PAPER • OPEN ACCESS

Methods for the estimation of the energy stored in geothermal reservoirs

To cite this article: A Franco and F Donatini 2017 *J. Phys.: Conf. Ser.* **796** 012025

View the article online for updates and enhancements.

Methods for the estimation of the energy stored in geothermal reservoirs

Alessandro Franco, Franco Donatini

Department of Energy, Systems, Territory and Constructions Engineering
University of Pisa, Largo Lucio Lazzarino, 56126 PISA

Corresponding author e-mail: alessandro.franco@ing.unipi.it

Abstract. The paper analyze the problem of the estimation of the potential of geothermal reservoirs with the objective of sizing of geothermal power plants in order to reach the goal of a correct matching of renewability and economic related issues. After an analysis of the typical approaches based on the First Order Method diffused in the literature since the late 70s and of the uncertainties connected with the use of simplified approaches, that have determined general overestimation of the geothermal energy stored in the reservoirs and of the size of the plants connected to various geothermal fields, the authors discuss about possible improvements based on the combination of theoretical simplified approaches with experimental data of heat flow, taking into account not only the energy stored, but also the possibility of producing a recharge.

1. Introduction

Geothermal energy is considered a strategic resource for the possibility of producing energy both for direct thermal use and electricity production but its characteristic of renewability are recognized only when a correct exploitation of the reservoirs is carried out. 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 considered "geothermal fields" and "hydrothermal systems". Until now only these areas have been targets for geothermal development for power generation purposes and direct used of thermal energy. The renewability of the resource itself is directly dependent on the type and rate of utilization and the durability of a plant are directly connected to the way the resource is explored and then exploited and to a correct knowledge of a potential assessment, [1, 2].

In the past, geothermal power plants have frequently been built ''as large as possible'' in order to meet economic convenience in a reduced time. But this approach has determined several problems, [3, 4]. In recent times the concept of renewability has been improved introducing the idea of sustainability: this concept include the idea of using geothermal resources using some compensative actions, like cultivation strategies and reinjection. [5, 6]. The proper matching between the reservoir capability and the plants parameters (power size, extraction/reinjection rate) is a critical key point. The main task of potential assessment and sustainable design of a plant is the perspective of resource durability, [7].

Interesting contribution on the definition and evaluation of the sustainability and renewability of the geothermal energy uses are available in the literature, both in some classical contribution, like the one by Muffler and Cataldi, [8] and in more recent papers by Hähnlein et al. [9] and Axelsson [10]. Mainly in case of innovative geothermal utilizations (like for example EGS) the long-term consequences on the environment are not completely known yet. The renewability (and sustainability) reference level can vary, as one can adjust the system size and extraction rate according to an acceptable durability.

In the recent paper by Fox et al. in [11] the renewable capacity of deep systems is assessed and discussed in order to elaborate a rotating utilization strategy. Drilling underground proves that the earth temperature rises with depth at a rate called "geothermal gradient". But the heat content of the earth is so huge, that if it could be utilized, it could cover the entire energy needs for a lot of years and it is practically inexhaustible for human terms. In general heat and suitable temperature are not enough for geothermal exploitation. The availability of fluids, like deep water or saturated steam is also necessary. But the intensive use on some zones caused that some intensive use of geothermal energy caused local cooling down of the reservoir and the extracted flow is not exactly renewed due to heat flow from below, this causing remarkable problems during the production phase.

The worldwide experience in geothermal energy uses demonstrates a lot of cases in which a progressive reduction of production levels after the construction of the power station has been observed so that reinjection has been considered a common practice in geothermal energy uses, [12]. The geothermal potential assessment can be considered a relatively recent field of research. It is well known that, the occurrence of a geothermal system requires a heat source and a working fluid to transfer heat. In general the interest in the use of geothermal energy is connected with the observation of a geothermal anomaly. Considering that the average heat flow in the earth's surface is approximately $60mW/m^2$, the occurrence of on anomalous gradient is connected to the relevation of strongest heat flow values, where volcanic activity and presence of fluids and activity transports, the heat flow values overcome the value of 100 mW/m^2 and reach upper levels of the order of 250-1000 mW/m^2 in places characterized by important geothermal activity, like Larderello or Monte Amiata. The estimation of the heat flow is a good basic element to understand the interest of a geothermal area, but is often not sufficient to clearly understand the capacity of a reservoir. The success of a geothermal project is mainly connected with the dimensions of the reservoir and with a well defined estimation of the energy storage so that a quite long life of the geothermal plant could be obtained.

In the first part of the paper meaningful examples of the techniques and approaches used in the evaluation of the geothermal energy potential are briefly described and discussed, with a particular attention for the medium-low enthalpy resources. Since the preliminary scientific analyses of the potential assessment of geothermal reservoirs it has been stated that a general methodology for every kind of geothermal field does not exist. Although in the literature a lot of different methods and reliable principles have been treated and tested, it seems quite difficult to find a complete multidisciplinary view of the problem, in which the connections between the parameters of plant design, geological and geophysical characterization and reservoir engineering can be clearly evidenced. In general the methods consist in the estimation of the thermal energy content in a reservoir, considering the different contribution from the solid and liquid phases, or from the main underground heat sources in a certain geometric domain. It is now interesting to show some of the main features and characteristics of these methods. Then the authors discuss the perspective of integration of the methodological "First order" methods based on the analysis of simple experimental data coming from geothermal drilling operation, like thermal gradient and local heat flow, for the definition of methods for the definition of sustainable levels of power production.

2. The problems connected with an uncorrected estimation of the energy potential
The excessive exploitation of a geothermal reservoir could determine problems in each kind of geothermal system. The reduction of power in case of vapour dominated geothermal field is well clear but not dramatic. The same problems can be evidenced in case of flash-steam power plants.

In several cases in the industrial practice, fluid extraction reached excessive rates and it has not been possible to maintain productivity in the long-term. The utilization of the Geysers area in California is a well-known example of excessive production [13], or the case of Momotombo geothermal field, analyzed by Porras and Bjornsson [14]. A sustainable perspective in geothermal projects appears to be particularly important in case of small size power plants (below 1 MW of net power produced) based on the utilization of ORC power plants: the high specific costs of the plants and drilling could suggest

over sizing and a consequent overexploitation of the reservoir. A temperature reduction of the geothermal source could cause the end of life of the plant because it could be impossible to maintain a correct pinch-point value in the heat exchanger (in Fig. 1 the decrease of the temperature profile of geothermal fluid, caused by a decrease of the source temperature, determines a reduction of pinch point value from the design value *PP1* to the reduced value *PP2*). This problem is important for each kind of ORC, but in particular with reference to advanced heat recovery solutions, like Rankine with superheater and supercritical and for $T_{geo} < 120\text{-}130\ °C$.
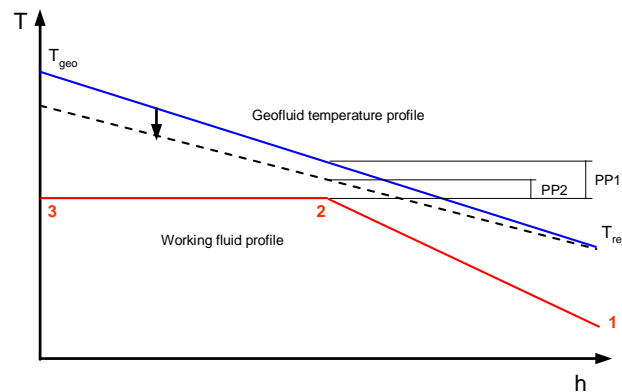

Figure 1. Effects of the temperature decline of the reservoir for the heat exchanger of a binary plant

3. Geothermal potential assessment of hydrothermal reservoirs

Considering the installation of a geothermal power plant the concept of renewability is defined as the ability to maintain the installed power capacity of a plant indefinitely without encountering any resource degradation and without any action; but renewable capacity is often too small for commercial development. In different terms the concept of sustainability has been proposed: this is defined as the ability to economically maintain the installed capacity, over the life cycle of a power plant, by taking practical action (such as, reinjection) in order to compensate for resource degradation (pressure drawdown and/or cooling). [1, 2]. In order to design a plant both with the perspective of renewability and the one of sustainability, the first important step is considered the Geothermal Potential Assessment. The greatest challenges lie in understanding the size and thermal energy of a reservoir as well as the constraints on extracting that thermal energy. A lot of different reliable methods have been used, but a general purpose methodology for every kind of geothermal field doesn't exist [15-16].

Several studies deal with specific geothermal fields worldwide, more than general value surveys. Different instruments and exploration techniques are available today to improve the detail of the information needed to design plants for energy purpose and consequently to estimate the assessment of the reservoir. The geothermal potential of a particular area means mostly the evaluation of temperature (T_{geo}) and pressure (p_{geo}) of the geothermal fluid and of the maximum mass flow rate ($\dot{m}_{geo}$) that can be extracted maintaining the thermal properties of the reservoir for a long time. It can also be defined as the estimation of the energy stored in a reservoir. Resource Estimation Methods can be grouped according two main categories: Methods with no production data and methods integrated with the use of production data. Some of the available methods are enumerated in Table 1.

Table 1. Methods for estimating the energy potential of a geothermal reservoir

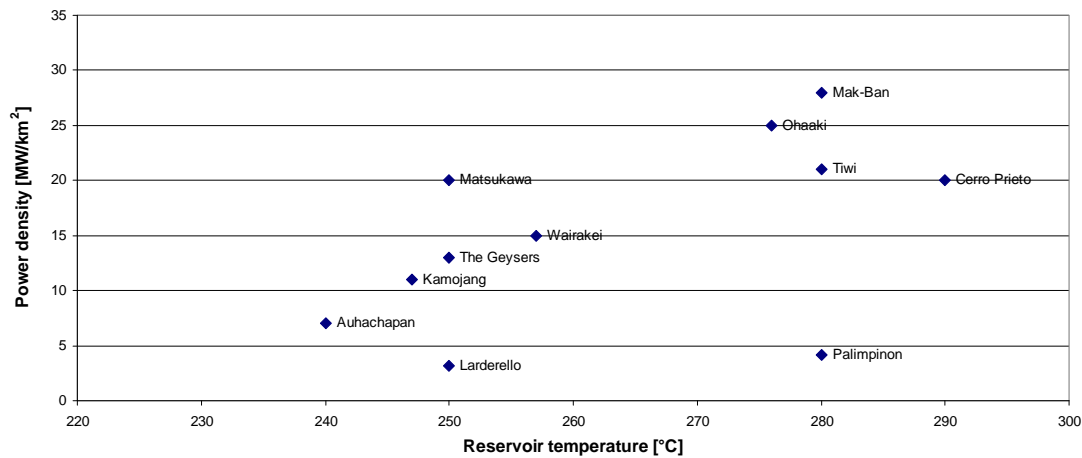| Methods without production data	Methods with production data:
• Heat Flow	• Lumped Parameter Models
• Areal Analogy (Power density)	• Decline Curve Analysis
• Volumetric Methods (deterministic & probabilistic)	• Numerical Reservoir Simulation

Figure 2. Power density sustained in developed geothermal fields [data available in 17]

Analyzing the data referred to the historical development of geothermal energy use, remarkable differences among the various geothermal fields can be clearly evidenced, as reported in Fig. 2, while the power density sustained in the main geothermal fields, in which industrial utilization of geothermal energy has been developed, is reported. It is possible to observe the differences among fields characterized by the same temperature (see the comparison among Mak Ban, Tiwi and Palimpinon).
One of the most widely and consistently usable methods during all stages is the Volumetric stored heat estimation, early defined in [8]. The basic method involves calculating (usable) heat in place using estimated reservoir volume, rock and fluid characteristics and average temperature, against a reference temperature. Recoverable heat is then estimated by introducing a *Recovery Factor,* which can be seen as fraction of the (usable) heat in place that could be produced feasibly by actual production wells over a reasonable (project) timeframe. Finally a feasible, sustainable plant capacity (MWe) for a given/estimated plant life, conversion efficiency, and power plant availability is defined.

Muffler and Cataldi in [8] identified four methods for assessing geothermal resources: surface heat flux, volume, planar fracture and magmatic heat budget. The total energy available is the fraction extractable and useful of the stored energy in the reservoir at favorable technical and economic conditions. It can be roughly estimated multiplying the total energy stored for an appropriate recovery factor (R), which value is between 0 and 1. The estimation of the recovery factor is not a trivial task, it depends from the site characterization and it can also be a result of estimation according to the individual experience. A brief list of the general results that should be evaluated is here proposed: thermal energy stored (at a certain time) in the reservoir; temperature, pressure and rate of the extracted fluid; chemical composition of the fluid and saltiness (to define the appropriate reinjection temperature T_{rej}); number of wells to be drilled and mutual distances between them; time interval to have an appreciable decrease in the rate and temperature of fluid (or productivity); definition of both the "Base" resource available and of the "Effective" resource, which is useful under favorable and sustainable (economic-environmental-technological) conditions; siting of the reinjection wells (number, mutual distances and interference effects); reinjection strategy (effects of reinjection on productivity); number of wells for compensation. Considering mainly water dominated geothermal field at moderate temperature, the energy potential can be first of all referred to the available temperature of the aquifer (T_R). An equivalent specific energy content of the reservoir (both rocks and fluid), namely $\varepsilon_{(T_R - T_0)}$, can be defined referring to the cooling down to a low temperature level, in this case the environment temperature T_0. Considering the reinjection temperature, T_{rej}, the useful temperature difference is $\Delta T = \left(T_R - T_{rej} \right)$, being $T_{rej} < T_0$ (see Fig. 1). This means that a higher mass flow rate should be extracted for power production, according to the upper limit given by

$$\dot{m}^* \cdot c \cdot \left(T_R - T_{rej}\right) \leq \dot{m} \cdot \varepsilon_{(T_R - T_0)} \tag{1}$$

The upper limit for the energy potential can be considered as a function of the whole "geothermal system", (as defined in the Introduction and remarked in Fig. 1) as in Eq. (2)

$$\Pi = f\left(geothermal \ \ system\right) \tag{2}$$

The meaning of the last two equations is that, for given values of maximum energy potential and a well defined value of the temperature difference $T_R - T_{rej}$, a maximum value of mass flow rate (extracted/reinjected) $\dot{m}^*$ can be defined. The value $\dot{m}^*$ clearly depends on a lot of variables (in connection both with natural and technical elements): permeability distribution, hydraulic linking between the production and the reinjection areas, siting of the wells, natural recharge (meteoric water) to the reservoir. So it is clear that the value of ΔT used is inversely proportional to the limit value of the mass flow rate extracted $\dot{m}^*$. If T_{rej} increases, as it can happen in case of rising chemical deposition, the mass flow rate $\dot{m}$ increases, and it could reach excessive values, causing unwanted cooling down of the whole aquifer. Consequently each reservoir presents an optimal combination of mass flow rate extractable and reinjection temperature and a correct design should follow this rule. As it can be seen, this optimization problem involves the whole "geothermal system" (plant, reservoir, environment and their mutual links), so the interdisciplinary approach becomes necessary. The difference $\Delta T=(T_R-T_{rej})$, together with the availability of geofluid and the environment reference temperature (T_0) permits to define the exergy and energy potential of the geothermal field. In evaluation of the commercial potential of a stimulated geothermal reservoir, three must be sufficiently estimated for investment decisions: the available heat content of the reservoir; the optimum thermal extraction rate and the total heat extracted respectively.

4. The first order methods for the definition of the reservoir potential
The thermal extraction rate for a specific reservoir depends on two sets of reservoir characteristics: the heat transfer properties of the reservoir and the flow regime for heat transfer.

The heat transfer properties are determined by the rock-type fracture network which controls the rate of conductive heat transfer to the rock-block surfaces. The energy stored in a geothermal reservoir can be basically determined with the following equation

$$E_R = \rho \cdot c \cdot V \cdot \left(T_R - T_{ref}\right) \tag{3}$$

where c is the volumetric specific heat of the reservoir rock, V is the volume of the reservoir, T_R is the characteristic reservoir temperature, and T_{ref} is a reference temperature.

The thermophysical properties are here referred to the weighted values in terms of mass fraction of rock and groundwater. They can be estimated for example considering that geothermal energy is the heat of the earth included in the rock matrix (for example about 90%) and the pore fluid (for example about 10%). An evaluation of the energy stored based on such a simplified approach determines an overestimation of the potential. Just to understand the problem, considering a volume of the reservoir of 3x3x1 km, typical dimensions of small size reservoirs, like as discussed in [18], a density of 2500 kg/m^3 and a specific heat of 1000 J/kg °C and a temperature difference of 100 °C an energy amount of more than 10^{18} J can be obtained considering some general data about the thermophysical properties ($E_R = 4.5 \cdot 10^{18}$ J). This corresponds to a value of about 108 MTep (about 60% of the total energy used in Italy). Considering the possible installation of a plant, the estimation on the size could be connected

to the perspective of maintaining a reduced value of the temperature decrease during the lifetime of the plant, maintaining this value in the range of some degrees (e.g 1°C after 10 years of operation).

Using the same data considered in the previous analysis a potential of more than 2000 MW can be obtained, so that considering a First Law efficiency in the range 0.1-0.15 a power ranging between 200 and 300 MW can be roughly estimated. If a system like the one of Larderello is considered, according to the model described in [19], a dimension of 70x70 km can be considered, so that a volume of about 600 times the one estimated and consequently a power installed of more than 100000 MW could be installed in the area. But this is surely an overestimated value if we consider that at the end of the 70s a running capacity of at least 500 MW caused the first problems.

Similar considerations can be applied to the other important Italian geothermal field: Monte Amiata. In this case, according to Barelli et al. [20], similar conditions of the fluid can be estimated, but a volume of 80 km^3 can be roughly estimated, so that a maximum level of 1200 MW can be estimated. But it is quite clear that such a simplified approach caused an overestimation of the real potential of the reservoirs.

The industrial production based on this kind of estimation has encountered a lot of problems, in connection with industrial exercise of geothermal plants: a real renewable level corresponds to quite low levels of the power, but the interaction with the reservoir (based on reinjection) determines the definition of a sustainable level. Considering this problem, the approach of the geologists has been to reduce the effective value of the energy stored as a function of the real nature of the reservoirs considering its porosity and the real density, and the availability of a geothermal fluid, characterized by the enthalpy value (h_{WH}). The thermal energy that can be extracted at the wellhead is given by

$$E_{WH} = m_{WH} \cdot \left(h_{WH} - h_{ref} \right) \tag{4}$$

where m_{WH} accounts for the effective nature of the reservoir

$$m_{WH} = V \cdot \left(0.5 \cdot \phi_e \cdot X \right) \cdot \rho_f = V \cdot \phi_R \cdot \rho_f \tag{5}$$

where ϕ_e is the effective reservoir porosity, 0.5 is the fraction of the reservoir that is porous and permeable, X is the degree of saturation, and ρ_f is the fluid density. Hence useful energy is here just the one related to the fluid content of geothermal volume. The ratio between Q_{WH} defined by Eq. (4) and the term defined by Eq. (3) determined a Recovery Factor

$$R_g = \frac{E_{WH}}{E_R} = \frac{V \cdot \phi_R \cdot \rho_f \cdot \left(h_{WH} - h_{ref} \right)}{\rho \cdot c \cdot V \cdot \left(T_R - T_{ref} \right)} \tag{6}$$

where ϕ_R, can be considered as a lumped "reservoir porosity". All of the variables in Eq. (6) are functions of reservoir temperature, pressure and chemical composition, except for ϕ_R, that is the only real unknown variable. According to different analyses reported in the literature, the values of the Recovery factor R_g can vary in general between 0.05 and 0.25 depending on the characteristics of the reservoir. The introduction of the corrections give reasons to a more realistic estimation of the potential of a geothermal reservoir so that reduced values of the energy stored in the reservoir and of the power of a plant using the resource for a well defined period of time (100 years), as reported in Table 2. Analyzing the data of Table 2 it is quite clear the motivation for what before the use of reinjection strategy, the reservoir has been subjected to pressure and temperature decay, causing a reduction of production. The overexploitation of the geothermal reservoir with an increase of the running capacity up to 2200 MW causes an important reduction of the power production during the 90s. The same problems occurred in the Larderello field at the end of the 70s, but the development of reinjection strategy permitted to overcome the problem. The methods discussed before are based on

the estimation of the thermal energy stored in the reservoirs. But the reservoir is a closed system with reduced natural recharge of geothermal fluid, while the use of geothermal energy is more directly associated to the fluid. The observation of the reservoirs used for power production shows that pressure and temperature declines continuously with time, particularly in systems that are closed or with small recharge. Production potential is, therefore, often limited by lack of water rather than lack of thermal energy.

Table 2. Properties, recovery factors (R_g) and estimated power production (P) for some reservoirs [16]

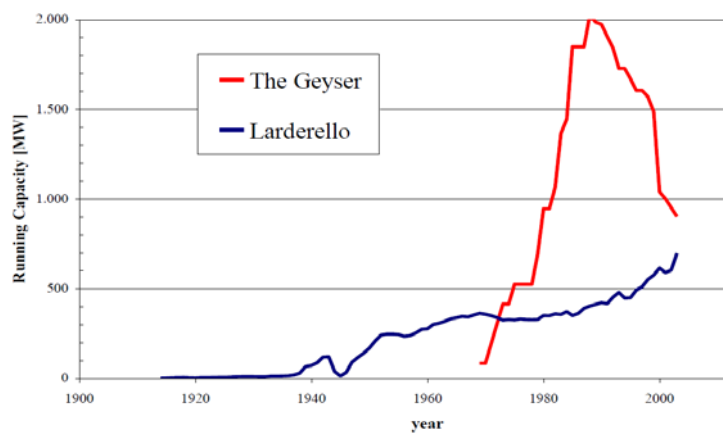| Field	T_R (°C)	V (km^3)	ϕ_R	R_g	P (MW$_e$)
The Geysers	240	150	0.05	0.11	1600
Coso	275	40	0.05	0.08	250
Dixie Valley	220	4/10	0.05/0.13	0.08/0.21	70

Figure 3. Larderello and The Geysers: a comparison between running capacity [21]

A different first order method consist in the estimation of the thermal energy content in a reservoir, considering the different contribution from the solid and liquid phases, or from the main underground heat sources in a certain geometric domain. In this way it is possible to clearly distinguish the contribution of the rock and of the fluid. Different volumes of rock or fluid are identified, their average temperature is estimated and used to calculate the heat stored, compared to a reference temperature (environment). The thermal energy of a reservoir, E referred to a i-th volume can be calculated from the following equation:

$$E_i = C_{vi} \cdot V_i \cdot \left(T_i - T_0 \right) \qquad (7)$$

where C_v is the volumetric heat capacity ($\rho \cdot c$) of the volume reservoir of volume V_i, T_i is the average temperature of the i-th volume and T_0 a reference temperature (e.g. environment). The volumetric domains containing rock or fluid phase are considered when defining the total porosity ϕ as the ratio between the volume of the empty spaces (V_v) and the total volume V so that:

$$\phi = \frac{V_v}{V} \qquad (8)$$

But in general not all the empty spaces in a rock domain are full of liquid or connected and the underground water flow is possible only between the interstitial inter-connected empty volumes, so the

effective porosity ϕ_e should be considered. ϕ_e takes into account the effectively interconnected voids, and for this reason it is generally less than ϕ. It is evident that the contribution to the thermal energy content of the reservoir E can be distinguished between the rock (subscript r) and fluid (subscript w):

$$E_i = E_{ir} + E_{iw} \tag{9}$$

$$E_i = (1 - \phi_i) \cdot c_{ri} \cdot \rho_i \cdot V_i \cdot (T_i - T_0) + \phi_i \cdot c_w \cdot \rho_w \cdot V_i \cdot (T_i - T_0) \tag{10}$$

In Eq. (10) c_r is the volumetric heat capacity of the rock and c_w the volumetric heat capacity of the fluid (geothermal water), while ρ_i and ρ_w are respectively the density of the i-th rock volume and the density of the water in the pores. The errors made in this case can be then reduced by means of the introduction of a recovery factor R, which can be defined as the ratio:

$$R = \frac{E_S}{E_R} \tag{11}$$

where E_S is the resource which is extractable in the current technological and economic conditions in a sustainable way and E_R is the total resource available in the reservoir. The definition of this factor is similar to indexes used in the oil and gas industry.

Even if with all the corrections introduced with respect to the basic simplified models determines more realistic values of the energy stored a lot of problems are connected to the estimation of the various parameters as largely discussed in the literature. Many factors can be uncertain in the use of the first order methods and those are largely discussed by authors. Among those surely there are: reservoir temperature and rejection temperature, reservoir Area/Size and reservoir thickness are object of specific attention as well as Rock Porosity. But the real problem connected to the use of the first order methods is the definition of the recovery factor. Just to understand the recovery factor varying from 0.05-0.20 in more recently published papers as [1], while values from 0.25 to 0.5 are considered in previously published papers, like [22], only to consider one of them. Considering this particular approach, different evaluation of the power production potential of the Larderello and Mt. Amiata geothermal fields can be estimated, as reported in Figs. 4-5.
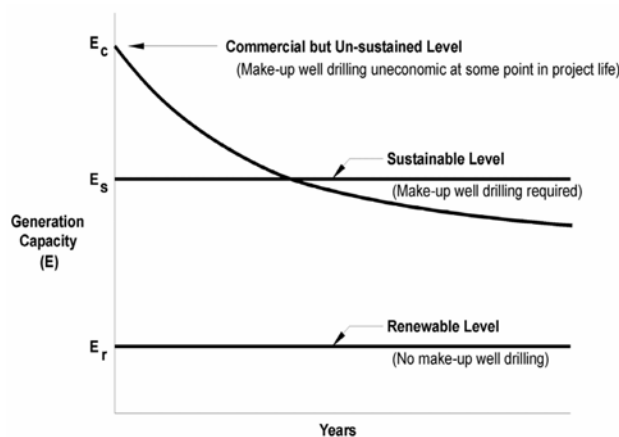

Figure 4. Difference among renewable, sustainable and excessive production connected to geothermal reservoirs: a schematic representation [1].
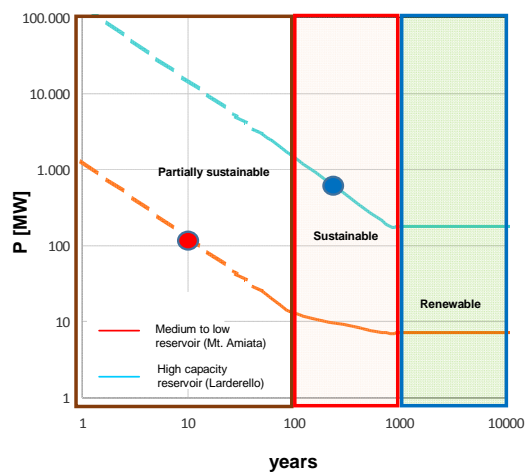

Figure 5. Definition of possible levels of output power for two different Italian geothermal reservoirs.

5. Estimation based on combination of numerical model of the reservoirs combined with geophysical measurement: the importance of natural heat flow

As discussed in the previous section, the "first order" methods, even if useful to have a preliminary evaluation on the energy stored in a geothermal reservoir, have some important intrinsic limitations. The concept of defining a kind of "hot" volume is physically based but important elements, like the permeability of the reservoir are not directly taken into account. The real challenges in the geothermal resource assessment lie in understanding the size and thermal energy of a reservoir as well as the constraints on extracting that thermal energy [16].

Strictly speaking, the power that can be extracted from a geothermal reservoir must be connected not only with the amount of energy stored, but mainly with the heat and momentum transport. So it is surely possible to think to some improvements of the first order methods combining such a kind of approach with some elements that can be derived by experimental data. The natural heat flow appears to be a key element. It involves estimating both convection and conduction components of the natural heat flow from the earth to the surface. The natural heat flow from a geothermal system is the combination of both its advective (e.g., fluid discharge from natural hot springs) and conductive parts and gives a clear indication not only about the energy stored, but also on the thermal recharge of the reservoir. Conductive heat flow, q, can be measured as:

$$\dot{q} = k \frac{dT}{dz} \tag{12}$$

where k is the thermal conductivity of the rock and dT/dz is the vertical temperature gradient. Considering the natural gradient dT/dz = 0.03 °C/m and a typical value of the rock thermal conductivity (k=1.5 – 3 W/mK) a basic value of the conductive heat flow in the range 45-90 mW/m^2! can be obtained. It is clearly possible to understand that the occurrence of heat flow higher than 100 mW/m^2 can be connected with an anomalous value of the thermal gradient as well as the presence of a fluid (water or steam) at a well defined temperature and circulating at a velocity w_f so that the heat flow con be connected to the additional avvective term related to temperature difference between fluid and rocks, ΔT_f and to the velocity of the fluid:

$$\dot{q} = k \frac{dT}{dz} + \rho \cdot c_p \cdot \Delta T_f \cdot w_f \tag{13}$$

If the total heat flux is sensibly higher than 100 mW/m^2, the convective component is remarkable. The term of velocity is directly connected to the hydraulic conductivity k. In general the measured heat flow stands in the range between 20 and 60 mW/m^2. In the oceanic zones the average heat flow is of the order of 100 mW/m^2. In particular cases, the heat flow is anomalously high (e.g. in some places of the Tirrenian coasts 100-450 mW/m^2). The heat flow is certainly better representative of the real energy potential of the reservoir and of the level of natural recharge because according to the description contained in Eq. (13) a direct connection with the fluid flow motion and consequently of the permeability of the shallow reservoir can be considered. The availability of water at a temperature of about 200 °C, considering the typical values for the permeability of shallow reservoirs, in the range between 10^{-9} and 10^{-7} m/s, made reason of additional heat fluxes in the range between 10 to 1000 mW/m^2. Lower are the values of the heat flow rate in case of superheated steam. If a fluid in two phase conditions is present, like in Larderello the heat flow is reduced but it is subject to local remarkable increases in the zones where liquid is available.

New approaches to the geothermal resource assessment involve geophysical techniques enhancements, improvements and public access to the databases, numerical simulation of the fields. Combining the indications furnished by the energy stored in the reservoirs (strictly dependent on the volume rather than on the thermodynamic conditions) and by the heat flow (function of the thermal

gradient and of the mass flow rate) it is possible to conduct a better estimation of the energy stored in the reservoir and the power that can be extracted with and without reinjection strategies.

A further refinement is the development of a complete simulation model of the reservoir. One of the authors of the present paper has already tested the aspects of the numerical models and integration with experimental data, [18]. The idea is that physical and hydrogeological analysis of the exploration data can be synthesized in a conceptual model of the reservoir. In this way it is possible to develop a method to pursue the sustainability of a geothermal project defining the production scenario and to meet the right matching between the renewability and the economic profitability of the investment.

6. Conclusions

The geothermal potential assessment is a relatively "young" field of research but it appears to be extremely relevant in order to prevent problems in the future development of energy systems based on the use of geothermal energy resources. In the last years a lot of enhancements have been elaborated and tested by several authors, but at present the problem is already open. The authors have discussed the value of the methods and the application to two Italian geothermal reservoirs, Larderello and Mt. Amiata. Observing the recent history connected to the exploitation of geothermal fields it is possible to conclude that it is not easy to estimate the energy potential of a reservoir, but it can be observed that:

- The idea of a complete renewability is not good for commercial exploitation of geothermal reservoirs: the perspective of sustainability is surely more suitable for giving indications about the and their role in arriving at a decision on the plant capacity which a reservoir can support.
- Even if used for a long time the potential assessment of a geothermal reservoir cannot be related only to the thermal energy content of a reservoir: this gives a general overestimation of the potential while only a part of this energy can be used: the first order methods are not useful.
- The production potential of geothermal fields is often limited by the presence of the fluid rather than of the energy stored; for this reason, the lack of water rather than lack of thermal energy explain a lot of problems connected to the energy production systems.
- The analysis of heat flow measurements could be an important tool for characterizing the potential of shallow geothermal reservoirs, particularly in areas where magmatic heat input does not complicate interpretation of the data that should be correlated to the thermal gradient and to the presence of a fluid at an interesting temperature and of a mass flow rate.

References

[1]   Sanyal S K, 2005. Sustainability and renewability of geothermal power capacity, Proceedings of the World Geothermal Congress, Antalya, Turkey.

[2]   Rybach L, 2003. Geothermal energy sustainability and environment. *Geothermics* **32**, 463-470.

[3]   Stefansson V, 2002. Investment cost for geothermal power plants. *Geothermics* **31**, 263–272.

[4]   DiPippo R, 2008. Geothermal power plants: principles, applications, case studies and environmental impact, second ed., Butterworth-Heinemann, New York.

[5]   Franco A and Vaccaro M, 2014. A combined energetic and economic approach for the sustainable design of geothermal plants. *Energy Conversion and Management* **87**, 735-745.

[6]   Franco A and Vaccaro M, 2012. An integrated "Reservoir-Plant" strategy for a sustainable and efficient use of geothermal resources. *Energy* **37**, 299-310.

[7]   Vaccaro M, 2013. Multidisciplinary approach for the sustainable utilization of medium-low temperature geothermal resources, Ph.D. thesis, University of Pisa: http://etd.adm.unipi.it/.

[8]   Cataldi R and Muffler P, 1978. Methods for regional assessment of geothermal resources. *Geothermics* **7**, 53–89.

[9]   Hähnlein S, Bayer P, Ferguson G and Blum P, 2013. Sustainability and policy for the thermal use of shallow geothermal energy. *Energy Policy* **59**, 914-925.

[10] Axelsson G. 2010. Sustainable geothermal utilization case histories; definitions; research issues and modeling. *Geothermics* **39**, 283-291.

[11] Fox D B, Sutter D, Beckers K F, Lukawski M Z, Koch D L and Anderson B J, 2013. Sustainable heat farming: modelling extraction and recovery indiscretely fractured geothermal reservoirs. *Geothermics* **46**, 42–54.

[12] Kaya E, Zarrouk S J and O'Sullivan M J, 2011. Reinjection in geothermal fields: A review of worldwide experience. *Renewable and Sustainable Energy Reviews* **15**, 47–68.

[13] Khan M A, 2010. The Geysers Geothermal Field, an Injection Success Story, *Proceedings of the World Geothermal Congress*, Bali, Indonesia.

[14] Porras E A and Bjornsson G, 2010. The Momotombo reservoir performance upon 27 Years of Exploitation, *Proceedings of World Geothermal Congress*, Bali, Indonesia.

[15] Mendrinos D, Karytsas C and Georgilakisa P S, 2008. Assessment of geothermal resources for power generation. *Journal of Optoelectronics and Advanced Materials* **10**, 1262-1267.

[16] Williams C F, 2004. Development of revised techniques for assessing geothermal resources, *Proceedings of the Twenty-Ninth Workshop on Geothermal Reservoir Engineering Stanford University*, Stanford, California, SGP-TR-175.

[17] Van Campen B, 2014. Resource assessment, techniques and reporting, Internal Report, The Geothermal Institute University of Auckland Santiago de Chile, 26-29 May 2014.

[18] Franco A and Vaccaro M, 2014. Numerical simulation of geothermal reservoirs for sustainable design of energy plants: a review. *Renewable and Sustainable Energy Reviews* 30, 987-1002.

[19] Romagnoli P, Arias A, Barelli A, Cei M and Casini M, 2010. An updated numerical model of the Larderello–Travale geothermal system, Italy. *Geothermics* **39**, 292–313.

[20] Barelli A, Ceccarelli A, Dini I, Fiordelisi A, Giorgi N and Lovari F, 2010. A review of the Mt. Amiata geothermal system, Italy. *Proceedings of World Geothermal Congress*, Bali, Indonesia.

[21] Bertani R, 2010 Strategic vision for the development of geothermal energy towards 2015, *Proceedings of the Conference of Italian Geological Society*.

[22] Ogena M S and Freeston D H. 1988, Sensitivity analysis of the greater Tongonan field resource assessment, *Proceedings of the 10th New Zealand Geothermal Workshop*, 67-72.