World Geothermal Assessment

Valgardur Stefansson

Orkustofnun, Grensasvegur 9, 108 Reykjavik, Iceland

E-mail address: vs@os.is

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ABSTRACT

The terrestrial energy current flowing from the mantle to the surface of the Earth is more intense at plate boundaries than within the tectonic plates. At the surface of the Earth, the most obvious manifestations of this energy current are active volcanoes and high temperature geothermal fields. Geothermal assessments have only been carried out for a limited number of countries or regions, while the distribution of active volcanoes in the world is fairly well known. As the volcanoes and the high temperature geothermal fields are manifestations of the same energy current, the distribution of active volcanoes should reflect the geothermal potential of the world. An empirical relation between the number of active volcanoes and the technical potential of high temperature geothermal fields in 8 regions of the world has been established in the paper. This relation is consequently used to estimate the technical potential of high temperature geothermal fields in the world as a whole. The result is that the most likely value for the technical potential of geothermal resources suitable for electricity generation is 240 GW_e. Theoretical considerations based on the conditions in Iceland and USA reveal that the magnitude of hidden resources is expected to be 5-10 times larger than the estimate of identified resources. If this is the case for other parts of the world, the upper limit for electricity generation from geothermal resources is in the range 1 – 2 TW_e. Furthermore, the frequency distribution of the temperature of geothermal resources in Iceland and USA indicates that the magnitude of low-temperature geothermal resources in the world is about 140 EJ/year of heat. For comparison, the world energy consumption is now about 420 EJ/year. Comparing estimates of the generating capacity for individual geothermal fields obtained on one hand by simulation models and on the other hand by the volumetric method indicates that the volumetric method gives on the average 4 – 5 times higher values than simulation models. Taking the results of the simulation models as an estimate of the lower limit of the geothermal potential, the lower limit of the world geothermal potential for electricity generation is estimated to be about 50 GW_e and the corresponding value for direct use to be 1 TW_{th}.

1. INTRODUCTION

Geothermal energy is the heat that can be extracted from the interior of the earth. This subsurface heat appears in two forms, a) as continuous energy current from the mantle to surface (dynamic) and b) the heat stored in the crust (static). Both the dynamic and the static part of the terrestrial energy contribute to the geothermal energy used by mankind and this dual nature has sometimes caused confusion in the classification of geothermal energy resources. The terrestrial energy current corresponds well with the consept of renewable energy, whereas the long recovery time required to restore the stored heat in impermeable rocks causes it to be similar with finite energy resources.

The terrestrial energy current flowing from the mantle to the surface of the Earth is more intensive at plate boundaries than within the plates. At the surface of the Earth, the most obvious manifestations of this energy current are active volcanoes and high temperature geothermal fields. Geothermal assessments have only been carried out for a limited number of countries or regions, while the distribution of active volcanoes in the world is fairly well known. As the volcanoes and the high temperature geothermal fields are manifestations of the same energy current, it should be possible to use the distribution of active volcanoes to obtain an estimate of the geothermal potential of the world.

Theoretical considerations revail that a huge amount of geothermal energy is stored in the crust of the Earth. The question is how much of this stored energy and how much of the energy current is available for use by mankind. This paper describes an estimate of the technical potential of the geothermal resources of the world. The method used in the paper is similar to that presented in a previous paper (Stefansson, 1998), but the analysis and conclusions are completely revised in the present paper. An empirical relation between the number of active volcanoes and the technical potential of high temperature geothermal fields in 8 regions of the world is established in the paper. This relation is then used to estimate the technical potential of high temperature geothermal fields in the world as a whole. Furthermore, by using the temperature distribution of geothermal resources in Iceland and the USA, a lower limit for the potential of low temperature geothermal resources in the world is estimated.

2. TERRESTRIAL ENERGY CURRENT

The cooling of the Earh, or the vertical transport of heat through the surface of the Earth takes place through three crustal processes:

- Thermal conduction
- Advection of geothermal fluid
- Advection of magma in the crust which is sometime associated with volcanic eruptions

The heat loss is higher at plate boundaries than within the tectonic plates. This is due to the simple fact that all three energy transport processes are at work in the plate boundary regions and the thickness of the crust is less in these regions than within the crustal plates. Within the plates, thermal conduction is almost exclusively responsible for the energy transport from the interior towards the surface of the Earth.

The tectonic plates cover about 85% of the surface of the Earth, whereas about 15% of the surface area is classified as boundary regions (Gordon, 1995). Where plate boundaries are above sea level, the most obvious manifestations of this energy current are active volcanoes and high temperature geothermal fields.

Pollack et al. (1993) have estimated the global heat loss at 44 ± 1 TW. Their review is based on 24,774 heat flow measurements at 20,201 sites located both on the continents and on the ocean floor. Conductive heat flow measurements on the ocean floor were corrected for hydrothermal circulation in young oceanic crust. The average values obtained in the study of Pollack et al. (1993) were 101 mW/m^2 for the oceanic floor and 65 mW/m^2 for the continents. The weighted average for the Earth is 87 mW/m^2 giving a global heat loss of 44 TW as mentioned above.

Neither the heat loss through volcanic eruptions nor the hydrothermal circulation above sea level, at the continents, are considered by Pollack et al. (1993). Global heat loss is therefore somewhat higher than the 44 TW value presented by Pollack and coworkers.

The average flowrate of magma from volcanoes is estimated by Sigurdsson (2000) in the range 15-25 $*10^6$ km^3/million years. By assuming the following parameters: magma temperature = 1300 °C, specific heat of magma = 1 kJ/kg°C, and the latent heat of magma = 400 kJ/kg, we obtain an average heat flow of volcanic eruptions in the range 2.4 – 4.0 TW. In this paper we will adopt the Figure 3 TW as an estimate of the average heat loss of the Earth through volcanic eruptions.

The remaining component of the heat loss of the Earth, namely the heat loss through land based hydrothermal circulation is one of the most important figures for a theoretical estimate of the geothermal potential of the Earth. This component comprises the dynamic part of geothermal activity and it is also related to the renewability of geothermal energy. The size of this component of the terrestrial energy current might be similar to the heat loss through volcanic eruptions, since an important feature of the two components, volcanic eruptions and high temperature geothermal fields, is that they are correlated geographically. Active volcanoes and high temperature geothermal fields are concentrated at the plate boundaries of the Earth. Furthermore, these two phenomena are surface manifestations of the same terrestrial energy current. Therefore, it can be expected that there is a correlation between the distribution of active volcanoes and the intensity of high temperature geothermal activity.

3. ENERGY STORAGE IN THE CRUST

Electric Power Research Institute (EPRI, 1978) has estimated that the heat stored in the rocks down to 3 km depth below the continents is $12 * 10^{12}$ GWh$_{th}$ or $43 * 10^6$ EJ. For comparision, the world energy consumption is now about 420 EJ per year. This means that the heat stored in the uppermost 3 km of the continental crust is equivalent to the energy consumed by mankind for some 100,000 years at the present rate.

The continents comprise about 30% of the surface of the Earth and the heat flow through the continents is lower (65 mW/m^2) than at the ocean floor (101 mW/m^2). Taking this together, the terrestrial energy current through the continents can be estimated to be approximately 10 TW.

The time required for this energy current to fill up the storage of $43 * 10^6$ EJ is about 140,000 years.

These circumstances sometimes create some confusion about the nature of geothermal resources. The static component, the stored energy in the rocks, is very large, whereas the dynamic component, the terrestrial energy current, is relatively small, so at the continents, it takes a long time to restore the energy within the crust through thermal conduction. On the other hand, at the plate boundaries, convection process restores the energy much faster, so locally the energy is restored on a similar time-scale as the extraction of energy from the resource.

4. FINITE AND RENEWABLE ENERGY SOURCES

Finite resources like minerals and hydrocarbons are truely site specific within the crust, meaning that these resources are located at specific places and do not move around. On the other hand, renewable resources like wind, geothermal energy, and fish stocks in the ocean are moving around and these resources are only approximately site specific.

These circumstances influence the assessment methods applicable on the different types of energy resources. An advanced assessment method has been developed in mining where concepts like resource base, resource, and reserve are defined in detail (UN, 1997). This assessment method (McKelvey diagram) is, however, based on the assumption that the resources are site specific, meaning that the resources are fixed in the crust and do not move around. Strictly speaking, the assessment methods of site specific resources adapted in the mining industry can therefore not be applied to the non-site specific renewable resources like geothermal energy.

Nevertheless, the volumetric method (Muffler and Cataldi, 1978) is frequently used to estimate the size of geothermal resources. This method is based on an estimate of the heat stored in a given volume of rock and it´s merit is that it is relatively simple to estimate the heat stored. On the other hand, it is open for discussion whether the stored heat in the rocks is a suitable parameter for estimating the possible energy extraction from the resource. It is assumed in the volumetric assessment method that only a small fraction of the stored heat can actually be extracted and this ratio or fraction is poorly known. In many cases, the volumetric assessment method can give false confidence on the generation capacity of a given geothermal resource.

5. GEOTHERMAL ASSESSMENT

The volumetric assessment method is more or less the only simple assessment method for geothermal resources. This is the assessment method that has been used to estimate the geothermal potential of the United States (Muffler, 1978), Iceland (Palmason et al., 1985), and the Tuscany region of Italy (Muffler and Cataldi, 1978). Additional estimates have been published for countries like Japan, Indonesia, New Zealand, Phillipines, and Mexico but these estimates are based on more uncertain assumptions than used in the volumetric method.

A more accurate assessment method is the use of geothermal simulation models to estimate the generation capacity of a given geothermal field. A prerequisite for this assessment method is relatively detailed knowledge on the internal conditions in the geothermal reservoir under consideration. Therefore, this method can hardly be applied until several wells have been drilled into a given reservoir and simulation modelling is usually only applied after

exploitation has started. Simulation methods can be applied for a single geothermal resource but are not as suitable to estimate the geothermal potential of a whole country or a large region.

Comparison of the results obtained by the volumetric and the simulation assessment methods shows that the estimates by the volumetric method tend to be about 4-5 times larger than the estimates obtained by simulation methods (Steingrimsson et al., 1992). This result is based on a consideration of the following geothermal fields: Ahuachapan in El Salvador, Palinpinon and Tongonan in the Philippines, Olkaria in Kenya, Ohaki in New Zealand, Krafla, Svartsengi, and Nesjavellir in Iceland (Steingrimsson et al., 1992).

In this paper we use the estimates of the geothermal potential of whole countries or regions as basis for an extrapolation resulting in an estimate of the geothermal potential of the whole world.

6. PLATE BOUNDARIES

The heat loss of the Earth is more intensive at plate boundaries than elsewhere on the surface of the Earth. Almost all active volcanoes and high temperature geothermal fields are in the plate boundary regions of the Earth (Simkin and Siebert, 1994).

We will assume in this paper that from the heat loss point of view, there is not a significant difference between creative and destructive plate boundaries and we will simply assume that the number of active volcanoes in a given area is an estimate of the terrestrial energy current flowing through that particular area. This might be a simplification because Stefansson (1988a, 1988b, and 1988c) has observed that the mean distance between active volcanoes on islands in the Pacific seems to be larger than corresponding distances in Iceland. However, for the statistical nature of the method used here, it is not justified to make a distinction between different types of volcanoes.

Most of the geothermal fields suitable for generation of electricity are located at plate boundaries. An estimate of geothermal potential of plate boundaries would therefore approximately yield the total geothermal electricity generation potential of the Earth.

7. CORRELATION BETWEEN THE NUMBER OF VOLCANOES AND GEOTHERMAL ASSESSMENT RESULTS (ELECTRICITY)

In this chapter, the number of active volcanoes in a given country or region is compared with the estimate of the size of geothermal resources for electricity generation in the same country or region. The number of active volcanoes is taken from Simkin and Siebert (1994) and references to the different estimates of the geothermal potential for electricity generation is given in Table 1.

There is a clear positive correlation between these two parameters as shown in Figure 1. The correlation coefficient R^2 is 0.91 and the relative error in the relationship between the number of volcanoes and the geothermal potential is 13%.

During the last 10,000 years, 1511 volcanoes have been active in the world (Simkin and Siebert, 1995). Using that figure and the correlation given in Figure 1, the geothermal potential of the world is estimated to be about 240 GW_e. The statistical error in this extrapolation is $\pm$ 31 GW_e.

Table 1. Number of active volcanoes and estimated geothermal potential for electrical generation in selected countries or regions.

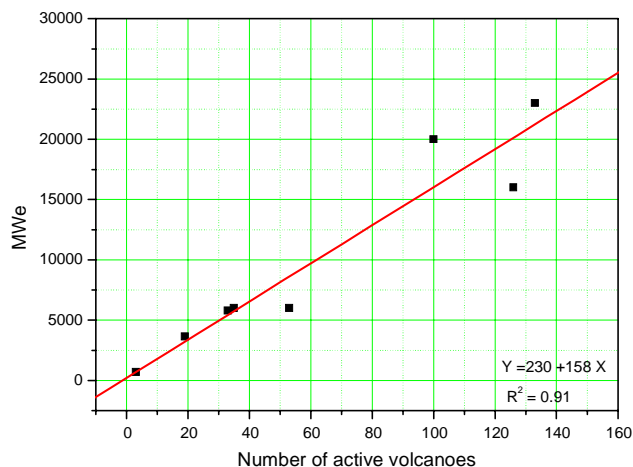|	Number of active volcanoes (Simkin and Siebert, 1994)	Identified resources MWe	References
Iceland	33	5,800	Palmason et al. (1985)
USA	133	23,000	Muffler (1978)
Indonesia	126	16,000	WEC (1998)
Philippines	53	6,000	Wright (1999)
Japan	100	20,000	Takashima (1980)
Mexico	35	6,000	Mulas de Pozo et al. (1985)
New Zealand	19	3,650	Lawless (2002)
Tuscany (Italy)	3	700	Muffler and Cataldi (1978)
Total	502	81,150	

Figure 1. Correlation between the number of active volcanoes and estimated geothermal potential in selected countries or regions.

Of the 1511 active volcanoes listed in Simkin and Siebert (1994), 189 volcanoes are not accessible because they are located on the sea floor or in the artic regions. Therefore, the number 1322 might be more appropriate as basis for the world geothermal potential. Applying the 1322 as the number of accessible active volcanoes in the world, the world potential would be 209 GW_e with a statistical error of $\pm$ 27 GW_e.

8. ESTIMATE OF LOW-TEMPERATURE GEOTHERMAL POTENTIAL

The geothermal potential estimated above refers to resources suitable for electricity generation, which in most cases mean the extraction of geothermal fluid in excess of 130°C. Furthermore, it is evident that this estimate is only valid for the plate boundaries of the Earth. Geothermal fluids with lower temperature than 130°C comprises the largest part of the world´s geothermal energy. In order to estimate the magnitude of the geothermal potential with lower temperatures than 130°C, we use the frequency distribution of geothermal resources as function of temperature.

In Figure 2, the frequency of geothermal resources as function of the temperature is plotted on a lin-log graph. On this scale, the observables follow a straigt line resonably well. This means that the frequency distribution follows an exponential function.

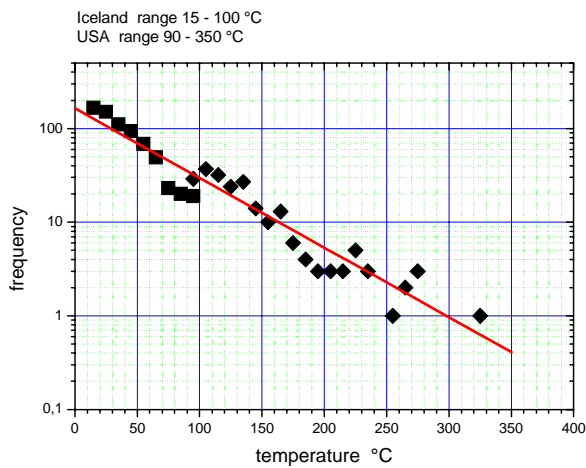

Iceland range 15 - 100 °C
USA range 90 - 350 °C

Figure 2. A lin-log plot of the frequency of geothermal resources within a given temperature class as function of temperature shows that the shape of the exponential frequency distribution of low temperature geothermal resources in Iceland and the geothermal resources in USA above 100°C is the same.

Furthermore, it is well known that the energy per mass unit of a geothermal resource increases with temperature. The amount of energy within a given temperature class is the number of geothermal resources within that temperature class multiplyed with the specific energy valid for the resource within that temperature class. By assuming that the volume of a geothermal resource is independant of temperature of the resource, it is possible to construct the shape of the curve describing the magnitude of geothermal energy as a function of the temperature of the resources. Such function is shown in Figure 3.
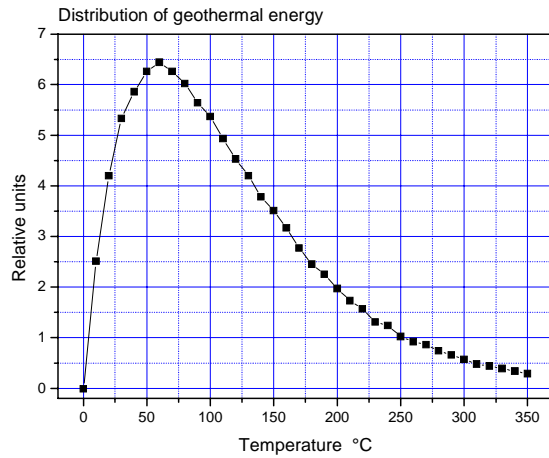

Distribution of geothermal energy

Figure 3. Calculated distribution of the magnitude of geothermal energy as function of temperature of the resource.

The function in Figure 3 shows that the low temperature resources, having temperatures of 130°C or lower comprises 68% of the total geothermal energy considered, whereas the remaining 32% of the total are resources with temperature higher than 130°C.

Having estimated the magnitude of the geothermal resources with temperatures higher than 130°C in section 7, Figure 3 indicate that this estimated energy amount is 32% of the total geothermal potential. In the estimate of the high temperature resources, the potential was referred to the amount of electricity that could be generated from these resources. In order to apply this ratio between low energy resources and the high enthalpy resources it is needed to translate the electrical potential to a thermal potential.

By assuming that 10% of the thermal energy can be converted to electical energy, the estimate of 209 GW$_e$ corresponds to an additional potential of about 4400 GW$_{th}$ from resources of lower temperature than 130°C. The capacity of 4400 GW$_{th}$ is equivalent to 139 EJ per year. For comparision, the total energy consumption in the world is at present about 420 EJ per year (IEA, 2002).

9. HIDDEN RESOURCES AND SIMULATION MODELS

Surface manifestations like hot springs and fumaroles are usually the most reliable indicators of the existence of geothermal resources at depth in the crust. In other cases, geothermal resources have been identified where no surface manifestations are present. Such resources are called "hidden" or unidentified resources. In general, it is assumed that the number of undiscovered hidden resources is larger than the number of identified resources.

In the geothermal assessment for the USA, it is estimated that the total geothermal potential is in the range 4-6 times the identified potential. Undiscovered resources are not mentioned explicitly in the assessment for Iceland, but their size is implicit in the results presented. The total potential of usable electical energy for the whole country is estimated 54 EJ, but the sum of usable electrical energy from 28 identified high temperature fields is estimated 5.6 EJ. This means that the total electrical geothermal potential is 9.6

times larger than the identified potential in the Icelandic geothermal assessment.

These considerations indicate that total potential of geothermal resources might be five to ten times larger than the potential of identified resources. Such estimates could be defined as the upper limit for the estimate of the geothermal potential.

In the study of Steingrimsson et al. (1992) it was found that the generation capacity calculated by simulation models was on the average 4-5 times lower than the results obtained by the volumetric method. Here, it is assumed that this result may be used globally to estimate a lower limit for the geothermal potential.

In the estimate of the geothermal potential of the world, it is assumed in this paper that the most likely value is the result obtained by the volumetric assessment method on the identified resources as described in table 1 above. By using the estimate that hidden resources are 5-10 times more frqent than identified resources, the maximum value for the potential is obtained. The minimum value of the potential is obtained by applying the results of Steingrimsson et al. (1992) that the estimates obtained by simulation methods tend to be 4-5 times lower than results obtained by the volumetric assessment method.

In summary the above results can be presented in the following way:

Table 2. Overview of estimated technical potential of geothermal resources in the world.

	Lower limit for the potential of geothermal resources	World geothermal potential for identified resources	Upper limit for total world geothermal potential
Resources suitable for electricity generation	0.05 TW$_e$	0.2 TW$_e$	1 – 2 TW$_e$
Resources only suitable for direct use	1 TW$_{th}$	4.4 TW$_{th}$	22 – 44 TW$_{th}$
Total potential	1.5 TW$_{th}$	6 TW$_{th}$	30 – 60 TW$_{th}$

10. DISCUSSION

It should be noted that the upper limit for the geothermal potential of the world is estimated to be of similar size as the total heat loss of the Earth. This might appear to be very high, but it is not necessarily unrealistic. The estimate is primarily based on the heat stored in the crust (volumetric assessment method) and the estimate is not directly constrained by the dynamic component of the geothermal resources.

The recovery factor applied in the volumetric assessment method is an assumption rather than an empirical fact. Assessments carried out by simulation models on single geothermal resources seem to give systematically lower values than the results of the volumetric method

(Steingrimsson et al., 1992). On the other hand, the simulation method is in most cases applied in a conservative way, meaning that only known conditions of the resource are used as parameters in the calculations.

The extrapolation from the known geothermal assessments listed in table 1 to the world geothermal potential is moderate. The sum of the identified resources in the eight countries listed in table 1 is 81 GW$_e$ whereas the world potential is estimated 210 GW$_e$. This means that 39 % of the world geothermal potential for electricity generationn is located in the the eight countries listed in table 1. Therefore, it is not likely that the extrapolation is causing large uncertainties in the world estimate.

The uncertainities in the recovery factor in the volumetric assessment method and the question of the size of unidentified resources are the parameters causing the wide range of the world potential presented in this paper. The upper limit of the geothermal potential is estimated to be 25 times larger than the lower limit. This range in the estimate describes the state of knowledge of the size of the geothermal resources in the world.

Utilization of geothermal energy is based both on the thermal energy stored in the crust and the energy current causing the cooling of the Earth. In some cases, the utilization mode might be primarily dependent on the stored heat in the crust, but in other locations, the dynamic component of geothermal energy is governing the utilization mode.

At present, the installed electrical capacity of geothermal energy in the world is about 7 GW$_e$. This means that about 3.5 % of the world potential for electricity generation has been taken into use so far. For direct use of geothermal energy, the installed capacity in the world is about 10 GW so in this case the fraction of energy used is only 0.2 %. The average value for all geothermal resources is 1.3%.

11. CONCLUSIONS

An estimate of the world geothermal potential is presented in this paper. The basis for this estimate is geothermal assessment carried out in eight selected countries and the distribution of active volcanoes in the world. There is a good correlation between the number of volcanoes and the estimated geothermal potential for electricity generation in the eight countries considered. It is found that the most likely value for this technical potential is 6 TW.

The frequency distribution of the temperature of geothermal resources in Iceland and the USA are used to estimate the ratio between high temperature geothermal resources (suitable for electricity generation) and low temperature resources (suitable for direct use). It is found that 68 % of the geothermal energy has temperatures lower than 130°C and the remaining 32 % of the energy is found in resources with temperatures higher than 130°C.

Uncertainities in the recovery factor used in the volumetric assessment method define the lower limit of the world geothermal assessment to 1.5 TW and the upper limit is estimated to be in the range 30-60 TW depending on the size of unidentified geothermal resources.

comments and suggestions have improved the paper considerably.

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