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ESTIMATE OF THE WORLD GEOTHERMAL POTENTIAL

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ABSTRACT

The geothermal potential of the world is estimated by applying an empirical relation between the number of active volcanoes and the estimated high-temperature geothermal potential in 8 regions of the world. Available data from Iceland and the USA indicate that the size of undiscovered resources is 5-10 times larger than the size of identified resources. The results obtained are that 11,200 TWh/a electricity can be generated with conventional technique and that about 22,400 TWh/a electricity should be available from geothermal resources if binary turbines are also considered. The lower limit of the low-temperature geothermal resources is estimated from the size of the high-temperature resources by applying an empirical relation between the frequency distribution as function of temperature of the geothermal resources in the USA. The result obtained is that the low-temperature geothermal potential is larger than 1400 EJ/a.

1. INTRODUCTION

Finite energy resources provide 78% of the world energy consumption, whereas the share of renewable energy sources is only 22%. The role of renewables has been discussed for a long time. Already in 1961, the United Nations organised a Conference on New Sources of Energy (Rome, 21-31 August 1961). The subject has received additional impetus in the last decade as a consequence of the Rio and Kyoto conferences. Both national and international institutions have made declarations on energy policies where the intention has been that renewable energy sources replace hydrocarbons and other finite energy sources. Sustainable energy exploitation is considered an attractive objective of long time energy planning.

An important question in this context is how much renewable energy is available in the world for the desired transfer from finite to renewable energy sources. The potential of some of the renewable energy sources (hydro) has been estimated with reasonable accuracy whereas the size of other, like geothermal energy, is poorly known. Several estimates have been published on the resource base of geothermal energy (EPRI, 1978; Aldrich et al., 1978; Rowley, 1982) but the limitations of these estimates are that only a small fraction of the resource base can be used and it is poorly known how large this fraction might be.

Usually, world-wide potential is determined by adding up the estimates for individual countries or regions. In the case of geothermal energy, this is a difficult approach because the knowledge on geothermal energy resources is quite low in most countries. A detailed geothermal assessment exists only for USA, Iceland, and part of Italy (Tuscany).

A different approach is applied in this paper. An empirical relation is established between the distribution of active volcanoes and the potential of geothermal energy. This empirical relation is used to estimate the total potential of high-temperature resources in the world. Furthermore, the frequency distribution between high-temperature and low-temperature resources in Iceland and the USA is used to estimate the total size of both high- and low-temperature resources in the world. The results obtained are that the high-temperature resources could generate 11,200 ± 1,300 TWh/a of electricity and that at least 1,400 EJ/a are available from the low-temperature resources for heating purposes.

2. STATIC AND DYNAMIC CONSIDERATIONS

The nature of an energy resource determines the conceptual model used for the estimate of how much energy can be extracted from a given resource. For geothermal energy, both the static and dynamic components influence the potential development of the resource. Geothermal energy consists of three components:

- The energy current through the crust in the form of material transport (magma, water, steam, gases).
- The flow of heat by conduction
- The energy stored in the rocks and fluids within the crust.

Assessment of geothermal resources are usually only based on the static component of the resource, viz. the energy stored in the rocks and fluids in the crust. Where the temperature distribution is known with some accuracy within the crust, it is relatively simple to calculate the energy stored in the crust for an given area or region. This is the basis for the so called "volumetric method" (Muffler and Cataldi, 1978). The assessment of the geothermal resources is obtained by assuming that certain fraction of the energy stored can be recovered to the surface (recovery factor). This method is applied in the detailed assessments of the USA (Muffler, 1978), Iceland (Pálmason et al., 1985), and Tuscany (Cataldi et al., 1977). The influence of the energy current by material transport on the geothermal assessment has not been considered in these estimates. Bödvarsson (1982) estimated the size of the energy current through the Icelandic crust and Stefánsson and Elíasson (1998) have pointed out the importance of the energy current for the sustainable exploitation of geothermal energy.

3. IDENTIFIED AND UNDISCOVERED RESOURCES

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

The volumetric method considers geothermal energy as a static property of the crust as in mining. In a similar way, the resources are divided into identified and undiscovered resources. This issue is worked out in the USA assessment and the results obtained are summarized in Table 1.

Table 1: USA accessible resource base for electricity generation (T > 150°C)
(Source: Muffler, 1978)

	(EJ)	**Electricity**	
		(MWe - 30 years)	**(TWh/a)**
Identified resources	950	23,000	200
Undiscovered resources	2,800-4,900	72,000-127,000	630-1,100
Total	3,750-5,850	95,000-150,000	830-1,310

Undiscovered resources are not mentioned explicitly in the Icelandic assessment (Pálmason et al., 1985), but their size is implicitly given in the results presented. The main results of the Icelandic assessment are given in Table 2. This table shows that the total energy available above 130°C is ten times larger than the energy available in the 28 identified high-temperature fields of the country. This means that the ratio between the total and identified resources in Iceland is about ten. The situations in Iceland and the USA are summarised in Table 3. In the following calculations, it is assumed that the total sizes of the geothermal resources are 6.4 times the identified resources.

Table 2: Geothermal potential of Iceland
(Source Pálmason et al, 1985)

Type of energy	**(EJ)**	**(TWh)**	**(TWh/a) for 30 years**
Technically exploitable thermal energy at wellhead (T>5°C)	3,500	972,000	32,400
Usable thermal energy from plants (T>40 °C)	1,700	486,000	16,200
Usable thermal energy suitable for electricity generation (T>130°C)	540	150,000	5,000
Usable electrical energy from the whole country (T>130 °C)	54	15,000	500
Usable electrical energy from the 28 identified high-temperature fields (T>130°C)	5.6	1,550	51

Table 3: Potential for electricity generation
(in TWh/a for 30 years)

	USA	**Iceland**
Identified recoverable resources	200	50
Undiscovered recoverable resources	630-1,110	450
Total	830-1,310	500
The ratio: total/identified	3.6 – 7.7	10

4. HIGH-TEMPERATURE RESOURCES ASSOCIATED WITH VOLCANIC ACTIVITY

The association between geothermal resources and volcanic activity has been recognised for centuries (Bunsen 1847a, b; Beamont 1847). This association has most frequently been interpreted in geological terms, viz. that the high-temperature geothermal resources are found in the volcanic areas of the world (Muffler, 1976). On the other hand, Bödvarson (1982) has considered the energy aspects of the association and he pointed out that the advection current of magma in the crust of Iceland is the source of both volcanism and the advection current by water in the high temperature geothermal fields in that country.

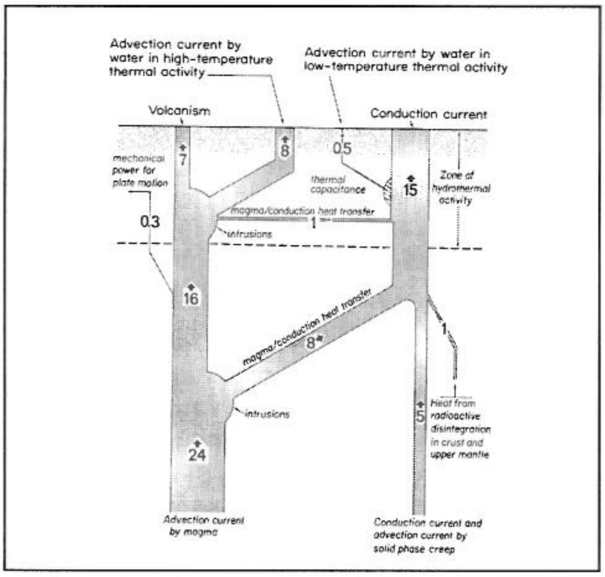

Figure 1: The terrestrial energy current (GW) in Iceland (from Bödvarsson, 1982)

Figure 1 is taken from the paper of Bödvarsson (1982) and it shows the terrestrial current in GW through the crust of Iceland. The conceptual model of Bödvarsson (Fig.1) shows clearly the direct association of the energy realised through volcanic eruptions and the energy current observed at surface as high-temperature fumaroles and hot springs. These considerations indicate that the distribution of volcanoes might be applied to estimate the geothermal potential of a given area or a region.

One of the first estimates of the geothermal potential of East Africa was in fact carried out on the basis of the distribution of volcanic activity in the region (McNitt, 1983) and Stefánsson (1988a, b, c) applied similar methods to estimate the geothermal potential of islands in the Pacific.

The energy released through volcanic eruptions is difficult to estimate, but the numbers of active volcanoes in the world is relatively well defined (Simkin and Siebert, 1994). Figure 2 shows the distribution of active volcanoes in the world. If an empirical relation can be established between the geothermal potential in a given region and the number of active volcanoes in the same region, the distribution of volcanoes could be used to estimate the geothermal potential of regions where the knowledge on geothermal resources is limited.

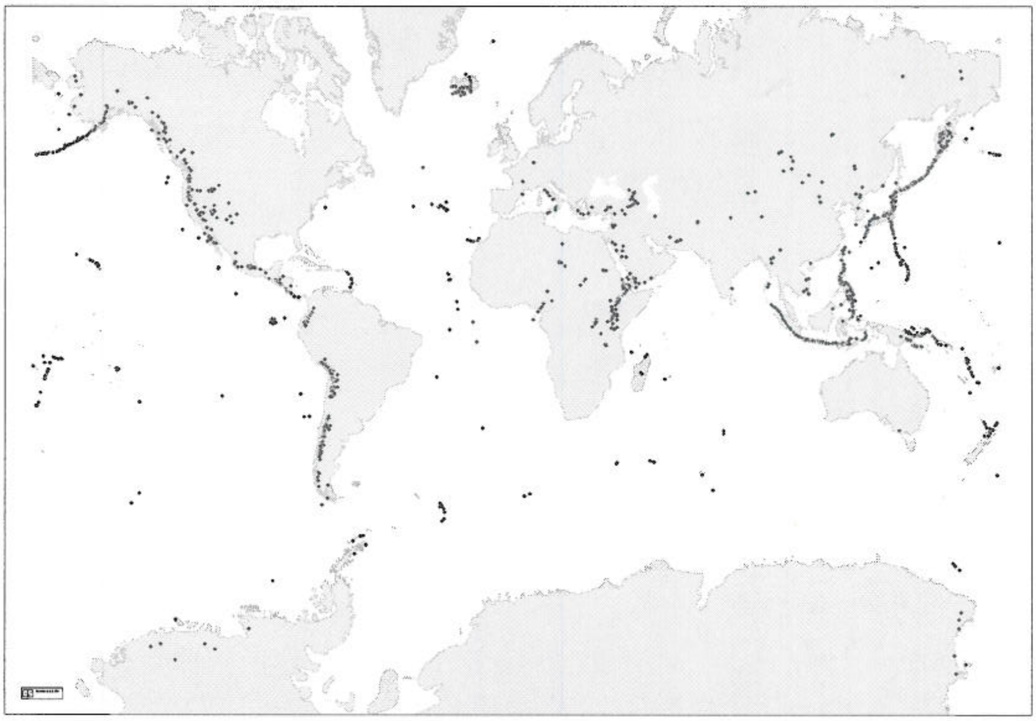

Figure 2: Distribution of volcanoes in the world

Estimates of the potential of high-temperature geothermal resources are available for 8 regions of the world. These are Iceland, USA, Indonesia, Philippines, Japan, Mexico, New Zealand, and part of Italy (Toscana). The estimated amount of electrical energy available in these 8 regions is given in Table 4. In three cases (Iceland, USA, and Tuscany) the total (identified and undiscovered) resources have been estimated. For the other 5 regions (Indonesia, Philippines, Japan, Mexico, and New Zealand), the capacity of identified resources have been estimated.

In Table 4, the total resources are assumed to be 6.4 times larger than the identified resources in the cases where the estimate of total resources are not available. In the conversion between capacity (MW) and energy (TWh/a), the reference time 30 years is chosen.

Table 4: Estimates of geothermal resources;

	Identified resources		**Total resources**	
	(MWe)	**(TWh/a)**	**(MWe)**	**(TWh/a)**
Iceland	5,800	51*	57,000	500*
USA	23,000	200*	125,000	1,100*
Indonesia	19,000*	166	120,000	1,060
Philippines	8,000*	70	50,000	450
Japan	20,000*	175	128,000	1,100
Mexico	6,000*	52	38,000	300
New Zealand	2,500*	22	26,000	140
Tuscany (Italy)			5,600*	49

* = Basic information, other figures are calculated; reference time in calc. is 30 years; Total resources are assumed 6.4 times larger than identified resources, where the estimate of total resources is not available.

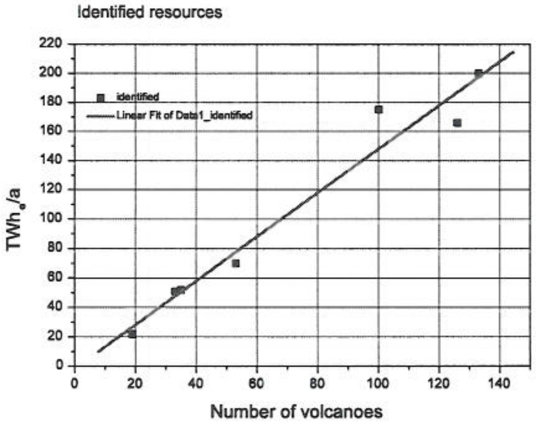

Figure 3: Relation between the number of active volcanoes and estimated geothermal potential of identified geothermal resources

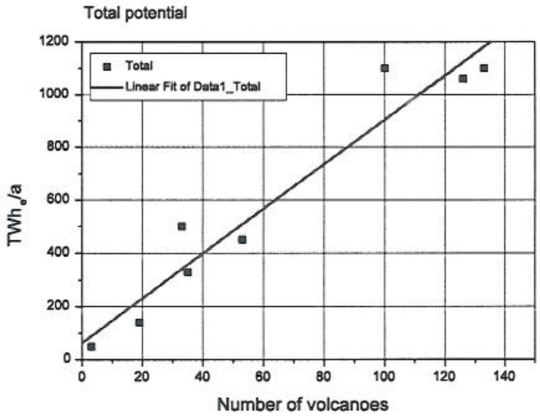

Figure 4: Relation between the number of active volcanoes and the estimated total potential of geothermal resources

Figures 3 and 4 show the relation between the numbers of volcanoes in each of the 8 regions and the identified and total geothermal potential of the regions listed in Table 4. There is a remarkably high correlation between these parameters. The correlation coefficient is 0.98 for the identified resources and

0.967 for the total resources. By applying the statistical uncertainties in the correlation in Figures 3 and 4, we obtain:

$$\text{TWh/a (identified)} = (-2 \pm 11) + (1.5 \pm 0.1) \times n$$

and

$$\text{TWh/a (total)} = (63 \pm 71) + (8.4 \pm 0.9) \times n$$

where n is the number of active volcanoes in the given region. The number of active volcanoes is taken from Simkin and Siebert (1994).

We like to stress the statistical nature of this approach and that the method applied will not give a meaningful result for a small area and/or a few volcanoes involved. If the equations above are applied on a single volcano ($n = 1$) the obtained range for identified resources is -11.6 to 10.6 TWh/a and for the total resources, the range would be -0.5 to 143.3 TWh/a. In both cases the result of zero can not be excluded so this exercise will not give a meaningful information for a region with a single volcano.

On the other hand, we see that for a region with 100 active volcanoes the total potential of geothermal resources in that area would be 903 ± 161 TWh/a and the identified resources in the range 148 ± 21 TWh/a. In this case ($n = 100$) the statistical uncertainty is 18% for the total resources and 14 % for the identified resources.

During the last 10,000 years, 1511 volcanoes have been active in the world (Simkin and Siebert, 1994). Of these, 189 volcanoes are not accessible (sea floor, antartics). By using the equations above, the 1322 accessible volcanoes would define the world potential of geothermal potential as:

Total resources: 11,000 ± 1,300 TWh/a

Identified resources: 2,000 ± 140 TWh/a

These figures represent the technical potential of geothermal resources in the world. It is not known how large part of the technical estimate should be considered economical. For comparison, the hydropower potential has been estimated (Björnsson et al., 1998):

Technical potential:	14,300 Twh/a;
Economic potential:	13,100 Twh/a;
Practicable potential:	10,480 TWh/a

If a similar ratio is valid for geothermal energy as for hydro, it might be expected that the level of economical geothermal resources is about 10,000 TWh/a. It is interesting to note that the size of hydro and geothermal resources for electricity generation are quite similar.

4. RELATION BETWEEN HIGH-TEMPERATURE AND LOW-TEMPERATURE RESOURCES

The estimated geothermal potential presented in the previous section covers only the high-temperature resources suitable for electricity generation. Low-temperature resources are on the other hand found almost everywhere in the world, both inside and outside of volcanic areas (regions with active volcanoes). Countries like Hungary, Poland, Romania, and Ukraine have considerable potential of low-temperature resources, but no active volcanoes are located within these countries according to the reference used to define the distribution of active volcanoes in the world (Simkin and Siebert 1994). The question then arises how can we estimate the size of low-temperature resources in the world?

The method applied here is to use the frequency distribution of high- and low-temperature resources in the USA and Iceland to determine the lower limit for the low-temperature resources in the world. The active volcanoes of both Iceland and USA are restricted to the volcanic zones of these countries, whereas the geothermal resources have been mapped both inside and outside of the volcanic zones. Resources with lower temperatures are more frequent than resources with higher temperatures and it seems that the frequency distribution as function of temperature follows a simple exponential function. Figures 5 and 6 shows the frequency distribution of geothermal resources in the USA and Iceland respectively as function of temperature.

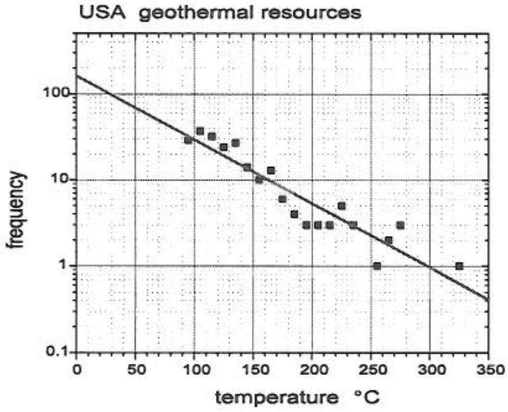

Figure 5: Frequency of geothermal resources in the USA as function of resource temperatures; (data from Muffler, 1978)

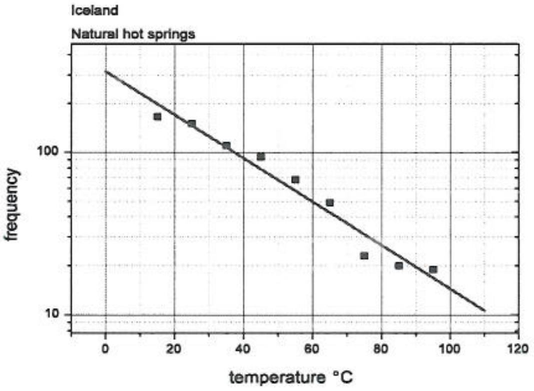

Figure 6: Frequency of natural hot springs in Iceland (t<100°C) as a function of surface temperature (unpubl. data from Orkustofnun)

In the case of the USA, the temperatures in Figure 5 represent the temperature of the resources (geochemical geothermometers), whereas the temperatures in Figure 6 are simply the surface temperatures of the hot springs in Iceland where the surface temperatures are lower than 100°C. In both cases, a linear relationship is obtained on a lin-log plot. This empirical relation is used in the following to determine the lower limit of the low-temperature resources in the world. For this estimate we need the following assumptions:

- The frequency of geothermal resources as function of temperature is an exponential function.
- The energy of a given resource is a linear function of the temperature of the resource.
- The geothermal reservoir volume is independent of the temperature of the resource.

With these simple assumptions and the frequency distribution defined in Figure 5 we can construct the relative energy distribution of geothermal resources as function of temperature as is shown in Figure 7.

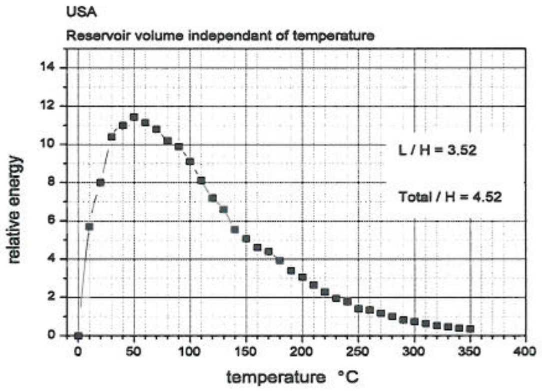

Figure 7: Distribution of the energy of geothermal resources in the USA

By assuming that the same distribution function is valid for the whole world as for the American continent, we can estimate the energy of low-temperature resources from Figure 7. In the USA assessment, the temperature 150°C is used as the limit between high- and low-temperature resources. Figure 7 shows that the total thermal energy above 150°C is about 25% of the total energy under the curve, or that the ratio between the energy below 150°C to the energy above 150°C is 3.52.

Figure 7 shows also that the thermal energy above 100°C is about two times larger than the energy above 150°C (ratio 2.1). The use of binary turbines for electricity generation allows for the use of geothermal resources down to about 100°C, whereas conventional turbines are usually not considered for lower temperatures than 150°C. The geothermal potential (for electricity generation) is about two times larger when the 100°C limit is used instead of 150°C.

5. WORLD-WIDE POTENTIAL OF GEOTHERMAL RESOURCES

The exercise presented in Figure 7 is based on the frequency distribution as function of temperature in the Western part of the) USA. This part of the world might not be representative for the whole world. In general, it might be expected that low-temperature resources are suppressed in relation with high-temperature resources in this region. If this is the case, the energy of low-temperature resources will be higher than the ratio 3.52 calculated from the data in Figure 7. Therefore, we state that the potential of low-temperature resources estimated from Figure 7 is the lower limit for these resources. From Figure 7 we obtain:

$$\text{Energy } (t < 150°\text{C}) / \text{Energy } (t > 150°\text{C}) > 3.5$$

Previously we obtained that for the world:

$$\text{Geothermal potential } (t > 150°\text{C}) = 11{,}200 \text{ TWh/a electricity generation;}$$

or

$$\text{Geothermal potential } (t > 150°\text{C}) = 112{,}000 \text{ TWh/a heat } (403 \text{ EJ/a})$$

By using the ratio defined in Figure 7 we obtain for the world:

$$\text{Geothermal potential } (t < 150°\text{C}) > 392{,}000 \text{ TWh/a heat } (1410 \text{ EJ/a})$$

For comparison it should be noted that the world energy consumption is about 370 EJ/a.

As has been mentioned before, the method applied in this paper should not be used for small regions or countries of the world. It should however be possible to divide the world potential on the main regions of the world. Table 5 shows this distribution of the geothermal potential.

6. CONCLUSIONS

The potential of geothermal resources in the world has been estimated by applying an empirical relation between the number of active volcanoes and the estimated high-temperature geothermal potential in 8 regions. The results obtained are that 11,200 TWh/a electricity can be generated with conventional technique and that about 22,400 TWh/a electricity should be available if binary turbines are also considered. The statistical correlation between the number of volcanoes and the estimated potential puts only a 12% uncertainty on these results.

Table 5: Geothermal potential

	High-temperature resources suitable for electricity generation		**Low-temperature resources suitable for direct use**
	Conventional technology (TWh/a - electricity)	**Conventional and binary technology (TWh/a - electricity)**	**(EJ/a - heat) (lower limit)**
Europe	1830	3700	> 370
Asia	2970	5900	> 320
Africa	1220	2400	> 240
North America	1330	2700	> 120
Latin America	2800	5600	> 240
Oceania	1050	2100	> 110
Total world	**11 200**	**22 400**	**> 1400**

The lower limit of the low-temperature geothermal resources in the world is estimated from the size of the high-temperature resources by applying an empirical relation between the frequency distribution as function of temperature of the geothermal resources in the USA. By assuming that the frequency distribution is exponential, that the resource energy is a linear function of the resource temperature, and that the reservoir volume is independent of the temperature, the relative energy distribution as function of temperature can be constructed. This energy distribution function is used to determine the ratio between low- and high-temperature resources. The result obtained is that the low-temperature geothermal potential is larger than 1400 EJ/a.

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