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Geothermal Resources for Electric Power Production: Their Present Status and Future Prospects *

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This paper attempts to evaluate the institutional and economic factors which will play a part in determining the future scale of geothermal development in the short term. A complete evaluation of the future of geothermal resources development would require evaluation of technical factors also, such as probable developments in exploration techniques, the prevention of scale formation in hot water fields, the disposal of mineralized water, the use of geothermal energy in non-power applications such as space heating and cooling and water desalination and, for the long term, an evaluation of the technology for the extraction of thermal energy from hot rock at depths of several kilometers. Since this paper, however, is concerned only with the future scale of geothermal development and since technology is developed and technical problems are solved when institutions which can command the finance required choose to solve them, a passing reference only to some of the technical problems mentioned above will be made in this paper.

Over the past two years, there has been a growing concern over the continued availability of natural resources, the demand for which is growing and is expected to continue to grow at a high rate. At the same time, growing awareness of the environmental effects of the unregulated use of natural resources has led to the enactment of legislation in many countries aimed at the control of environmental damage and restricting the way in which natural resources and in

* The views expressed here are those of the author and to not necessarily represent those of the United Nations.

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particular energy resources can be developed and used. In the United States, for example, environmental considerations coupled with the need to import increasingly large quatities of oil and natural gas has led to the re-evaluation of the potential of indigenous energy resources, including geothermal energl resources. Since the present status of geothermal resources development and their future prospects on a world scale are in many respects reflected in the present situation in the United States, an analysis of that situation can be instructive for those who are also interested in geothermal development in other countries.

The development of geothermal energy on a significant scale has been the subject of much enquiry in the United States in recent months and several estimates of potential by the year 1985 of the year 2000 have been published, for example, by the United States Geological Survey (1), the National Petroleum Council (2), the Hickel Geothermal Resources Research Conference (3), and by other concerned with geothermal resources development (4) (5). There is general agreement about the total quantity of heat stored in the earth down to any given depth, but there is very little agreement about how much of this heat can be exploited, and by what date any given rate of exploitation can be achieved.

In the present state of technological development, we can say that exploitable geothermal resources consist of hot water or steam contained in permeable rock at a depth which can be reached by drilling. As this definition implies, there are two kinds of geothermal resource: one produces only steam at the wellhead and is said to be a « dry steam » or « vapour dominated » geothermal field; the other produces either hot water alone or a flashing mixture of hot water and steam and is said to be a «wet steam» or «hot water» geothermal field.

The first geothermal field to be devepoped was a dry steam field, at Larderello in Italy where the present generating plant, operated by the State Electricity Authority (ENEL), has a capacity of 380MW.

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(1) U.S. Geological Survey, Circular 650, Washington, 1972.
(2) U.S. Energy Outlook, National Petroleum Council, Washington, 1972.
(3) *Geothermal Energy*, A Special Report by W. J. Hickel, University of Alaska, Washington, 1972.
(4) D. E. White, in « *Geothermal Energy* », Stanford University Press, Stanford, California, 1973.
(5) U.S. Geological Survey, Prof. Paper 820, Washington, 1973.

Another dry steam field has also been developed in Japan, at Matsu-kawa, where a 20MW plant which serves the Tohoku Electric Power Company began operation in 1961.

In the United States, the first geothermal power production began from a dry steam field at the Geysers near San Francisco. At the Geysers, expansion of steam production by the Magma-Thermal Power and Union Oil companies is now progressing at a rate equivalent to 110MW each year; the Pacific Energy Corporation was reported recently to have agreed to supply the Pacific Gas and Electricity Company with steam for an initial 55MW plant, and the Signal Oil Company has undertaken the sale of further steam supplies at a rate equivalent to 135MW each year to Pacific Gas and Electricity. The total installed capacity at the Geysers field will be 900 megawatts in 1976 ([6]). The ultimate capacity of this field has been estimated to be over one thousand megawatts.

The cost of a geothermal production well drilled to 8,000 feet is about $ 250,000, excluding mobilization costs. Production from such a well in a dry steam field can range to over 100 tons of steam per hour at a pressure of 10 atmosphere and a temperature over 200°C. The price paid for such steam at the Geysers field, for example, is about 30 US cents per ton and the cost of disposing of the condensed steam after use is an additional 5 cents per ton of steam produced, also paid by the power company. If the alternative source of power is from an electric power plant burning fuel oil, then the opportunity cost of 200°C geothermal steam is about 50 cents per ton when fuel oil costs $ 3.50 per barrel and 70 cents per ton when fuel oil costs $ 5.00 per barrel.

The three fields already mentioned, one each in Italy, the United States and Japan are the only dry steam fields to have been developed so far and this type of field therefore appears to be less common than the hot water type. From the point of view of electric power production, it will be unfortunate if further exploration confirms that this is so, since dry steam field operation is relatively simple, and in economic terms highly competitive with alternative sources of electric power.

The first hot water or wet steam field to be devepoped for the production of electric power was the Wairakei field in New Zealand

([6]) PG and E Week, Friday, 24 August 1973.

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where a 192MW generating plant is operated by the New Zealand Electricity Department. Other hot water fields now producing power are in New Zealand at Kawerau, in Japan at Otake, in the USSR at Pauzhetska and Paratunka, in Iceland at Namafjall and in Mexico at Cerro Prieto.

Operation of a wet steam field for electric power production differs from that of a dry steam field because a geothermal well in a hot water field, while producing steam in quantity comparable to that from a well in a dry steam field, also produces hot water which may be equal to three times the weight of the steam produced. All wet steam fields which are used to generate electric power using steam turbines therefore have centrifugal separators to separate the steam and water. The steam is then handled in the same way as the steam produced in dry steam fields and the water is taken by pipe or by channel to a disposal point. If the geothermal water has been « double-flashed », that is if the water from the first steam-water separation is allowed to flash at some suitable lower pressure and the steam and water are again separated, then the geothermal water to be disposed of will have a temperature close to 100°C and by weight will amount to about 70 per cent of the water originally produced. This hot water can then be used for heating or cooling at a cost which is lower than those of alternatives, if demand is concentrated in a market which is located within a few miles of the geothermal field. If there is no such heating or cooling demand, and the mineral content of the geothermal water is not of value, then the residual geothermal water must be discarded. Three methods of disposal have been adopted or tested in the past. In New Zealand, where the salinity of the geothermal fluids is about one-tenth the salinity of sea water, and is therefore relatively low, the geothermal water is simply discharged into a large neighbouring river, with negligible environmental effects. In El Salvador, the occurrence of a geothermal brine with a salt content about half that of sea water, and the relatively small flow of the neighbouring river during some seasons, have led to the study of a plan to carry the rejected water some 30 km by channel to the sea. A third method of disposal, some aspects of were tested experimentally in El Salvador, is by reinjection of the water beneath the surface. In El Salvador geothermal water at a temperature of 160°C was continuously reinjected for six months. The maximum rate of reinjection achieved without pumping was of the order of 800 tons per hour into a single well which had a 9-5/8″

diameter conductor casing and was drilled to a depth of roughly 900 m. The tests carried out in El Salvador were in all respects successful but in order to establish that disposal by reinjection of large quantities of geothermal water can be achieved on a 20 year or 50 year basis, further tests are required to establish criteria for the siting of reinjection wells so that these can contribute recharge water to the reservoir under exploitation without degrading the thermal quality of the geothermal water being produced from the area of steam production.

An average production well in a hot water field drilled to 3,000 feet costs about $ 150,000. Production from a geothermal well in a hot water field with a reservoir temperature near 230°C may be about 400 tons of steam and water per hour. If this water is allowed to flash in two stages then 72 tons of steam at five atmospheres and a temperature of 154°C and 48 tons of steam at 0.8 atmospheres and 93°C can be obtained. Depending on the turbine and the inlet pressures used, this steam can generate about as much power as the well in a dry steam field which delivers 100 tons per hour of dry steam at 200°C. It may appear that since the wells are commonly more shallow and therefore drilling costs lower, the cost of electric power from wet steam fields should be less than that from dry steam fields. However, other factors such as the increased turbine costs involved in using larger quantities of low pressure steam — the turbine section using steam at one atmosphere and below costs twice as much as the section using higher pressure steam (7) — and the cost of disposal of the relatively large quantities of geothermal water have to be considered. Disposal costs by reinjection for example were estimated in one case to be from 2.9 to 4.7 cents per ton of water produced, which would add roughly 9.7 to 15.7 cents per ton to the cost of producing the steam. But even with the higher disposal costs for wet steam fields the electricity produced still remains competitive with that produced in thermal stations.

The National Petroleum Council has estimated that the United States geothermal resources can be developed to supply 1,900 to 3,500MW of electric power by 1985. The Hickel Conference on the other hand has estimated the developable potential as 132,000MW by 1985. Other estimates are 2,400 to 16,000MW assuming a 25 year life

(7) B. Wood, in « *Geothermal Energy* », UNESCO, Paris 1973.

for the resource [8]. The largest of these estimates would supply almost 20 per cent of the estimated United States power requirement in 1985 and the smallest of them only about 0.5 per cent. There are, therefore, almost two orders of magnitude between the highest and lowest estimates. These are very considerable differences, but at the present time, unfortunately, these appears to be no certain way to determine which of them is more nearly correct. As we have seen, geothermal resources, given existing technology, consist of hot water or steam at drillable depth and their existence or absence can be proved only drilling. So far, there has been relatively little geothermal exploration drilling in the United States or indeed in any other country.

If the average geothermal production well yields steam at a rate equivalent to 5MW then 26,000 productive wells will be needed to produce 132,000MW in 1985. Koenig [9] reports that at the end of October 1969, geothermal drilling to a depth in excess of 3,000 feet has taken place at ten locations in the United States, that fluid at a temperature greater than 180°C was encountered at four of these, but because of scaling and environmental problems, only one of them, the Geysers field, where dry steam was encountered, has been developed for electric power production. The total number of wells drilled in these ten locations was 119 of which 78 were located at the Geysers field. Most of the wells at the Geysers are producers. In the United States, then, at ten locations where drilling has taken place, discoveries were made at four (though electric power production is under way at present at only one of these) and about 60 per cent of the wells drilled can be classed as producers. If the same success ratio is maintained, then the total number of wells required in the United States by 1985 to produce 132,000MW will be about 42,000. This number can be compared with the yearly total of United States onshore oil well completions which in 1969 for example, was about 30,000 or about nine times the rate needed to drill 42,000 geothermal wells by 1985. If the cost of the average geothermal well is estimated, conservatively, at $ 150,000 and lease, rental and exploration costs are assumed to be in the same ratio to drilling costs as for the onshore

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(8) See D. E. White, in « *Geothermal Energy* », Stanford University Press, Stanford, California, 1973.

(9) J. B. Koenig, *Geothermal Exploration in the Western United States*, « Geothermics », Special Issue 2, Pisa, 1972.

oil industry in 1969, then a total expenditure on geothermal exploration and drilling of the order of $ 10 billion will be required to produce steam equivalent to 132,000MW by 1985. This implies an annual investment of risk and development capital equal to roughly 15 per cent of such expenditure by the oil industry in the United States in 1969.

An obvious question to ask is whether geothermal drilling, if it continues at the rate now under way, will achieve the steam production projected by the Hickel Conference. Sources close to the industry estimate that these may be the equivalent of ten drilling rigs at work continuously in the United States at present, indicating an average drilling rate of 60-100 geothermal wells per annum which is only about one-fortieth of the rate required to meet the Hickel projections. Or, to look at the matter another way, to drill 42,000 wells by 1985 beginning with an annual rate of 100 in 1973 will require an annual increase of 50 per cent in the number of wells drilled continuing through 1985.

If geothermal power is as competitive economically as suggested above then it may be asked why it is that relatively little geothermal drilling is now taking place in the United States. Several answers to this question have been given. It is pointed out that the major geothermal resources of the United States are located in the western states in which sixty per cent of the geothermally prospective areas are Federal land which has not yet been released for geothermal exploration and development. Federal leasing requirements are more onerous for known geothermal resources areas (KGRA's) than for other prospective areas and since many non-Federal prospective areas are adjacent to Federal lands, there is a reluctance of the part of geothermal operators to carry out exploration drilling and prove geothermal resources on these non-Federal lands because the adjacent Federal lands may then be reclassified as KGRA's.

In the past, there have been two industries which have mobilized and deployed risk capital for natural resources development on the scale now required for geothermal development. These are the mining and oil industries. It might be expected that the oil industry in particular could now easily move an appreciable part of its resources from oil to geothermal exploration and development. Yet this has not occurred, at least on the scale required by the Hickel projections. The reason may be that while oil, and also minerals, may be traded nationally and internationally, geothermal resources cannot be but must be used close to the place where they are produced for the generation of electric power or to supply thermal energy. In the United States only a public utility may sell electric power and so the oil companies should seek utilities as partners in geothermal development if power production is the objective, yet this kind of association is not customary for the oil companies and may tend to inhibit their activities in the geothermal field.

At the risk of some oversimplification it can be said that our main sources of energy now and in the short term future are the hydrocarbons with, in the background, the possibility that nuclear fission may be developed into a significant energy source. It is instructive to examine investment costs and the relative profitability of these energy sources. The approximate average capital investments required are given in the following table:

Capital and Generating Costs of Electric Power

	Initial Investment in Fuel Production	Investment in Generating Plant [13]	Electric Power Cost, Mills/kWh
A	\$ 2.80/kW [10] [11]	\$ 107/kW	10 [14]
B	\$ 81.40/kW [10]	\$ 107/kW	10 [14]
C	\$ 75.40/kW [12]	\$ 117/kW	6 [16]
D	\$ 4.00/kW [15]	\$ 360/kW	12

A — Persian Gulf Oil and Oil-Fired Generating Plant
B — U.S. Onshore Oil and Oil-Fired Generating Plant
C — U.S. Geothermal Steam and Geothermal Generating Plant
D — North American U_3O_8 and Nuclear Generating Plant

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(10) Average investment per initial daily barrel delivered to a loading terminal in the Persian Gulf. Prices from. M. A. ADELMAN « *The Word Petroleum Market* », Johns Hopkins University Press, Baltimore, Md., 1972.

(11) An investment of roughly \$ 38 per kw in tanker capacity is required to deliver oil to the U.S. but is not taken into account here.

(12) It is assumed that the average geothermal well costs \$ 150,000 and delivers steam equivalent to 5 MW, that the ratio of drilling to total development costs is 1 to 1.6 and that 60 % of the wells drilled are producers.

(13) Approximate investment costs of plant operating in California in 1970.

(14) Assuming a fuel cost of US \$ 3.50/barrel for low sulphur crude.

(15) W. M. GILCHRIST, Mining Engineering, March 1969. This represents the investment cost of producing « yellow cake » at the mine mouth. The cost of supplying the initial charge of unenriched uranium in a form suitable for use in a reactor is about \$ 50/kW. See, *e. g.*, L. R. HAYWOOD *et al.*, *Peaceful Uses of Atomic Energy*, 8, United Nations, N. Y., 1972, p. 185-214.

(16) Assuming the price paid for geothermal steam is 3.0 mil/kWh.

It is interesting to note that the initial capital investment in fuel production per kilowatt for uranium production is almost as low as that for Persian Gulf Oil, but that the relatively high cost of nuclear generating plant and environmental problems appear to have held down demand, prices and profitability for uranium ore producers.

If it may be presumed that the production of onshore oil in the United States is a profitable industry then the costs quoted above indicate that even if the profit margin per barrel of Persian Gulf Oil is smaller than for U.S. oil, those companies with access to Persian Gulf or comparable overseas oil and U.S. markets (in general the major companies) may find it more profitable to invest in the production of that oil rather than alternative domestic energy sources such as geothermal steam. On the other hand those oil companies without access to Persian Gulf or similar sources of oil may find geothermal steam production worth consideration if a suitable arrangement with one of the electric utilities is possible.

The utilities, if they are to generate substantial quantities of geothermal power, will need to adjust to the concept of building generating plant in multiples of small units (55MW is the largest geothermal unit now in operation) close to the geothermal field rather than close to the centre of demand, with the disadvantage that long transmission lines may be required in some cases. The utilities themselves, if they chose to mobilize and deploy risk capital, could enter the field as steam producers. Through if the utilities were to choose to diversify into the development of primary energy sources there remains for them the question of assessing the relative profitability of offshore oil and gas production in relation to geothermal steam.

Some industries, the aluminum industry for example, now facing electric power shortages in the United States, could develop geothermal power resources for their own consumption in order to achieve security of supply.

Two factors which have not been discussed in relation to geothermal energy development are matters which are of concern at the national level - these are security of supply and foreign exchange costs for imported fuels. Since geothermal resources must be consumed domestically and involve no recurrent foreign exchange costs, these two factors might lead to government policies favouring the development of geothermal resources. Such policies might be implemented either by some form of legislation favouring geothermal energy or by direct government action in exploring for and developing the resource which then would be exploited by the utilities.

Many of the factors influencing the development of geothermal resources in the United States affect other countries also. Any country which is a net importer of energy would do well to examine its geothermal energy potential,and even those countries which export oil and gas might consider whether geothermal energy might not substitute for oil or gas at a lower cost as a source of energy and whether there may not be some special application, such as space heating or cooling, or the production of desalted water or of hydrothermal minerals, where geothermal resources have a role to play. That geothermal energy is cheaper than alternatives in many cases is certain; and the prospect of rising prices for oil and gas and other energy sources in the future means that the competitive position of geothermal energy is unlikely to change. That geothermal energy will continue to be developed successfully and profitably in the United States and in other countries seems certain but what is uncertain is that in the United States the industry will receive that massive investment that will be required to achieve the Hickel projections.

In the United States there is no tradition of exploration for and development of fuels by the state, and the likely scale of geothermal development therefore is difficult to determine because the oil and mining companies, traditionally the investors of risk capital in natural resources development may not find investment in geothermal energy as profitable as investment in Middle Eastern or other oil resources. The outcome will depend upon the policy decisions of governments as well as on istitutional and financial factors and, in the United States, on how the oil and mining companies and the utilities react to the problems and challenges of geothermal energy development. In other countries, and particularly in developing countries where the separation between the sectors of the economy engaged in exploring for and developing energy resources on the one hand and generating electric power on the other, may not be so clear cut, or where the state is itself active in the development of energy resources, geothermal energy may have a part to play in substituting at lower cost for future energy needs which otherwise would require the use of oil, coal or nuclear fission.

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