable heat energy calculations.

4. Recovery factor has also a significant importance for the calculation of recoverable heat energy, based on sensitivity analysis.

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