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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Geothermal Power [and Discussion]

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Geothermal power

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This paper deals mainly with the development of utilization of endogenous fluids in the world and particularly in Italy, together with a forecast of the potential increase in geothermal production.

At the end of 1972 the installed capacity of the world's geothermoelectric plants was approximately 1000 MW, of which 390.6 MW are installed in Italy. In the same year the electric energy generated by Italian power stations was 2582.4 GW h. In some countries, geothermoelectric energy costs ranged from 1.4 to 2.5 U.S. mills/MJ (5 to 9 mills/kW h) as compared with 1.66–3.9 U.S. mills/MJ (6–14 mills/kW h) for alternative sources.

The total geothermal capacity in the world is expected to double and perhaps to triple in the 1980s, as new installations are being constructed or planned in several thermal areas. The utilization of geothermal fluids for evaporating low-boiling liquids (freon, isobutane, etc.) or for driving a gravimetric loop, offers attractive possibilities of using thermal waters also for the generation of electricity.

In many countries, low enthalpy fluids are used directly for other purposes (domestic and greenhouse heating, refrigeration and air-conditioning, production of fresh water, drying seaweeds and diatomites, etc.).

The cost of geothermal heat thus employed is 0.7–1.2 $/GJ as compared with about 2.6 $/GJ if fossil fuels are used. Due to this attractive cost, in the next few years there should be a remarkable development in this type of utilization of low enthalpy fluids.

Introduction

As is known, the terrestrial heat flow on the continents has an average value of about 6.3 μJ cm^{-2} s^{-1}. It is a tremendous amount of energy. If the total terrestrial heat flow could be transformed to electricity by means of a process having a 10% average efficiency (Noguchi 1970) the resulting energy would cover the forecast electricity demand up to the year 2000.

In some areas, particularly in those where magmatic bodies are at relatively shallow depth, the heat flow may reach a value which is 10–20 times its average value (Burgassi *et al.* 1970; Hayakawa 1970; Dawson & Dickinson 1970).

Part of the enormous quantity of heat carried by the magma is dispersed by volcanic eruption. Another part heats the fluids which are contained within the country rock and the overlying geological formations.

After heating, these fluids may reach the surface and give rise to hot springs, geysers and fumaroles. But if the ascending path is blocked by a cover of low-permeability rocks, recirculation of hot fluids takes place at a certain depth and a large convection system is established below the cover. The heat loss of the system to the surface is in this case rather small because heat diffusion occurs by conduction only. On the other hand, if the cover is cut by open fractures, or drilled by a well, the circulation of fluids in the deep layers will be accelerated, thermal leaks at the surface may occur and heat conveyance to the surface is mostly achieved by convection.

The heat flow carried to the surface by the fluids of exploited geothermal areas is greater than the heat flow dispersed by conduction and can attain values about 200–1700 times the average terrestrial conductive heat flow. Values of this magnitude can be considered sufficiently valuable for industrial exploitation, either for transformation into electric energy by means of conventional equipment or for heat-requiring processes. In the boraciferous region, for instance, the heat of the fluids extracted from the wells amount to 2.4 GJ/s. The average heat flow in this region (170 km^2) is therefore 1410 $\mu J\ cm^{-2}\ s^{-1}$.

In the Larderello–Valle del Secolo area proper (10 km^2) the heat extracted from the wells amounts to 1.06 GW, with an average heat flow rate of 10600 $\mu W\ cm^{-2}$. Of course, although enormous, the amount of energy in a geothermal reservoir is finite. This amount can be evaluated with reasonable approximation, but the evaluation itself depends on the assumptions made regarding base temperature, porosity, pressure, etc., existing in the reservoir. This means that at the beginning of a geothermal project, in spite of the progress achieved in the preliminary evaluation of the reservoir capacity, some uncertainties remain on the maximum value of exploitable energy.

One could therefore conclude that the potential or recently discovered resources can only be assessed approximately. Therefore, an investment in a geothermal project always incurs a considerable initial risk.

Once a natural steam field has been located and explored, its energy can be exploited with acceptable capital costs and reasonable expense. In Italy, for instance, the average well length is 610 m, based on 670 drillings carried out up to now. The economic results of geothermal energy exploitation have been satisfactory and competitive with other sources (Facca & Ten Dam 1963; Leardini 1970).

The possibility of transporting geothermal energy by means of steam ducts is very limited, under the pressure and temperature conditions existing in the geothermal field. As a consequence, the heat flow carried by the fluid must be utilized directly where the wells are located. If the heat is to be utilized for industrial processes or agricultural purposes, the manufacturing plants or the greenhouse to be heated must be located near the endogenous steam-extraction area. Plants having high process heat requirements should be considered where steam is available. Endogenous steam, in fact, cannot be stored in the reservoir for a long period, and cannot be transported at surface for long distance. The exploitation of geothermal steam via conversion into electricity, on the contrary, offers many advantages if it is done on the spot.

Endogenous fluids can be exploited safely and economically only when the extraction rate is continuous. The incidence of cost of the steam in geothermal electric production is low compared to the fuel cost in the other thermoelectric plants (liquid, solid or gaseous fuels, nuclear fuels). Therefore, the electric output of a geothermal plant should be constant over the year and it should be incorporated into the base load that the generating plant system is called to produce.

Up to now geothermal resources have been exploited to generate electricity in relatively limited areas at Larderello and Mount Amiata (Italy), Wairakei and Kawerau (New Zealand), The Geysers (U.S.A.), Cerro Prieto and Pathé (Mexico), Otake and Matsukawa (Japan), Pauzhetka and Paratunka (U.S.S.R.), and Namafjall (Iceland). In El Salvador, near Ahuachapan, engineering and design work for a 30 MW power-station is under way.

Sources of endogenous hot fluids that are or could be used in the primary form (heating, and other industrial uses) are more frequent, and may be found in larger areas. The utilization of such fluids is of interest not only to the above-mentioned countries but also to many others: Algeria, El Salvador, Chile, France, Greece, Hungary, Turkey, the Philippines, Taiwan, etc. Moreover, many other countries are now starting, or have already started studies and research (see figure 1) on the identification, harnessing and utilization of endogenous fluids.

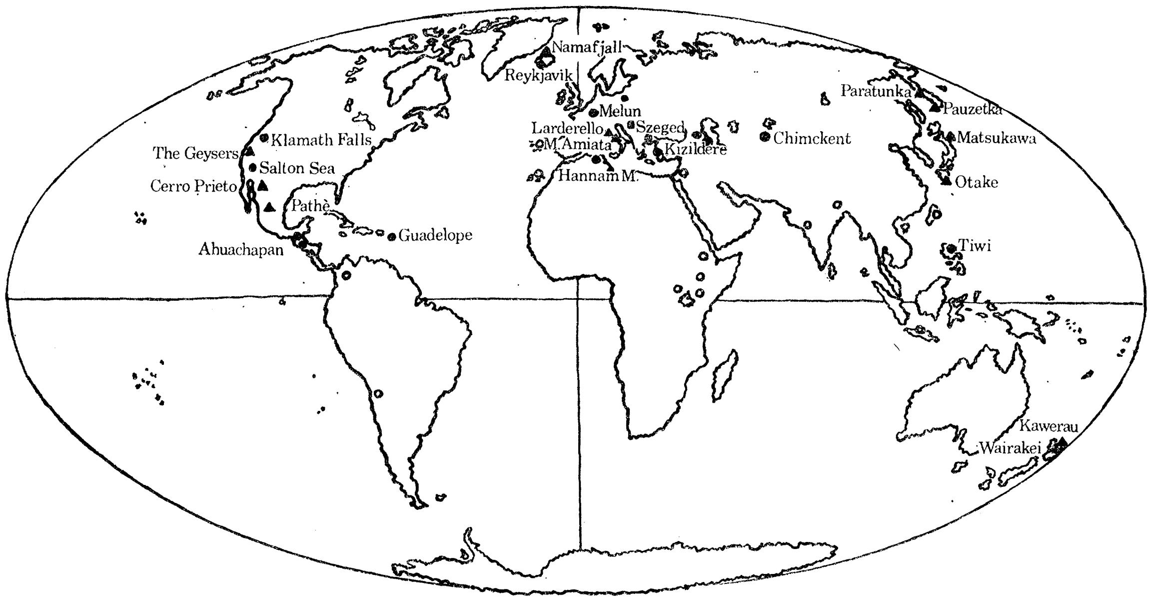

FIGURE 1. State of world geothermal research and exploitation. ▲, Countries in which geothermal power plants are in operation; ●, countries in which geothermal fluids are used for heating, agricultural and industrial purposes; ○, countries in which research is under way.

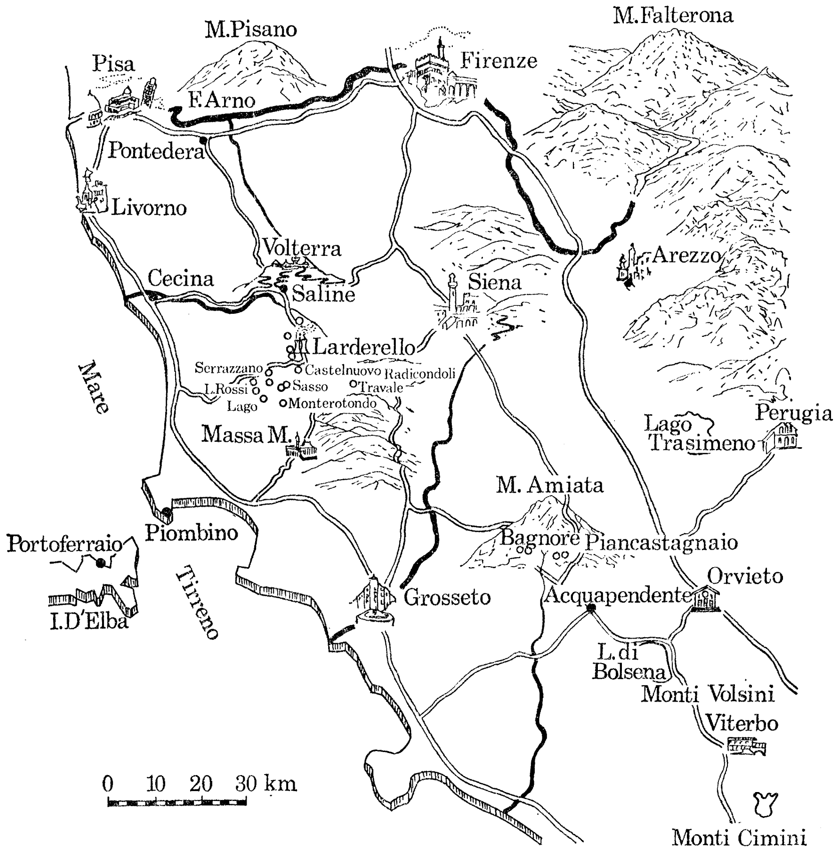

FIGURE 2. Geothermal areas in Italy. ○, Geothermal power station.

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Geothermal power in Italy

Tuscany, one of the regions of central Italy, is well known all over the world for a particular industrial exploitation. In the Larderello area, about 100 km to the south of Florence (see figure 2) man succeeded for the first time in utilizing geothermal energy in industrial activity. At first (1827) natural thermal energy was used in the boric acid industry, later (1904) it was utilized for both chemical and electric production; since 1964 only electricity has been produced.

The most striking thermal manifestations in the Larderello area consisted initially of fairly strong and noisy jets of steam, the so-called 'soffioni', escaping from rock fissures and of bubbling gas in small natural pools ('lagoni') where rainwater and condensed steam had collected. The extraction of boric acid from the pools at first encountered great technological and practical difficulties, due to the lack of previous experience. The boric-bearing pool water was transferred to sedimentation tanks, fed into iron boilers and then suitably concentrated, using wood from the neighbouring forest as fuel. The solid product was obtained by means of subsequent crystallization. From 1827 onwards, natural thermal energy obtained from shallow wells was used in place of wood, which was becoming increasingly short.

The consequent outstanding increase in production of boron and ammonium compounds, the fast growth of trade and gradual growth in chemical plant capacity led, between the end of 1800 and the early decades of the present century, to the development of a flourishing chemical industry of international renown (Mazzoni 1954).

Steam exploration by means of drilling was initially concentrated in areas with natural manifestations. It was subsequently extended to a very large area in the Larderello region and was carried out with continually improved drilling equipment.

The generation of electric power with endogenous fluids was first obtained in 1904, by Prince Piero Ginori Conti: it was accomplished by admitting into a reciprocating engine the steam separated from the accompanying water. The engine exhausted to the atmosphere and was coupled to a d.c. generator which produced electric lighting for the town of Larderello.

In 1913 a 250 kW turbo-alternator replaced the reciprocating engine: geothermoelectric production on an industrial scale dates from this year. Studies carried out on the direct utilization of natural steam with condensing turbines showed that at the time the consumption of energy required for cooling-water circulation and gas extraction from the steam would have been too expensive. On the other hand, in order to extract boric acid from the steam, it was necessary to condense the natural steam in heat exchangers. These allowed the recovery of the fluid thermal energy by generating secondary pure steam for the turbines. In this manner corrosion was also eliminated and the handicap met in driving engines by direct steam was overcome.

The troubles arising from the heat exchangers and the resulting losses in energy led to experiments with impulse and back-pressure turbines directly fed by natural steam. This proved that the endogenous fluids could be utilized with direct inlet turbines exhausting to the atmosphere (cycle 1) as well as with the condensing turbines driven by pure steam produced by the aforesaid exchangers (cycle 2). The direct-inlet turbines exhausting to the atmosphere were quicker to install owing to their simple design, and cheaper to operate, as compared to the condensing units driven by indirect steam. On the other hand, the heat rate (20 kg of fluid at 500 kPa 185 °C, 5 % gas content by mass, per saleable kW h net) was considerably higher than in the condensing units fed by indirect steam (14 kg of endogenous fluid per saleable kW h net).

The amount of boric acid carried by the steam gradually decreased; at the same time its economic values also decreased when rich deposits of colemanite (Turkey), rasorite and kernite (U.S.A.) were discovered and exploited. Since then, natural steam was increasingly used for power production. The growing interest in the electrical aspects of geothermal utilization led to improved drilling equipment (Giovannoni 1970) and prospecting of wider areas.

Italian equipment manufacturers began developing condensing steam turbines designed to utilize natural steam, despite its high content of incondensable gases and its carry-over of boric acid and other chemicals.

Table 1. Geothermal-electric development in Italy

31 December ...	1920	1930	1940	1950	1960	1970	1972
number of geothermal power stations ...	2	4	5	6	11	17	17
cycle 1 power plants							
no. of turbo-alternators	—	4	5	5	5	10	10
installed capacity/MW	—	5.20	8.70	16.5	16.5	42.9	42.9
cycle 2 power plants							
no. of turbo-alternators	3	4	9	12	8	—	—
installed capacity/MW	9.25	9.25	64.25	123	79	—	—
cycle 3 power plants							
no. of turbo-alternators	—	—	—	3	14	26	26
installed capacity/MW	—	—	—	72	189.7	347.7	347.7
total no. of turbo-alternator units	3	8	14	20	27	36	36
total installed capacity/MW	9.25	14.45	72.95	211.5	285.2	390.6	390.6
average electric power (gross)/MW	0.82	6.53	60.97	145.91	239.51	311.04	294
plant capacity factor (%)	8.8	45.2	83.6	69	84	79.6	75.3
average electric power (net)/MW	0.78	5.92	55.71	134.21	217.24	287.38	269
auxiliary services and transformation loss (%)	4.9	9.3	8.6	8	9.8	7.6	8.5
fluid on stream:							
to power plants/t h^{-1}	50	150	1000	2150	2760	3400	3190
other uses/t h^{-1}	250	350	1000	70	80	100	100
average fluid rate/kg kW^{-1} h^{-1} net	64.18	25.34	17.95	16.02	12.71	11.38	11.86
cumulative net energy from 1904							
GW h	69.05	374.76	1991.80	8434.87	25515.25	49025.51	53828.43
10^{15} J	0.25	1.35	7.17	30.3	91.8	176.5	193.8
cumulative drilling from 1904/km	5	13.18	38.07	68.77	205.73	376.42	401.90
drilling per saleable GW h net/m	72.41	35.17	19.11	8.15	8.06	7.67	7.40
no. of completed wells	70	106	203	272	457	642	665
no. of wells on stream	50	60	100	123	171	199	204
average output per productive well/t h^{-1}	6	10	20	18.05	16.61	18.23	16.13
length of pipelines network/km	2	5	20	30	71.8	105	113
explored areas/km^2	0.5	1	3	5	50	215	215

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Mixture condensers, equipped with powerful centrifugal gas extractors (Dal Secco 1970) led to a solution of problems arising from incondensable gases, so that the direct condensation system turbine (cycle 3) rapidly took over the task of energy production. In this way it was possible to obtain an important reduction in the specific fluid consumption (an average 10 kg of fluid at 500 kPa, 185 °C, 5 % gas-content by mass is required to produce 1 saleable kW h net). The principal stages of geothermoelectric activity in Italy are summarized in table 1 and in figure 3, from which the following considerations emerge:

(1) Up to 1930 geothermal development was not achieved in a systematic way. The reasons for this were: the scarcity of geological, geophysical and geochemical information; an exploration philosophy based only on empirical criteria; the technical difficulties involved in drilling

large boreholes in heterogenous rocks having a very high temperature; the poor resistance to corrosive substances of the materials utilized in the construction of power plants, etc. As regards technology, great difficulties were found at the beginning (1930) in making suitable turbine blades, pump rotors, heat exchanger tubes, etc. These difficulties accounted for both the low production of steam and electric energy. In the first 30 years of exploitation, in fact, the plants of the whole area produced only 1.35×10^{15} J (375×10^{6} kW h). The overall length drilled was 13180 m.

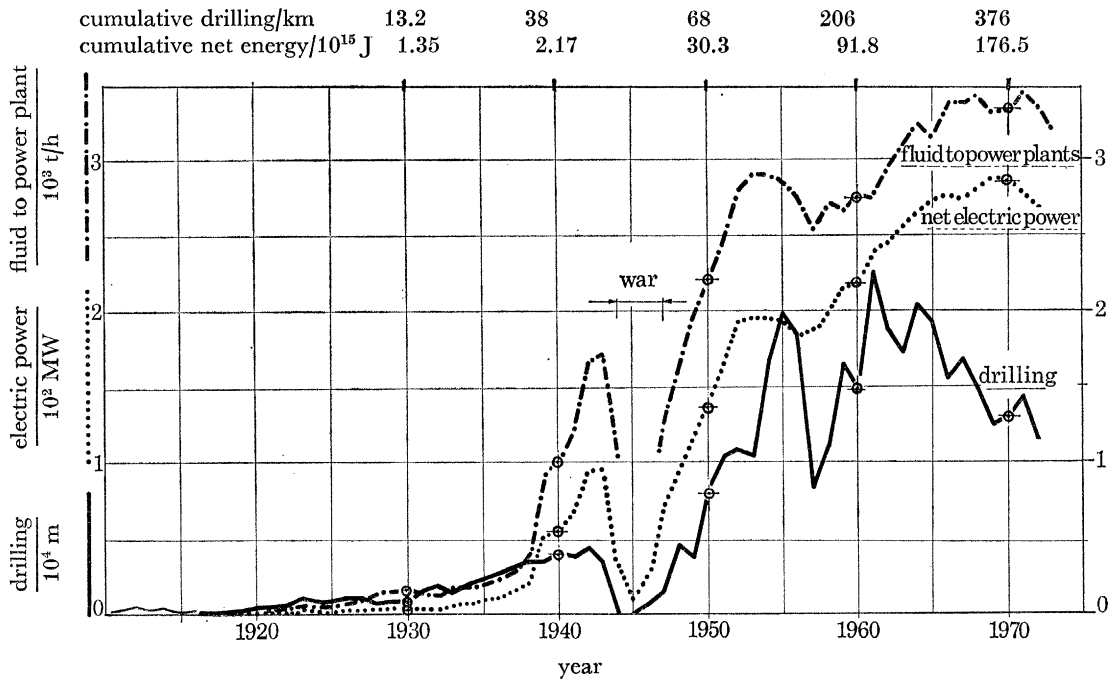

FIGURE 3. Geothermal electric development in Italy.

(2) The wells drilled in the subsequent 20 years (1930–1950) achieved a production of approximately 2200 t/h of natural superheated steam; at the beginning of their life some wells delivered up to 200 t/h of superheated steam, due to this remarkable increase in steam production. In 1938 it was possible to build and put into operation the first large geothermal power plant (Larderello 2).

(3) The decade from 1951 to 1960 is very important in the history of geothermal electric exploitation in Italy. In fact: (*a*) the first power plant (Larderello 3) equipped with condensing turbines directly fed by primary steam (natural steam), came into operation and a total yearly production of 7.2×10^{15} J (2×10^{9} kW h) was attained; (*b*) the construction of the power plants in Serrazzano (28.5 MW capacity) and Lago (19 MW initial capacity), operating with primary steam and condensing units, allowed the lowering of the average specific steam consumption from 16 to 12.7 kg/kW h and increase of the yearly plant capacity factor; (*c*) the discovery of new steam fields in Travale and on Mount Amiata (20 and 80 km respectively to the east and southeast of Larderello) encouraged the hope that other steam fields could be discovered outside the main Larderello area; (*d*) the power plant Larderello 3 was built in the years 1952–4, and in 1955 it produced over 3.25×10^{15} J (900×10^{6} kW h), with a plant capacity factor of 90.4 %. On the other hand, in the Travale area, despite the initial high

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flow from the wells, the power plant (which was installed in 1951, with a capacity of 3.5 MW) could never reach full load and had to be stopped after a few years for shortage of steam. These two cases (Larderello 3 and Travale) illustrate that success and failure are always possible in geothermal ventures.

(4) In the years 1955–7 an unforseen event, however, stopped the increase in production of both steam and electric energy. Research and experiments proved that too short a distance between boreholes had previously been adopted, so that there was a mutual influence between wells. At the end of 1960, for example, 162 wells had been drilled over 10 km² in the Larderello area proper, from which 126500 kW were supplied.

TABLE 2. INSTALLED CAPACITY, FEEDING AND OPERATION CHARACTERISTICS OF ITALIAN GEOTHERMAL POWER PLANTS, 1972

power plant	total installed capacity MW	fluid at intake: pressure kPa	fluid at intake: temperature °C	fluid at intake: gas content in mass (%)	fluid at intake: output t/h	net capacity MW	specific consumption kg/kW h
		Boraciferous region					
1. Larderello 2	69	400	196	7	422	47	11.2
		300	166	6	106		
2. Larderello 3	120	420	195	7	690	68.5	10.1
3. Gabbro	15	740	220	10	115	12.2	9.4
4. Castelnuovo V. C.	50	460	185	13	180	23.6	14.4
		200	165	4	130		
		100	140	3	30		
5. Serrazzano	32	500	194	3.2	293	29.8	9.8
6. Lago 2	33.5	500	172	2.2	250	29.6	11.2
		200	143	1.6	80		
7. Sasso 2	15.7	500	180	3	164	16.4	10
8. Monterotondo	12.5	460	170	2	120	13.1	9.2
total condensation power stations	347.7	—	—	—	2580	240.2	10.7
9. S. Ippolito-Vallonsordo†	0.9	250	188	20	10	0.1	—
10. Lagoni Rossi 1	3.5	500	190	3	65	2.5	26
11. Lagoni Rossi 2	3	400	203	3.9	65	2.7	24.1
12. Sasso 1	7	500	185	3	65	3.2	20.3
13. Capriola	3	460	170	3.8	60	2.8	21.4
total exhausting-to-atmosphere power station	17.4	—	—	—	265	11.3	23.4
total power stations in the Boraciferous region	365.1	—	—	—	2845	251.3	11.3
		Mt Amiata region					
14. Bagnore 1	3.5	300	136	7	46	1.3	35.4
15. Bagnore 2	3.5	330	142	7	54	2	27
16. Senna‡	3.5	—	—	—	—	—	—
17. Piancastagnaio	15	900	186	20	245	14.3	17.1
total Mt Amiata region power stations	25.5	—	—	—	345	17.6	19.6
grand total	390.6	—	—	—	3190	269.1	11.9

† Started up 21 December 1972.
‡ Shut down 26 November 1971 for overhaul.

(5) Since 1961 research on and exploitation of geothermal energy in Italy have been directed on a more advanced basis and clear-cut criteria of investigation and utilization (Chierici 1961; Cataldi, Ceron, Di Mario & Leardini 1970; Corti, Di Mario & Mondolfi 1970). On the basis of the preceding experience in geothermal utilization in Italy, a better knowledge of the basic phenomena and new survey methods have been resorted to for field exploration. The results of electric exploitation in Italy for the period 1960–72 may be summarized as follows: (*a*) The overall electric energy fed to the national electric grid was 10^{17} J (28×10^9 kW h); (*b*) The average production was 3300 t/h of superheated steam; (*c*) The average drilling was approximately 16300 m/year; (*d*) The length of new steam pipelines (with diameter ranging between 250 and 810 mm) was 41 km.

In the period considered, the turbines operated with secondary steam have been abandoned. In general, they have been replaced by condensing turbines fed by natural steam. In some areas, however, where the high content of incondensable gases (20–80 % by mass) does not economically justify a condensing cycle (Zancani 1959) a few back-pressure exhausting-to-atmosphere turbines still operate.

A list of power plants in operation in 1972 and their features is given in table 2.

Geothermal energy in other countries

Until 1958 Italy was the only country where natural steam was used on an industrial scale for power generation. Since then, other countries have started to exploit geothermal fluids (Facca 1970). At the end of 1972 the installed capacity of the world geothermoelectric plants was as follows:

Italy		
Larderello	365100 kW	
Monte Amiata	25500 kW	
total		390600 kW
U.S.A.		
The Geysers		298000 kW
New Zealand		
Wairakei	192000 kW	
Kawerau	10000 kW	
total		202000 kW
Mexico		
Pathé	3500 kW	
Cerro Prieto	75000 kW	
total		78500 kW
Japan		
Otake	13000 kW	
Matsukawa	20000 kW	
total		33000 kW
U.S.S.R.		
Pauzhetka	5000 kW	
Paratunka	750 kW	
total		5750 kW

Iceland	
Namafjall	3000 kW
grand total	1010850 kW

The countries using hot water and/or steam for heating and industrial uses are:

Algeria. Hot springs at a temperature of 90 °C are utilized at Hanmam Mescontine, southwest Annaba: deep drilling is under way in Sidi Zid.

Chile. Natural steam has been found in the El Tatio area and production wells have been programmed. The Chile project provides for threefold utilization of geothermal resources: power production, mineral extraction and desalination.

China. Geothermal energy in the form of natural steam is used for electricity generation in a number of areas. In some urban areas, natural hot water has been piped for heating purposes and for industries requiring a large supply of hot water (dye factories, paper mills, chemical works). In rural areas warm and hot springs have been channelled for use in nurseries and greenhouse, irrigating seedlings, saplings and vegetables. They are also utilized in poultry hatcheries and in certain fermentation processes (Takung Pao 1972).

France. In Guadaloupe, one geothermal field has been located. It produces a mixture of steam and water at a present flow rate of about 140 t/h at 160 °C. In the region around Paris a project is under way to provide domestic heating in Melun. The geothermal fluids are produced in the nearby region.

Hungary. Eighty hot water wells have been in operation since 1969. The total flow rate is 6800 t/h. The water temperature is 85–95 °C. The heat is utilized for heating 1200 homes in Szeged (southern Hungary) and greenhouses covering an area of 400000 m^2 (Boldizsar 1970).

Iceland. The most important utilization of geothermal fluids is that of space heating. Public administration buildings, as well as private homes, in Reykjavik and suburbs are centrally heated by endogenous fluids. More than 40% of Iceland's population live in homes heated by geothermal fluids.

Recent boreholes have increased potential wellhead energy (above 40 °C) for house heating to 1130 GJ/h (National Energy Authority, Reykjavik, 1973).

Greenhouses covering 110000 m^2 are heated by the above fluid, which yields 150 GJ/h. The annual capacity factor is 35–40%. A diatomite plant for the production of dry diatomaceous earth was built in 1966–7 near Lake Mayvatn: the plant produces 42000 t/year of diatomite and utilizes 50 t/h of fluids at a pressure of 700–800 kPa (Lindal 1970).

Japan. The fluids are also utilized for agricultural purposes (8000 m^2 greenhouses, poultry-farms, fish, and alligator hatcheries). The most impressive utilization of hot springs is that for recreational and therapeutic purposes: about 150 million people visit hot springs annually and over $870M are spent per year to this purpose (Komagata *et al.* 1970).

Mexico. The fresh water needed for construction and operation of the Cerro Prieto plant is produced by a pilot distillation plant fed by hot fluids. It is likely that more distillation units will be installed to cope with the needs of the surrounding semi-desert area.

New Zealand. In the Kawerau area, 75 km northeast of Wairakei, a mixture of steam and hot water is harnessed through a heat exchanger which produces secondary steam for the processing line of a nearby paper mill.

Philippines. Production wells are being drilled in the Tiwi (Luzon area): a small 2.5 kW pilot

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generator has provisionally been installed. At the same time a new geothermal field has been discovered on the island of Leyte.

Turkey. In 1968 the Kizildere geothermal field was discovered: one well has a potential of 30 t/h of dry steam and 250 t/h of hot water at a well-head pressure of 400–500 kPa. The Turkish Government is planning to build a geothermal plant as soon as possible (Ten Dam & Erontöz 1970).

U.S.A. The Salton Sea area (California) delivers very hot (340 °C) brine, carrying dissolved salts of many important elements (copper, uranium, silver, etc.) A pilot plant has therefore been installed to obtain the valuable elements from the salt brine. Heat is also used in different areas for air-conditioning and other purposes. At Klamath Falls (Oregon), for instance, 400 buildings are air-conditioned by hot water (100 °C) yielded by about 350 wells, drilled near the city.

U.S.S.R. Hot water (80–130 °C) sources are easily found in certain regions at very shallow depths. In the very cold region of Kamehatka, near Paratunka, a pilot power plant was installed in 1967 utilizing this kind of low-enthalpy source. The fluid operating the turbine is Freon 12, and is evaporated in heat exchangers and liquified in a condenser (Moskvicheva 1970). In Makhach-Kala, Grozni, Chimckent and Kamchatka regions some hothouse centres with an area of more than 150 000 m² are being built.

Technical and economical considerations

The production of geothermoelectric energy largely depends on the size of the natural resources, which vary greatly from one country to another. It is therefore difficult to find common criteria valid for an assessment of the technical and economical advantage of building power plants.

The first difficulty lies in assessing the amount of geothermal fluid available for exploitation and its characteristics, e.g. its energy content. In some fields (Larderello, The Geysers and Matsukawa) the fluid is superheated steam, carrying incondensables in an amount which may differ greatly from one site to another (6 % by mass at Larderello, 0.6 % at The Geysers, 1.7 % at Matsukawa). In other fields the fluid is dry saturated steam, or a mixture of steam and water (Wairakei, Cerro Prieto and many others) with a low incondensable gas content (0.5–0.7 % by mass). Some other fields (Paratunka and Reykjavick, for example) deliver hot water at a temperature near or slightly above boiling point (80–120 °C). Finally, the Salton Sea area delivers very hot (340 °C) brine, carrying a large quantity of dissolved salts.

Another figure which is difficult to assess is the specific density of electric energy which can be produced in a geothermal area. In effect, the possibility of yielding geothermal fluids from the reservoir differs greatly from one region to another and frequently also from one area to another in the same region. For instance, taking into account the specific energy density of the Larderello region, in the main production area of Larderello–Valle del Secolo, about 10 km², a peak value of 12.5 MW/km² is attained; but the average specific energy density in the whole region (about 170 km²) is 1.6 MW/km². At The Geysers, the present steam supply (produced from an area of about 85 km²) seems to be sufficient to operate a capacity of 710 MW (McMillan 1970), which brings the average specific density to approximately 8.4 MW/km². At Cerro Prieto, the drilled area (4 km² (Guiza 1973)) can at present supply fluid to feed 75 MW, i.e. an average specific density of 18.7 MW/km².

As regards the cost of endogenous fluids, the recent data available are contained in the report of the Thermal Power Co., who deliver endogenous steam to P.G. & E. for generation of electric energy in The Geysers power plants. This report states: 'The price of steam...is up 10.41 % over 1972 to 2.65 mills. Additionally, we receive 0.5 mill per kW h for effluent disposal which brings the total payment to 3.15 mills per kilowatt hour' (Annual Report Thermal Power, 1972). This price (1 mill = 0.1 cent) includes the cost of research, survey and exploitation, steam transport to the power plant, the disposal or reinjection of cooling water, taxes, amortization, general costs and benefits. The steam is delivered to the power plant at about 500 kPa, 175 °C, and contains 0.6 % by mass of incondensables.

Ragnars, Saemundsson & Benediktsson (1970) evaluate the cost of steam delivered to the power plant Namafjall at 20 U.S. cents per tonne. When revising these costs to take into account devaluation and auxiliary services, this cost increases to 24.8 cents per tonne of saturated steam at 1 MPa, 181 °C, 0.2 % by mass of incondensables. On the basis of the average specific steam consumption (10 kg/kW h) achieved at The Geysers plant, the cost per kW h at Namafjall would come to 2.45 mills (0.66 mill/MJ), which is in very close agreement with the 2.65 mills (0.74 mill/MJ) of the selling price of Thermal Power Co. in the United States.

A recent report by Cataldi, Di Mario, & Leardini (1973) gives an evaluation of the experience in Italy during some 70 years of exploitation. When approaching a new geothermal project, some figures are foreseeable, based on this experience.

Preliminary investigations and drilling of four or five wells may cost U.S. $0.2–1M respectively. If preliminary drilling confirms favourable conditions at depth, the quantity of fluid which may be expected from the exploration wells is of the order of 80 t/h, once the flow rate has stabilized. If the cost of the steam-ducts is to be added (which can be assumed at U.S. $0.1M), the total expenditure is U.S. $1.3M.

By applying to this cost the same amortization percentage indicated by McMillan (1970) for The Geysers power plants (13.5 %), the resulting total cost for a tonne of superheated steam (500 kPa, 185 °C, 6 % by mass of incondensables) is 25 U.S. cents. This brings the cost to 0.7 mill/MJ (2.5 mills/kW h) when condensing equipment for the electric plants is adopted.

The cost of a power station, however, can be determined more accurately. The cost per unit power in geothermal power plants is approximately the same as for a fossil fuel power plant. This cost, however, may differ considerably from one area to another (even in the same country) owing to the following reasons:

(1) First of all, cost is influenced by the steam conditions. Plants utilizing water–steam mixtures have additional expense in drying cyclones, draining devices, multiple-inlet turbines, etc. (as in the dase of Wairakei), which involve higher costs than those of plants utilizing superheated steam (Larderello, The Geysers, etc.).

(2) A high gas content in the geothermal fluid requires bigger gas extractors, whose capital cost may amount to 20 % of the total.

(3) A sizeable content of chlorides and other corrosive chemicals requires the use of expensive corrosion resisting metals for steam ducts, turbine blades, pumps, extractors, etc.

(4) Another cost item to be assessed for each site is that of the cooling towers, needed when the power plant is installed far from natural lakes or rivers, as often happens.

(5) The local standard capacity may affect the costs. In countries necessitating purchase from abroad, shipping fees, customs, etc., also affect the costs and may result in a large increase in installation costs.

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(6) The prevailing social and economic conditions also influence the costs, because of the different cost of money, amortization periods, etc., and the difference may be quite important.

(7) As regards the plant construction cost, the literature gives plenty of information and figures. By updating data reported in the literature (U.N. 1970), the actual cost per kW of power plant can be given approximately as follows:

Condensing-turbine power plants

Larderello
net capacity 2 × 26 MW: 170 U.S.$/kW;
net capacity 1 × 15 MW: 226 U.S.$/kW;

The Geysers
net capacity 2 × 55 MW: 125 U.S.$/kW;
net capacity 2 × 28 MW: 135 U.S.$/kW;

Back-pressure power plants

Larderello
net capacity 1 × 15 MW: 95 U.S.$/kW;
net capacity 1 × 4 MW: 105 U.S.$/kW;

Namafjall
net capacity 1 × 3 MW: 60 U.S.$/kW.

The higher cost per kW of the Italian condensing power plants is mainly due to the fact that very large turbo-compressors are needed for the extraction of incondensable gases from the condensers. These large turbo-compressors are necessary because the incondensable gas content at Larderello is up to 10 times higher than that at The Geysers field. The higher specific cost is also partly explained by the increase in labour cost at Larderello for the reasons which will be explained later on.

The first back-pressure power plant at Namafjall shows a rather low installation cost. This, however, is attributable to the fact that it is equipped with a very simple turbine, which was recovered from an earlier plant.

As regards the operating costs, it is not easy to give figures of general validity. These values change greatly from one country to another, because of the differences in labour legislation, in the basic wages and salaries and in the type of social welfare schemes. To take one example, social costs are very high in the Larderello boraciferous region, because of its remote location. Housing, schools, hospitals, sports grounds, entertainment must all be provided by the Electric Utility, exploiting the endogenous steam in Larderello and some other power plants (Serrazzano, Lago, Sasso Pisano, etc.). Automation and remote control have been applied in almost all the Italian exhausting-to-atmosphere power plants many years ago (Di Mario & Tagliabue 1958), but they have been extended to some condensing units only in 1969. This is one of the reasons for the higher operating costs of Italian stations.

As regards the high-capacity sets (2 × 26 MW), the operating cost is on the average 0.55 mill/MJ (2 mills/kW h) net, and it is somewhat more for smaller units. The exhausting-to-atmosphere power plants, which are technologically less sophisticated, have an operating cost of about 0.45 mill/MJ (1.6 mills/kW h) net. Finally, for the remote-controlled sets, the operating cost is further reduced to 0.166 and 0.22 mill/MJ (0.6 and 0.8 mill/kW h) net for exhausting-to-atmosphere and condensing units, respectively.

McMillan (1970) estimates that the operating cost of the highly automated units 5 and 6 of The Geysers plant is some 0.125 mill/MJ (0.45 mill/kW h) net. This figure, when updated, is of the order of 0.147 mill/MJ (0.53 mill/kW h) net.

Hayashida (1970) reports, for the Otake power plant (13 MW capacity), a cost of 0.166 mill/MJ (0.6 mill/kW h) net for normal maintenance and 0.28 mill/MJ (1 mill/kW h) net for repair work. The total updated operating cost could thus amount to 0.54 mill/MJ (1.9 mills/kW h) net.

Before concluding the cost analysis, a few remarks should be made on the yearly average production of a geothermal power plant. From the figures available for Italy and partly for other power stations in the world, it can be said that while the load factor (the ratio between the operating hours and total hours of the year) can attain values as high as 98% (Ricci & Viviani 1970), the plant capacity factor (the ratio between the available power and the installed capacity) generally ranges from 75 to 85%. The loss of availability is due to accidental failures and, most of all, to lack of steam to operate the plant. Therefore, it seems reasonable to consider the following average values: 8000 h/year and 8500 h/year, respectively, for the condensing and exhausting-to-atmosphere units.

From the preceding analysis of cost components, a conclusion can be drawn regarding the present costs of geothermal energy. They are shown in table 3, where reference is made to the main plants in operation. As table 3 shows, the total cost ranges between 1.4 and 2.5 mills/MJ (5 and 9 U.S. mills/kW h) net. No detailed information is available for the present cost of geothermal energy produced in condensing power plants supplied by steam flashed from mixtures of water and steam, like Wairakei, Otake, etc. Presumably, their present cost should be somewhat higher than the above values.

A comparison can be made between costs of geothermal energy and of that produced by a few conventional plants by reference to the cost figures given by Kaufmann (1970), which can be updated as follows:

				capital cost in U.S. mills (13.5%)		operating cost in U.S. mills		total cost in U.S. mills	
power plant	type	capacity MW	plant factor (%)	per kW h	per MJ	per kW h	per MJ	per kW h	per MJ
Fall River Mills	hydro	56	60	5.13	1.43	0.63	0.175	5.76	1.6
Humboldt Bay	steam	102	60	4.64	1.29	9.02	2.5	13.66	3.8
Humboldt Bay	nuclear	60	70	8.25	2.29	6.27	1.74	14.52	4.04

Endogenous fluids can be utilized not only for geothermal electric production, but also for other purposes. The exploitation of hot water, which occurs in large parts of all the continents, is also important (Einarsson 1970). Today hot water is principally exploited for domestic heating, particularly in Iceland and Hungary. The Reykjavik Municipal District Heating Service in Iceland now supplies hot water to the houses in Reykjavik at a price of 0.16 U.S. \$/m^3. The temperature of the water is about 80 °C and the heat utilized is on the average 176 kJ/kg. This gives an energy price of 0.9 U.S. \$/GJ, which is almost half the price of heat from fuel oil (Palmason & Zöega 1970). The geothermal district heating plant in Sgezed (southern Hungary) is economically a very successful project, actual heating cost; including amortization is

TABLE 3. GENERATING COST OF GEOTHERMOELECTRIC ENERGY

kind of natural steam ...	superheated steam						superheated steam		wet steam
	with condensing units						with exhausting-to-atmosphere units		
power plant ...	The Geysers		Larderello		Matsukawa		Larderello		Namafjall
net capacity/MW	2 × 55	2 × 28	2 × 26	1 × 15†	1 × 20	2 × 20	1 × 15	1 × 4†	1 × 3‡
cost of research, drilling and pipelines/10^6 U.S. $	20.53	10.45	7.70	2.22	unknown		3.78	1.26	0.76
cost of power station/10^6 U.S. $	13.75	7.56	8.84	3.39	unknown		1.42	0.42	0.18
total cost/10^6 U.S. $	34.28	18.01	16.54	5.61	7.88§	10.52§	5.20	1.68	0.94
total capital cost (13.5 %)/ 10^6 U.S. $	4.63	2.43	2.23	0.76	1.06	1.42	0.70	0.27	0.13
use of plant capacity/h year^{-1}	8000	8000	8000	8000	8000	8000	8500	8500	8500
net annual production									
GW h	880	4.48	416	120	160	320	127.5	34	25.5
10^{15} J	3.17	0.016	1.50	0.43	0.576	1.15	0.46	0.12	0.09
capital cost per MJ (kW h)									
fluid/U.S. mills	0.875 (3.15)	0.875 (3.15)	0.69 (2.5)	0.72 (2.6)	unknown		1.11 (4)	1.39 (5)	1.11 (4)
power plant/U.S. mills	0.59 (2.12)	0.63 (2.27)	0.78 (2.8)	1.06 (3.8)	unknown		0.42 (1.5)	0.47 (1.7)	0.36 (1.3)
total/U.S. mills	1.465 (5.27)	1.50 (5.42)	1.47 (5.3)	1.75 (6.3)	1.83 (6.6)	1.22 (4.4)	1.53 (5.5)	1.86 (6.7)	1.47 (5.3)
operating cost per MJ (kW h)/ U.S. mills	0.148 (0.53)	0.288 (1.00)	0.55 (2.0)	0.22 (0.8)	0.53 (1.9)	0.288 (1.0)	0.44 (1.6)	0.17 (0.6)	0.14 (0.5)
total cost per MJ (kW h)/ U.S. mills	1.61 (5.80)	1.78 (6.42)	2.03 (7.3)	1.97 (7.1)	2.36 (8.5)	1.50 (5.4)	1.97 (7.1)	2.0 (7.2)	1.61 (5.8)

† With remote and radio-control system. ‡ Pilot station, with a turbine of the simplest possible type. § Data by Mori 1970 updated.

0.7 U.S. $/GJ, as compared to the 2.6 U.S. $/GJ of a coal-fired district heating plant of the same output (Boldizar 1970).

The geothermal plant near the Lake Myvatn (Iceland) for the drying of diatomite has been in use for some years. The exploitation of this product would have involved $12 per tonne if fuel oil had been used, while the actual cost by using the heat of geothermal fluids is $2 per tonne.

Future prospects of geothermal energy

In the countries which at present utilize geothermal energy, research is very active.

In *Italy*, the discovery of steam fields in the Mt Amiata region, in an area where no surface thermal manifestations occur, marks a fundamental turning-point in the research on geothermal fields, and demonstrates that such research in new areas may increasingly be improved by adopting advanced prospecting techniques. The improvements in prospecting techniques makes research even more economical, since the less favourable areas are rapidly located and discarded and costly deep drilling is therefore reduced.

To these aims E.N.E.L. (State Electrical Power Board) and C.N.R. (National Research Council) have launched a joint programme to examine the possibility of increasing the supply of energy from geothermal sources through the discovery of steam fields in new regions (Leardini & Tongiorgi 1968). Already under way are preliminary surveys and prospecting in regions where desk studies had previously indicated the presence of favourable conditions, such as in the areas of Travale-Radicondoli, Monti Volsini, Monti Cimini (see figure 2), etc. At the same time, investigations are carried out in order to improve the basic knowledge of the factors which determine the conditions necessary to the existence of a geothermal field. Based on this policy, careful attention is given in Italy: to reduce the research cost and risk; to extend geothermal investigations to new and wider areas; to obtain higher efficiencies from the fluids exploited in the already known geothermal fields.

A new well with a flow rate of 326 t/h of superheated steam at 184 °C, 1 MPa and 12 % by mass of incondensable gas was put into production, in an area near Travale-Radicondoli (Tuscany) in 1972. A back-pressure unit rated 15 MW has come into operation in this area since July 1973.

A further possibility of increasing geothermal energy production in Italy depends on the replacement of exhausting-to-atmosphere units and the increase of the efficiency of the existing condensing power plants. The new sets installed recently at Larderello (e.g. Ciapica 1970) ensure a fluid consumption of less than 9 kg per net kW h at the station terminals. If an average specific steam consumption for the areas of Larderello and M. Amiata of 10.5 kg of fluid per kW h can be reached, (which seems a reasonable target) a 12 % increase in output could be attained.

In June 1973 the 'Alfina 1' well, drilled in an area near Acquapendente (Monti Volsini), has resulted in a powerful jet of gas and steam. It is planned that deep drilling will proceed in this area in the near future, and a 15 MW unit will be installed with the same characteristics as that recently installed at Travale-Radicondoli.

New sources discovered in the Larderello region are being initially utilized in back-pressure units. For a better utilization of these new sources a 15 MW condensing turbo-generator is being added to the Serrazzano power plant. This unit will come into operation in 1975.

As regards the availability of the primary energy source, it is worth recalling that the total

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increase of fluid obtained in recent years in the Larderello and M. Amiata regions was achieved only with difficulty, owing to the fact that the limits of production potential have been reached. Therefore, any future and substantial increase in fluid production is closely dependent on the discovery of new geothermal fields in the other Italian regions where research and exploration are in hand.

In the *U.S.A.* research is being carried out in several areas and the investment of considerable capital is foreseen for the future. In the Geysers area, the current schedule calls for startup of units 9 and 10 at the end of this year. The connecting pipelines are being laid and will be ready to deliver steam at the required times; these units will add another 106 MW to the capacity of the existing power plants. Applications for permission to build units 11 and 12 have already been sent to the California Public Utilities Commission. These units are scheduled for construction in 1974 and 1975, respectively. Each one of the latter units will be rated 106 MW net, thus bringing the total installed capacity of the Geysers area up to more than 600 MW. This capacity could produce electric energy sufficient for the needs of a city like San Francisco (Thermal Power 1973).

Geothermal projects have already been started in other areas, like Brady's Hot Springs in Nevada, Klamath Falls in Oregon, Imperial Valley in California, etc.

It was estimated that the Nation's geothermal resources could supply 132000 MW by 1985 and 395000 MW by the year 2000 if an intensive programme of research was developed quickly (U.S. Department of Interior 1972).

In *New Zealand* attention is focused on the recently discovered Broadlands field, which has an estimated potential of 120 MW.

In *Mexico* research and drilling on the producing field of Cerro Prieto are in progress. The estimated potential of the field is such as to allow doubling the present 75 MW capacity in the near future. New research programmes are being developed at Pathé, Los Negritos and Ixtlan de los Hervores.

The *Japan* National Natural Resources Committee estimated that it is possible to develop between 30000 and 50000 MW of geothermal power in Japan. The Committee reports that the current state of geothermal electric energy development in Japan is as follows: (1) in the Hachimantai area a 10 MW turbine-generator set, which will be in operation by the end of 1973, is now being installed; (2) at Onikobe, in the Tohoku District, an initial 25 MW power plant is being built; (3) at Katsukonda, Japan Metals and Chemical Co. has successfully delineated a new geothermal field and plans to install 200 MW in four sets rated 50 MW each; (4) at Hatchobaru, near Otake, an initial 50 MW geothermal units is scheduled for operation in 1975. A possible increase up to 200 MW is foreseen.

In the *U.S.S.R.* research has been extended to wide regions of the country and, according to Soviet experts, a possibility of step by step increase of approximately 100 MW is foreseen in the near future.

In *El Salvador*, the first research stage at Ahuachapan is practically completed and a first unit rated 30 MW is under construction. It represents part of a power station that is planned to reach 90 MW at least by 1978.

The government of the *Philippines* constituted a panel to negotiate a loan from New Zealand for the development of geothermal energy in Leyte. Preliminary studies showed that the geothermal energy sources in Tongonan, Buravan, and Leyte can generate 100 MW of power sufficient to supply Leyte and Samar in the near future.

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In the *South Sulawesi* (*Indonesia*) it is expected that nearly 250 MW can be generated from nine geothermal fields initially. The exploitation of hot waters, which are present in large areas of all the continents, is also important for geothermoelectric production and offers wide prospects for the future. In order to utilize the energy contained in the thermal waters, experiments have been carried out and pilot plants are being designed in many countries of the world.

In Italy an experimental small-capacity ethyl-chloride plant was operated for a short time in 1942 on the Ischia Island using the geothermal fluids there. In these last two years an experimental gravimetric loop has been under construction, working on the principle of the circulation due to the weight difference of two columns of fluids in a closed two-phase (Water-Freon 11) loop. This equipment will use a normal hydraulic turbine rated 1000 kW (Pessina, Rumi, Silvestri & Sotgia 1970).

In the U.S.S.R. experiments with the Freon hot-water plant installed near the Paratunka river are continuing: prospected reserves of thermal waters over the range of temperature from 50 to 200 °C have been tentatively estimated in U.S.S.R. as being over 8×10^6 m^3/day (Tikhonov & Dvorov 1970).

In the United States, power plants using pressurized geothermal fluids pumped through a heat exchanger (which utilizes isobutane as a working fluid) are being designed. These plants would harness the hyperthermal waters of the Salton Sea and Brady's Hot Springs geothermal fields, where 50 MW and 10 MW are scheduled respectively for 1978.

In brief, the proposed increases in geothermoelectic capacity in the world in the next years can be summarized as follows:

Italy			
Travale-Radicondoli	15 MW		started on 4 July 1973
Serrazzano	15 MW		start in 1975
efficiency improvement of existing units	—	45 MW	in the near future
Alfina	15 MW		start in 1976
U.S.A.			
The Geysers units 9 and 10	106 MW		start in 1973
The Geysers units 11 and 12	212 MW		start in 1975
Salton Sea and Brady's Hot Springs	60 MW		start in 1978
New Zealand			
Broadlands field	120 MW		start in 1976
Mexico			
Cerro Prieto	75 MW		start in 1980
Japan			
Hachimantai	10 MW		start in 1974
Onikobe	25 MW		start in 1975
Hatcobaru	50 MW		start in 1975
Hatcobaru	—	150 MW	in the near future

Katsukonda	50 MW		start in 1977
Katsukonda	—	150 MW	in the near future
U.S.S.R.			
Kamchatka	50 MW		start in 1980
Kamchatka	—	50 MW	in the near future
El Salvador			
Ahuachapan	30 MW		start in 1975
Ahuachapan	60 MW		start in 1977
Philippines			
Leyte	30 MW		start in 1978
Leyte	—	70 MW	in the near future
Indonesia			
South Sulawesi	—	250 MW	in the near future
total prospected increase	923 MW +	715 MW	

The total geothermal world's capacity of power plants is therefore expected to double and perhaps to triple in the near future, if the scheduled installations will actually be constructed.

Geothermal energy also offers interesting prospects for the so-called 'multiple uses' of natural fluids. The future geothermal development strategy may be directed towards the installation of multi-purpose plants, capable of producing power, drinkable water, valuable minerals, etc.

Finally, it is worth while to recall a recent research programme which is aimed at increasing the supply of geothermal energy. This programme is based on the possibility of extracting thermal energy from the Earth's crust in areas where hot, but essentially dry, rocks can be found at depths less than 6 km. The method of extracting geothermal energy from these areas is really quite simple, since it attempts to reproduce artificially by hydraulic fracturing the heat-transfer mechanism of natural geothermal systems. The water to increase the permeability in this closed-loop system would be maintained in the liquid phase by applying an adequately high pressure (Brown, Smith & Potter 1972).

In conclusion, future geothermal development strategy may be directed first towards the installation of as many as possible electric power stations: since these plants operate on an endogenous energy source, taken from wet and/or dry fields, no foreign exchange costs for importing fuel arise.

In addition to this main use, there are other applications which include the exploitation of terrestrial heat for the heating of houses and other buildings, soil and greenhouses for horticultural purposes, for crop drying, air conditioning and the breeding of animals. Also the installation of multi-purpose plants, capable of simultaneously producing power, drinking water and valuable minerals is being actively considered.

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Discussion

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The geological factors necessary for hot water, wet steam or dry steam hydrothermal fields are essentially similar to those required for hydrocarbon fields – reservoir rocks, cap rocks and structural conditions suitable for the migration and entrapment of fluids. The additional requirement of a source of natural heat of great output which is confined to late Tertiary and recent volcanic belts greatly limits the exploration field and also introduces exploration difficulties due to structural and lithological variations. Those who wish for a general introduction to the subject of geothermal energy and its possibilities will find it useful to read no. 12 of the UNESCO Earth Sciences series under that title, Paris 1973. This contains 15 papers written by a team of international experts.

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