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Estimates of the Geothermal Resources of Iceland

GUNNAR BODVARSSON

School of Oceanography, Oregon State University, Corvallis, Oregon 97331, USA

ABSTRACT

More than two decades ago, attempts were made to estimate the total amount of terrestrial heat which could economically be extracted from geothermal resources in Iceland. Results published by Bodvarsson in 1956 indicated that in terms of electrical power, the total recoverable potential of the high-temperature (above 150°C) resources amounted to a steady power of 300 MW and a depletable reservoir of 20 000 MW years. These results were conservative estimates based on very incomplete field data. In particular, little information was available on the deeper parts of the geothermal systems. No figures were given for the low-temperature resources.

A considerable amount of geophysical exploration and deep drilling has been carried out in Iceland during the past 20 years. Much more detailed data on the characteristics of the geothermal systems and their geological setting are now available. A more complete theory of heat extraction from geothermal resources has been developed and this information is now available to revise the earlier estimates. Present estimates for the high-temperature systems are almost an order of magnitude higher than the earlier data. Moreover, estimates for the available heat resources of the low-temperature geothermal systems indicate that effective low-temperature heat in the amount of 4×10^9 petroleum-equivalent tons could be extracted from them.

INTRODUCTION

Geothermal energy is already of considerable economic importance in Iceland. About half of the total population of 220 000 now lives in houses heated by geothermal energy. Moreover, there is a considerable application of geothermal energy for agricultural and recreational purposes. Although the great hydroelectrical resources of Iceland will remain the principal sources of electrical energy for some time to come, there is now an increasing interest in the use of geothermal energy for the generation of electrical power. One small geothermal power plant of 3 MW was built in 1968 and a new plant of 60 MW is now under construction.

For the planning of future energy policies, it is of great importance to have available reasonably reliable estimates of the total energy resources of the country. According to the National Energy Authority of Iceland the total effective hydroelectrical resources of Iceland amount to 35 TWhr/yr (1 TWhr = 10^9 kWhr). The available peak power is on the order of 7 GW (1 GW = 10^6 kW). Estimates of comparable quality for the total geothermal energy resources of Iceland have not been available.

Unfortunately, no satisfactory or reliable methods are available for the estimating of geothermal resources. In most cases the difficulties are compounded by the lack of geological and physical field data. At this juncture, it is therefore impossible to produce anything but order-of-magnitude estimates of the geothermal energy resources.

In a first attempt by Bodvarsson (1956), the total effective geothermal resources of Iceland were estimated at 300 MW steady power which could be sustained for centuries plus a depletable reservoir of almost 20 000 MW years. The geothermal resources were thus estimated to be one order of magnitude smaller than the hydroelectrical resources. These results were obtained on the basis of very incomplete field data, in particular on the physical conditions in the deeper parts of the high temperature systems. Moreover, the results were deliberately conservative.

A considerable amount of research and drilling has been carried out in the geothermal areas of Iceland during the past two decades. Perhaps the single most important scientific contribution has been the complete seismic refraction mapping of the substructure of Iceland by Palmason (1971). Drilling for geothermal energy has been very successful and has provided a wealth of data of practical importance. Drilling to depths of 2 to 3 km is now routine and opens up great heat resources. There is, therefore, a strong reason to revise previous estimates of the total resources of the country.

REVIEW OF RESOURCE CHARACTERISTICS

In terms of thermal terrestrial processes, Iceland is one of the most active regions in the world. Located at the crest of the mid-Atlantic ridge, it is a center of sea-floor spreading and other manifestations of global tectonics. The 100 000 square kilometer area of Iceland contains a greater number of volcanoes and geothermal areas than perhaps any comparable area in the world. To illustrate the magnitude of the thermal processes, Bodvarsson (1954) has estimated that during the 10 000 year post-glacial period the space-time average of the total amount of terrestrial heat dissipated at the surface of Iceland amounts to not less than 0.25 W/m^2 (6 HFU in cgs units). This may be a low estimate. About 50 percent of the heat flowing to the surface is transported by conduction, 30 percent by magma, and 20 percent by thermal waters.

There are two main types of geothermal systems in Iceland (Bodvarsson, 1961). The first consists of low-temperature systems of nonvolcanic origin with base temperatures below

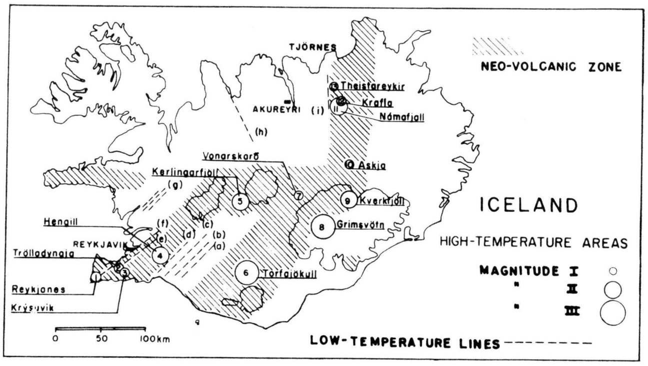

Figure 1. Map of Iceland showing areas of volcanism and geothermal activity. Magnitude scale for high temperature areas is based on the rate of heat dissipation at the surface, (I) = 20 to 100 MW (heat), (II) = 100 to 500 MW (heat) and (III) = 500 to 2,500 MW (heat).

150°C. Most of these thermal areas are located on the lowlands in the south, west, and north of Iceland. The second type of high-temperature systems are those with base temperatures of up to more than 300°C which are of direct or marginal volcanic association and are located in the neo-volcanic zone, as shown in Figure 1. There are surface manifestations of high-temperature systems in 13 locations, but the actual number of systems may be greater. About 90 percent of the heat dissipated by geothermal activity in Iceland is delivered by the high-temperature systems. Their integrated surface dissipation of heat has been estimated on the order of 400 MW (heat).

According to Palmason (1971), the flood-basalt series of Iceland has a thickness ranging from 2 to 9 km and is underlain by a formation of considerably higher density. There is strong evidence (Bodvarsson, 1961) that most of the geothermal systems are embedded in the flood-basalts and that the unusual hydrological properties of this formation combined with a high geothermal gradient and active volcanism provide the physical basis for the very active geothermal manifestation in Iceland. The flood-basalts have a high conductivity to fluids along the contacts of individual lavabeds, and the vertical conductivity is provided mainly by basaltic dikes and to a lesser extent by faults. The circulating water is heated on its passage through the open horizontal or quasi-horizontal lavabed contacts. The open contacts are found at various depths in the formation and there is evidence that the water can flow over horizontal distances on the order of 50 to 100 km.

METHODS OF RESOURCE ASSESSMENT

Suitable methods for obtaining order-of-magnitude estimates of the economically recoverable power and total energy of geothermal resources embedded in flood-basalts have been discussed previously. The theory of the heating of water flowing through narrow horizontal open spaces was presented first (Bodvarsson, 1962) and a more detailed version followed (Bodvarsson, 1974). The theory has been applied to the Hengill high-temperature thermal area (Fig. 1) in Iceland (Bodvarsson, 1970) with results which appear quite reasonable.

Based on the average number of open lavabed contacts as observed in deep boreholes, the principal result of these investigations is that one can expect, depending on conditions, an obtainable energy recovery factor on the order of 0.1 to 0.2. In other words, it should be possible to recover 10 to 20 percent of the total sensible heat stored in the rock. In principle, this result should apply to both low-temperature and high-temperature areas. The lower figure of 0.1 for the recovery factor should be used in more prudent estimates.

As an example, consider a high-temperature thermal area with a base temperature of 250°C. Using a temperature differential of 150°C, the sensible heat content per unit resource volume is of the order of 400 $\mathrm{MJ/m^3}$ (1 MJ = 10^6 joules). Applying a recovery factor of 0.1 and an overall power plant thermal efficiency of 10 percent, we find that the recoverable electrical energy should be about 4 $\mathrm{MJ/m^3}$ or about 1 $\mathrm{kWhr/m^3}$. Since a base temperature of the order of 250°C is quite common, this simple result is of sufficient accuracy to be used as an average estimate for all high-temperature resources in Iceland.

Low-temperature resources are not suitable for power generation and are used almost exclusively for heating and recreational purposes. Their energy, therefore, is preferably measured in terms of direct utilizable heat rather than electrical energy. It is quite likely that the average base temperature of the low-temperature resources of Iceland is about 100°C. Using a temperature differential of 40°C, the total sensible heat per resource volume is about 100 $\mathrm{MJ/m^3}$. Using a recovery factor of 0.1 and a heating plant thermal efficiency of 50 percent we find that the recoverable effective energy should be about 5 $\mathrm{MJ/m^3}$ of resource volume. On the other hand, the overall thermal efficiency of space heating equipment burning fossil fuel is 50 to 70 percent. Using the figure of 60 percent and petroleum as the basic fuel, we find that the effective energy is about 25 MJ/kg. A comparison of the two figures obtained gives an estimate of the recoverable effective energy from the low-temperature resources equivalent to 0.2 kg petroleum/$\mathrm{m^3}$ resource volume; that is, 2×10^5 PET/$\mathrm{km^3}$ (PET = petroleum equivalent tons).

The above figures provide only estimates of the total recoverable effective energy per unit resource volume. No clues are given with regard to the possible rate of recovery; that is, the electrical or heat power which can be maintained. This figure depends on the rate of flow of water through the hot rock which can be maintained by natural or artificial means. In other words, the power depends not only on the resource energy but also on the availability of water and the fluid conductivity of the resource formations. The maximum power which can be maintained by geothermal resources is therefore a quantity which in individual cases can be estimated only on the basis of a considerable amount of field data.

In the specific case of Iceland, it is to be noted that precipitation is fairly high, particularly in the areas where the main recharge of the geothermal resources takes place. Moreover, the extensive drilling for geothermal energy which has been carried out during the past four decades has indicated that the fluid conductivity of the flood-basalts is quite adequate and, from the practical point of view, there appear no severe limitations to the available power. Modern means of forced geothermal energy recovery by pumping and hydraulic fracturing have also proven to be of considerable importance (Zoega, 1974) and are obviously important means of enhancing the natural power of the geothermal resources.

RESULTS ON THE ENERGY RESOURCES

The results of the previous section provide means to arrive at an elementary order-of-magnitude estimate of the available geothermal energy resources of Iceland on the basis of the present state-of-art.

Having obtained estimates of the recoverable effective energy per resource volume, the final step consists in estimating the available volumes of the high-temperature and low-temperature resources. These estimates have to be based on the extent of surface manifestations, results of drilling and the seismic refraction data of Palmason (1971).

Since high-temperature geothermal systems are zones of vigorous convection, the reservoir volume within the flood-basalts is probably of a large vertical extension. An average reservoir thickness of 2 km and base temperature of 250°C can therefore be assumed as first order estimates. Using the data given in the previous section, these assumptions lead to a total recoverable effective energy resource of 2×10^9 kWhr/km^2 of horizontal area. Assuming an operation during 5 000 hr/yr and a depletion time of 50 years, the resulting recoverable effective power is 8 MW/km^2 of active horizontal area.

The high-temperature systems which are favorably located for power generation fall into five groups (Fig. 1). Using the figures in Table 1, this results in a power of 3.2 GW (1 GW = 10^6/kW) for a period of 50 years. The present estimate is considerably higher than the previous one by Bodvarsson (1956) although it must be noted that the steady power figure of about 300 MW which postulated in 1956 has been omitted. There does not appear to be a strong basis for maintaining this figure.

Table 1. High-temperature systems favorably located for power generation.

Group	Estimated active horizontal area
Reykjanes (4 areas)	50 km^2
Hengill	50
Torfajokull	100
Kerlingarfjoll	50
Northeast (3 areas)	150
Total	400 km^2

The principal low-temperature resources are located in the southwestern part of the country in an area which extends up to about 100 km north and east of the capital, Reykjavik. A considerable amount of exploratory and production drilling has been carried out within this area. There are strong indications that in large sections of this area, the temperature of the flood-basalts at the depth of 2 km is on the order of 100°C. If the total area under which this condition prevails is estimated at 10 000 km^2, the thickness of the active resource at 1 km, and using the results of the previous section, the total recoverable effective low-temperature heat under this area should amount to 2×10^9 PET. This is comparable to the total resources of some of the largest oil fields known.

The low-temperature resources in the north-central and northeastern, as well as other sections of Iceland, are less well known than those mentioned. However, it is by no means unconceivable that their magnitude is of the same order as the resources in the southwest. Hence, the total recoverable effective low-temperature resources may amount to 4×10^9 PET.

In conclusion, it is necessary to emphasize that the above results are based mainly on uncertain estimates: (1) the recovery factor; (2) the resource volume; and (3) the assumption that geothermal energy can be recovered only from the flood-basalts. The underlying denser formations have been neglected as a possible source environment. The writer is of the opinion that the estimates of the recovery factor are quite prudent and that modern stimulation methods may help to enhance the recovery above the ratio estimated here. Moreover, assumption (3) is somewhat questionable, mainly in the case of the high-temperature resources. It is well known from the work of Ward and Bjornsson (1971) that the microearthquake activity associated with the high-temperature resources extends to depths of more than 5 km. This can be taken as an indication that the reservoirs are thicker than are estimated herein. There are, therefore, indications that the above estimates are conservative. However, further progress in this field can come only on the basis of additional field data, mainly deeper drilling into the lower sections of the flood-basalts and the underlying denser formation.

ACKNOWLEDGMENTS

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