

# Assessment of geothermal resources for power generation

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Geothermal energy is the heat of the earth included in the rock matrix (90%) and the pore fluid (10%). It is renewable, all time available with a beforehand-predicted power generation potential. After defining the main parameters of a geothermal resource (area, volume, geology, geochemistry, temperatures, fluid properties, etc.) geothermal resources can be estimated by (i) calculating the natural heat flow of the area, (ii) by calculating the stored heat and multiplying it by the recovery factor and the conversion efficiency and expressing the result as MWe of installed power over a 20-25 years period, and (iii) by computer simulation of reservoir parameters under possible exploitation scenarios.

(Received March 13, 2008; accepted May 5, 2008)

**Keywords:** Geothermal Resources, Power Generation, Geothermal Exploration Surveys, Natural Heat Flow Method, Stored Heat Method, Reservoir Simulation Method, Renewable Energy Sources

## 1. Introduction

Geothermal resource assessment has been a major issue since the early days of geothermal development, as it has been the basis for sizing and financing geothermal power plant investments. In 1977-78, Muffler and Cataldi in their paper [1] evaluated the methods of “surface thermal flux” (natural heat flow), “volume” (stored heat), “planar fracture” and “magmatic heat budget”. At the same time, McNitt in his paper [2] evaluated the methods “energy in place” (stored heat) and “decline curve” from a United Nations point of view. Both papers concluded that all methods for estimating the geothermal resources were unsatisfactory with the stored heat method most promising.

At that time, geothermal exploitation was based on bringing the natural fluid present within the hot rocks at the surface through production wells. Since then, reservoir replenishment by reinjecting used fluids became a standard practice, new geophysical methods for geothermal exploration made possible three dimensional mapping of hot rocks with great accuracy [3], and advanced computer technology allowed modelling of subsurface fluid and heat flows and reliable prediction of the evolution of produced fluid pressure, temperature, specific enthalpy and chemistry transients over time during exploitation. In addition, recently the Soultz experiment of the European Union proved that reservoir development into hot dry rocks and the exploitation of enhanced geothermal systems is technically feasible [4]. Furthermore, the authors are aware of many geothermal power projects the development of which was based on successful application of the methodologies presented in this paper, and have not encountered a single project that has failed due to inadequate geothermal resources.

This paper expresses the authors point of view on geothermal resource assessment based on their experience

and is organized as follows. The nature of geothermal resources is presented in Section 2. Section 3 describes present methodology for geothermal exploration. The technique for the estimation of natural heat flow is presented in Section 4. The method for the estimation of stored heat is described in Section 5. The reservoir simulation method is presented in Section 6. Conclusions are drawn in Section 7.

## 2. The nature of geothermal resources

Drilling underground proves that the earth temperature rises with depth at a rate called “geothermal gradient”. Therefore, the earth interior is hot and the heat content of the earth is called geothermal energy. It is stored within the earth itself enclosed at both the rock matrix and the fluid present in its pores. The latter is usually pressurized water.

Apart from volcanoes, geothermal energy is also manifested at the surface by hot springs, steam vents, hot soil, boiling mud, geysers, hydrothermal craters, features attributed to underground circulation of hot fluids rising to the surface. These fluids comprise the convective component of the natural heat flow from the earth interior. There is also a conductive component to the natural heat flow of the earth, which occurs due to the temperature difference between deep underground and the soil surface, and is governed by the thermal conductivity property of the rocks.

The heat content of the earth is so huge, that if it could be utilized, it could cover the entire energy needs of mankind for many millions of years; it is practically inexhaustible for human terms. Due to this huge content of the earth interior, any rock portion that is cooled down due to intensive geothermal development, is renewed due to heat flow from below, stimulated by the temperature

difference. Geothermal energy is therefore a renewable energy form.

Some areas of the earth are well favoured in terms of the availability of both high temperature and subsurface fluid at relatively shallow depth. These areas are called “geothermal fields”, or better “hydrothermal systems” and until now only these areas have been targets for geothermal development for power generation purposes. Fig. 1 presents the conceptual model of Kawah geothermal field [5].

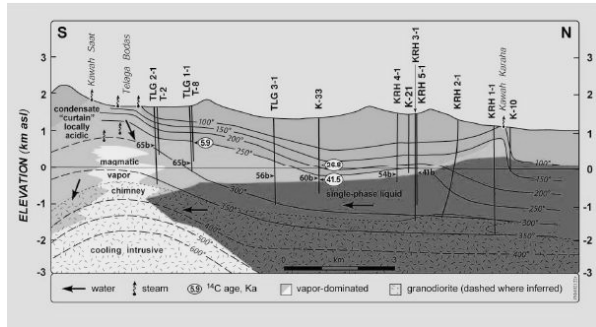


Fig. 1. Conceptual model of Kawah geothermal field: North-south cross section showing measured temperatures, pressures and main hydrologic regimes. Telaga Bodas is an acidic lake, Kawah Saat and Kawah Karaha are fumarole fields. Wells TLG 2-1, T-2, TLG 1-1, T-8, TLG 3-1, K-33, K-21 and KRH 2-1 have been studied in detail [5].

It was only recently that deep parts of sedimentary basins have been selected for geothermal power generation projects, but, apart a few exceptions, all relevant projects are still under development. It was only recently that the exploitation of rock parts with no or little natural fluid (termed as hot dry rock), proved technically feasible, but no such commercial projects are operating at present.

Traditional geothermal exploitation technology involves drilling wells through which the native fluid is conveyed at the surface, either by natural flow, or by pumping. These wells are called production wells. As the bulk of the heat is contained in the rock matrix, exploiting only the heat of the pore fluid yields energy output only a fraction corresponding to the order of 10% of available energy. For this purpose, and in order to maximize energy output from a geothermal field, after extracting its heat, the fluid is reinjected back to the deep horizons it was produced from, via wells termed as “reinjection wells”. That way, the pore fluid serves as the means through which the geothermal energy is extracted and only heat – not mass – is effectively extracted from the earth.

If geothermal energy is available at high enough temperature, it can be utilized for power generation. The main advantage of geothermal energy compared to other renewable energy sources, is that it is independent from outside whether conditions and is available all year round, 24 hours per day. In addition, the amount of energy output can be estimated beforehand, according to the methodology described in Section 4.

Regarding conversion technology, 95% of installed geothermal power plants are flash steam plants, which require at least 150°C source temperature. The other 5% are binary plants, the threshold for profitable operation of which is down to 90°C. Geothermal power plants can cover either and/or both base and peak electricity loads, with typical annual load factors of 95%, with 5% downtime for maintenance purposes. They can be fully automated, with the ability of remote monitoring, operation and control through a telephone or satellite link, enabling thus, a series of small plants to be operated from a central location.

### 3. Geothermal exploration methodology

Geothermal exploration aims at identifying the geothermal resource, in terms of surface extent, volume, rock and fluid properties, and collect all necessary information for taking decisions on investing towards a geothermal power plant. Geothermal exploration should include the following surveys [3], [6]:

**Geological survey:** The geological survey includes study of surface rocks in terms of mineral content, fluid inclusions, as well as studying the hydrology of the area, aiming at:

- Mapping surface geology and major fault zones.
- Identifying the age of rocks.
- Establishing local stratigraphy and possible permeable deep zones for geothermal exploitation.
- Identifying volcanic formations of recent geological age, which indicate the presence of hot magma chambers close to the surface.
- Identifying hydrothermally altered rocks, which are a product of a fossil or active hydrothermal system.

Data from existing wells, if available, are particularly helpful at this stage.

**Mapping thermal manifestations:** Thermal manifestations (steam vents, geysers, hot springs, hot ground, boiling mud, hydrothermal craters) are the outlet of rising hot fluids that prove the presence of an active hydrothermal system in an area, which may be the target for geothermal power generation. They may provide useful clues concerning the location, the temperature, the chemistry and the depth of the deep geothermal resource. In addition, the flow of each thermal manifestation is measured, which is necessary for calculating the convective heat flow from the area.

**Geochemical survey:** It includes sampling of surface and near surface waters, chemical analysis and application of geothermometers. The latter assumes that the chemical equilibrium of dissolved species remains unaltered during their rise from depth towards the surface, and as chemical equilibrium is a function of temperature, the deep temperature of the fluids can be derived. An experienced geochemist can derive credible estimations concerning the temperature and chemistry of the deep fluids.

**Thermal gradient measurements:** It includes drilling a set of shallow bores, of depths 50-100m, measuring downhole temperature, and defining the distribution of the geothermal gradient in the area, which, along with the thermal conductivity of the rocks, are the factors of conductive heat flow from the area.

**Gravity survey:** It concerns measuring the local gravity field, which depends on the density of subsurface layers. In volcanic environments where there is a large difference in the density between the upper volcanic formations and the deeper basement of metamorphic rocks, the gravity survey provides useful information concerning the thickness of the volcanic formations.

**Monitoring micro seismic activity:** The presence of an active hydrothermal system depends on the existence of open fractures, which allow the circulation of subsurface fluids. As rising fluids tend to deposit minerals which seal the fractures, these fractures are kept open, or new ones are formed, by the presence of local micro-seismic activity. Monitoring this activity can provide useful clues on subsurface zones of high permeability. By calculating the velocity field of the seismic waves, useful clues can be derived concerning the subsurface geology distribution. Fig. 2 presents a 3-D subsurface model derived from integrated interpretation of surface, seismic and well data at the Travale geothermal area [7].

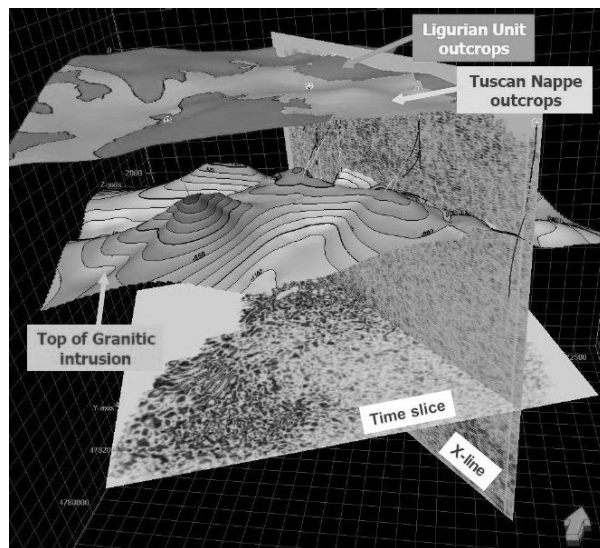


Fig. 2. 3-D subsurface model derived from integrated interpretation of surface, seismic and well data at the Travale geothermal area [7].

**Geo-electric surveys:** As the rock electric conductivity depends on the rock type, the minerals present, the fluid temperature and the fluid salinity, these surveys can provide excellent imaging of subsurface by delineating rock types, locating deep fault zones, and mapping subsurface hydrothermal zones which are characterized by extremely low electric conductivity. Related methods include DC resistivity soundings of Schlumberger

electrode arrangement, as well as the more advanced MT (magnetotelluric) soundings.

**Reflection seismics:** A method of high cost, but with credible penetration to depth down to 3 km, is the reflection seismics method [7]. It includes the creation of an artificial seismic event and monitors the seismic waves as they are reflected back to the surface. This method can provide excellent imaging of subsurface structures and fault zones. The latter are always associated with high permeability, and are targets of geothermal production wells.

**Deep exploration drilling and testing:** A geothermal resource is considered as proven, only if there is at least one deep geothermal production well. Apart from proving the resource, deep exploratory wells provide useful information on subsurface geology, rock properties, minerals present, fluid inclusions, as well distribution of key reservoir parameters, such as temperature, pressure, porosity and permeability, which are necessary to assess the quantity and quality of the geothermal resources. Related tests include sampling of rocks (cores), and fluid, wire line logging, production tests, pressure drawdown and build-up tests, injection tests and interference tests.

#### 4. Estimation of natural heat flow

The method for the estimation of natural heat flow involves estimating both convection and conduction components of the natural heat flow from the earth to the surface.

The conductive heat flow is calculated by multiplying the thermal conductivity of near surface rocks with the geothermal gradient. The thermal conductivity is estimated by core sampling and laboratory measurements. The geothermal gradient is estimated by drilling shallow bores and measuring bottom-hole temperature.

The corresponding calculations for the conductive heat flow component are:

$$H = \iint_A c \cdot \frac{dT}{dz} dA \quad \frac{dT}{dz} = \frac{T_b - T_a}{z}$$

where:

$H$	Conductive heat flow, Watt
$A$	Surface area, m <sup>2</sup>
$c$	Rock thermal conductivity, Watt/m°C
$\frac{dT}{dz}$	Geothermal gradient, °C/m
$T_b$	Bottom hole temperature, °C
$T_a$	Mean ambient temperature, °C
$z$	Depth, m

The convective heat flow component equals:

$$F = \sum \dot{m} \cdot C \cdot (T_f - T_a)$$

where:

$F$	Convective heat flow, kW
$\dot{m}$	Mass flow rate of thermal spring, kg/s
$C$	Heat capacity of fluid, kJ/kg°C
$T_f$	Fluid discharge temperature, °C
$T_a$	Mean ambient temperature, °C

Total heat flow equals  $H + F$ .

This method estimates the natural heat flow from a geothermal area that has occurred for thousands of years and will continue to occur in the future, corresponding to the minimum amount of geothermal resources that can be utilized in the area. This exploitation rate has minimal impact to the geothermal system of the area, and has no effect to subsurface temperature distribution.

However, present technology always allows, and economic feasibility directs geothermal energy exploitation rate by much larger factor, by extracting the heat stored in the hot formations beneath the surface and cooling down the rocks, during a time period of 20-25 years. For this reason, for geothermal power plant development purposes, the “stored heat” or “heat mining” method is preferred.

### 5. Estimation of stored heat (heat mining)

The stored heat method assumes that we extract the heat from a specific volume of rock, by cooling it down from its natural state to a base temperature. For this purpose we need to define the rock volume for heat mining by geothermal exploration [8].

As a base temperature, we use the lowest temperature of the produced fluid that allows commercial viability of the installed geothermal power plant. It depends on the type and design specifications of the geothermal plant.

Although this temperature threshold allows commercial power generation from surface installations, cooling the entire volume of rock down to it requires a very dense network of wells that results in extremely high costs, and/or may not be technically possible due to uneven distribution of permeability and pore structures. For this reason, the above stored heat amount is multiplied by a coefficient called recovery factor, in order to estimate the useful heat that can be extracted for the above rock volume. Recovery factors vary between 10-50% depending on the geological prevailing conditions, with an average value of 25% for hydrothermal resources [8] and 40% for enhanced geothermal systems [9]. Fig. 3 presents Recovery factor versus stimulated volume for a range of well geometries, fracture spacing, and permeability [9].

In order to calculate the geothermal power that can be generated, the useful extracted heat is multiplied by the heat to power conversion efficiency. Conversion

efficiency is the ratio of the generated electricity over the heat extracted from the earth. The higher the temperature, the higher the heat to electricity conversion efficiency. In general, most geothermal power plants, either flash or binary, operate with conversion efficiency around 10-15%. In order to express the geothermal resources in terms of MW<sub>e</sub> of power plant installed, we need to define the life of the plant (usually taken as 20-25 years) and the load factor (usually taken as 90-95% for base load plants).

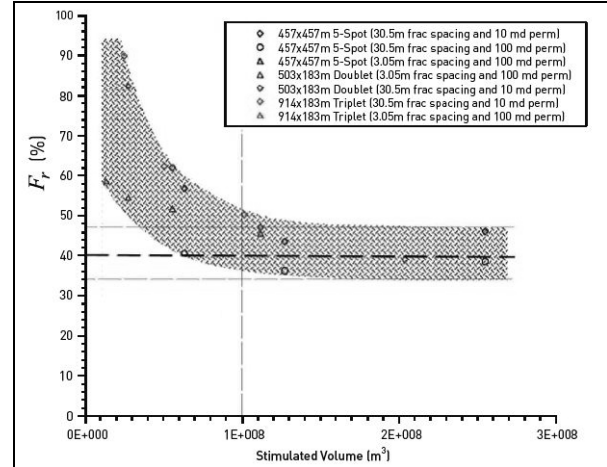


Fig. 3. Recovery factor vs. stimulated volume for a range of well geometries, fracture spacing, and permeability [9].

The equations used in the corresponding calculations are as follows:

$$E_{st} = [(1 - \phi) \cdot \rho_r \cdot C_r + \phi \cdot \rho_w \cdot C_w] \cdot V \cdot (T - T_b)$$

$$E_r = E_{st} \cdot R$$

$$N_e = \frac{E_r \cdot n}{f \cdot t}$$

where:

$E_{st}$	Stored heat, kJ
$E_r$	Recoverable heat, kJ
$\phi$	Porosity, (%)
$\rho_r$	Rock density, kg/m³
$\rho_w$	Water density, kg/m³
$C_r$	Rock heat capacity, kJ/kg°C
$C_w$	Water heat capacity, kJ/kg°C
$V$	Rock Volume, m³
$T$	Rock natural state temperature, °C

$T_b$	Base temperature, °C
$R$	Recovery factor
$N_e$	Installed power, MW <sub>e</sub>
$n$	Conversion efficiency
$f$	Load factor
$t$	Commercial life span of the plant, Msec

In the stored heat method two main types of geothermal resources are estimated: proven resources and inferred resources. Proven resources correspond to the rock volume delineated by the perimeter of productive wells, extended horizontally by the well drainage radius (~250m) and deeper by 500m from well bottom, if recharge from deeper hot fluids is evident. Inferred geothermal resources correspond to rock volume indicated by geophysical surveys as well.

Experience from geothermal development projects however, indicates that this method yields conservative estimation of installed power from geothermal resources, and recovery factors higher than 50% seem to be possible by well stimulation and field management practices.

## 6. Reservoir simulation

The reservoir simulation method uses a commercial available computer code in order to model the heat transport, the fluid flow and the chemistry within a geothermal reservoir during exploitation. The main input parameters are distribution of rock types and properties (density, heat capacity, thermal conductivity, temperature, porosity, permeability), fluid properties (temperature, pressure, chemistry, steam quality), as well as natural heat and fluid recharge, fluid production rates and location, and fluid injection rates, location and temperature. Fig. 4 presents a screenshot of such a reservoir simulator model output.

For the simulation purposes, the underground is divided into blocks, and the differential equations of mass conservation, energy conservation, momentum conservation (Darcy's law) and chemical species conservation are solved by a numerical method, usually finite elements. Calculated (solved) variables are temperature, pressure, vapour content, chemical concentration. Firstly a steady state model is formed by matching model output to measurements from well testing. Then the model is run for 20-25 years into the future, in order to predict the geothermal reservoir behaviour under different exploitation scenarios and select an optimum fluid production rate, which defines the installed capacity of the power plant [8].

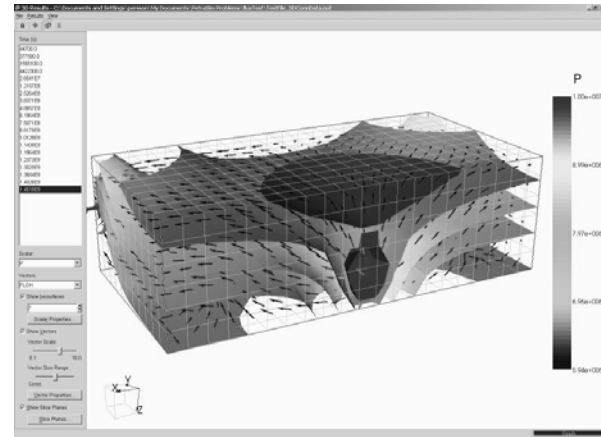


Fig. 4. Screenshot of a reservoir simulator model with subsurface layers, pressure distribution and flow patterns in the vicinity of a reinjection well.

The methods of “natural heat flow” and “stored heat” are more or less objective in the output of geothermal resources they yield, and can be used by an inexperienced geologist or engineer. However, in order to yield credible output from reservoir simulations, one or more experienced geothermal reservoir engineers are needed, who will design and run a well planned well testing program in order to collect all necessary data and estimate rock properties.

The reservoir model of a geothermal field is updated continually, as new data is gathered during field exploitation for power generation, and the reservoir model simulates better the behaviour of the geothermal resource.

## 7. Conclusions

Today a proven methodology for estimating the geothermal resources of a particular geothermal field or region is available, which can provide a reliable basis for geothermal power plant investments. It starts with a first estimation of natural heat flow, followed by geophysical and drilling exploration and estimation of stored energy and the corresponding capacity of the power plant, assisted by computer simulation of subsurface heat and mass transfer and prediction of future behaviour of the geothermal system.

## Acknowledgments

This work has been performed within the European Commission funded project of DG-RESEARCH ENGINE “Enhanced Geothermal Innovative Network for Europe” (contract number SES6/019760). The European Commission is acknowledged for partially funding this project.

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