International Developments in Geothermal Power Production

by
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Abstract

Geothermal energy is recognized today as the only one of the so-called alternate renewable energy resources that has proven itself technically and economically, and that is commercially available for electric power production. Seventeen countries now operate geothermal power plants. The total installed capacity is 5 gigawatts, with individual units ranging in size from a few hundred kilowatts to 135 megawatts. The identified but as yet untapped reserves are measured in the tens of gigawatts; the ultimate resource is immense. In this article, we trace the origins of geothermal power, following its growth from about the year 1900. We identify major milestones in the development of the technology, present a snapshot of the state of development around the world as of 1987 and look to the future for possible growth scenarios.

Humble Beginnings

The "chuff-chuff-chuff" of the tiny steam engine went unnoticed by the inhabitants of the small Italian town on that Friday, 15 July 1904. But history was being made. Geothermal energy was, for the first time, being harnessed to produced electricity.

The place was a Tuscan town situated among rugged hills that hissed and roared with the furious force of steam issuing from deep within the earth. The inventor was Prince Piero Ginori Conti, the son-in-law of Florestano Larderel, himself a descendant of Francesco Lardel, the executive manager of the original boric acid company founded there in 1818. The town became known as "Larderello."

Thus, the operation of that tiny 10 kilowatt (kW) dynamo, driven by a one cylinder engine fed with pure steam raised in a boiler heated by geothermal steam, marked the beginning of the modern geothermal age. For more than half a century, Italy remained the only country putting natural steam to use for power generation. During that time, Italian engineers and scientists developed the methods and the technology to improve the utilization of this resource (Burgassi, 1987).

Early Developments

Because the most common manifestations of geothermal energy are hot springs and steam vents, it is likely that early humans used geothermal energy for various simple purposes such as washing and cooking. Such uses would surely predate written records. We will begin our historical sketch with the advent of the modern age of technology, i.e., the age of the prime movers (Cardwell, 1972). Most people mark this period with Savery's invention of the steam-driven pump in 1698. This led to Newcomen's coal-burning steam engine in 1712. Crude but functional, Newcomen's engine was improved by others notably by Watt. By 1900, the steam engine had reached a reasonable level of efficiency. At first, the boilers were fired by wood or coal, and later by oil and gas. Conti's great contribution meant the elimination of the need for the burning of any fuel.

It is important to recognize that Conti did not inject geothermal steam directly into the cylinder of his engine, but rather used the steam as the heating medium to boil pure water. The clean steam generated in this process was used to power the engine. The natural steam was too contaminated for direct contact with the moving parts of the engine. Conti's first geothermal plant was, in today's nomenclature, a kind of binary plant — but one which used water as the working fluid. The other important difference between his binary plant and a modern one is that his ran on an open cycle whereas nowadays they operate as closed cycles (Milora and Tester, 1976).

The field at Larderello proved so prolific that steam could be won by relatively crude drilling techniques. Drill rigs with percussion tools struck the shallow steam zones in the volcanic formations. Rotary bits were developed later to drill to deeper depths and recover higher temperature steam. Centrifugal separators were installed to remove rock particles. Pipelines were designed and built to convey the steam from wells to the power plants with minimum losses. Valuable materials such as boron and ammonia were extracted from the geothermal fluids in the process of power generation. The enterprise flourished and the technology advanced (ENEL, 1970).

In the meantime, a few other countries, notably Japan, New Zealand and the United States, began to take notice of their geothermal resources (DiPippo, 1980). In 1925, a small experimental plant was constructed at Beppu on the Japanese island of Kyushu. The unit was rated at 1.12 kW; it was abandoned after a few tests. Also in the 1920s, attempts were made to develop The Big Geysers steam field in northern California and the Imperial Valley in southern California, but neither project proved successful. The first geological report on the spectacular volcanic region near Taupo on New Zealand's North Island was issued in 1937, but development would not take shape for another 20 years.

Thus by the time of World War II, the only geothermal power plants in the world were at Larderello and the surrounding towns. The installed capacity had grown to 132 megwatts (MW) by the end of 1943, and several types of power systems were in use depending on the characteristics of the particular steam wells. They were: (1) direct-intake, noncondensing plants for newly opened wells with high levels of noncondensable gases; (2) pure-steam condensing units with an integral reboiler that permitted the venting or recovery of noncondensable gases as well as mineral extraction from steam condensate; and (3) direct-steam units with condensers and integral turbo-compressors for the removal of noncondensable gases. The units ranged in size from 600 kW to 10 MW. The electricity from the Larderello plants powered a large portion of the Italian railway system. In 1944, practically the entire complex was reduced to rubble by demolition squads of the retreating armies. Only a tiny 23 kW training unit at Serrazzano escaped destruction. Within a year, the task of rebuilding the plants had begun and new plants were added. Today, Italy ranks fourth in the world in total geothermal power capacity. Several other fields are being explored and developed in a steady, systematic fashion.

In the 1950s, there was a resurgence of interest in geothermal energy in the United States, New Zealand and Japan. This time the efforts were crowned with success in each case. Exploration, drilling and testing resulted in the identification of several exploitable reservoirs. Not far from Taupo, the Wairakei power plant was built from 1956 to 1963, giving New Zealand a 192,600 kW facility, the first ever to be constructed at a liquid-dominated reservoir. The Pacific Gas and Electric Company (PG&E) inaugurated the geothermal age in the United States in 1960 with its 11,000 kW Geysers Unit No. 1. In 1951, the Japanese experimented with a 30 kW plant, the Hakuryu unit, near Beppu. In 1966, Japan became the fourth country to put geothermal energy to commercial use when the 22,000 kW Matsukawa plant came on line.

The other pioneering countries in geothermal power were: Mexico, which built a 3,500 kW plant at Pathe in 1959 (later decommissioned); the Soviet Union, which built two small plants on the Kamchatka peninsula in 1967; and Iceland, which built a small unit at Namafjall in 1968 (DiPippo, 1980).

Growth Pattern

Figure 1 shows the growth in installed geothermal power capacity from 1920 to the present. The first commercial-size unit came on line in 1913 at Larderello; it was rated at 250 kW. Growth was very strong in the first few decades, but settled down to an average annual rate of 7.9 percent between 1944 and 1960. From 1960 until 1978, the average growth rate slipped slightly to about 7.6 percent.

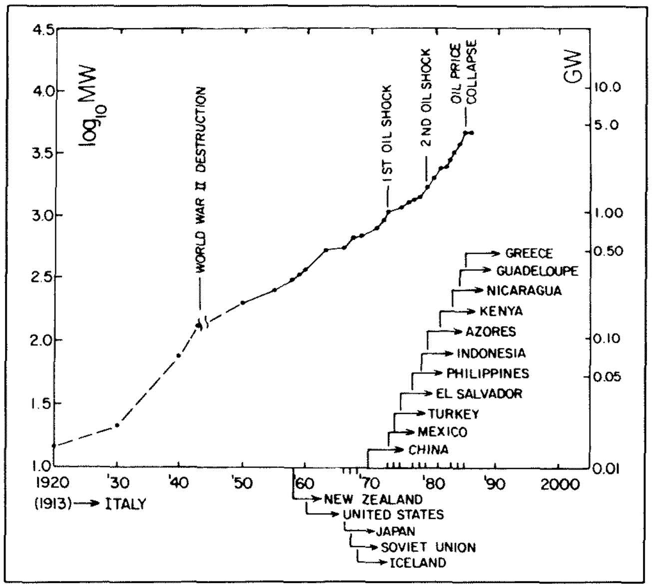

Figure 1. Growth pattern for geothermal power: installed megawatts versus year.

The most spectacular period of growth occurred from 1978 to 1985; the installed capacity grew at an average annual rate of about 17.2 percent. During this period, seven countries joined the ranks of geothermal power producers, raising the number of countries from 10 to 17. There is no question about the cause for this surge — the two oil shocks that hit in 1973 and 1979. The first shock spurred exploration for alternate, and in particular, indigenous and renewable energy resources; the second shock intensified that effort and led to the construction of geothermal plants in several countries seeking to reduce their dependence on imported oil and petroleum products.

In the United States, the dramatic jump in the price of oil had a very positive effect on geothermal development. At The Geysers, PG&E buys the geothermal steam it uses in its plants from the resource developers; the price is determined by a formula that incorporates the price for electricity generation by fossil and nuclear plants for the previous year Dutcher, 1976). For the years just prior to the first oil shock, PG&E had been paying about 0.27 mill/kWh; in 1973 and 1974, it paid an average of 0.34 mill/kWh. In 1975, the price jumped to 0.739 mill/kWh. This had a synergistic effect; more revenues for the resource developers meant more exploration and drilling at the same time that utilities were trying to move away from conventional oil-fired plants. Thus, more and larger plants were built at The Geysers while other areas in the country began to be developed, notably in the Imperial Valley.

The countries of Central America (DiPippo, 1986) along with Japan (Mori, 1985) and the Philippines (Tolentino and Buning, 1985), all heavily dependent upon foreign sources for their oil requirements, embarked on essentially crash programs to exploit their abundant indigeous geothermal energy resources.

In this crisis atmosphere, much was accomplished. The resource base was defined, methods of production and conversion were developed and improved, and international industry took shape, and many prospered. People around the world were afforded the benefits of reliable and inexpensive electricity, generated with minimal negative impact on the environment. Countries that are blessed with natural geothermal deposits now look to geothermal energy as an important component in their mix of generation sources. The integrated use of hydroelectric and geothermal plants is particularly attractive for many countries.

The essential role played by the United Nations as a catalyst for geothermal development must not be overlooked. In 1961 and again in 1970 and 1975, the U.N. sponsored landmark symposiums that brought together the world's experts on geothermal energy. The proceedings of these conferences form enduring references for those interested in the subject (United Nations, 1964, 1970, 1976). Besides these meetings, the U.N. funded and conducted reconnaissance studies in the 1960s that ultimately led to development projects in El Salvador, Turkey and Chile. During the 1970s, similar efforts resulted in projects in Kenya, Nicaragua, Ethiopia and India. All together, the U.N. has undertaken more than 30 projects in 20 countries throughout Europe, Asia, Africa, Central America, and South America. This important work is continuing today with the cooperation of third-party countries (Italy, Japan, Norway, and Sweden) that provide financial and technical assistance for particular projects (Berejick, in press).

Technical Milestones

Leaving aside the aforementioned pioneering works carried out in the early 1900s, the state of the art in geothermal power development has been advanced by the contributions of many individuals and companies from several countries. In this section, we highlight some of the most significant accomplishments.

First Deep Well at The Geysers

In 1955, B.C. McCabe formed the Magma Power Company and successfully drilled the first deep well (Magma No. 1) at The Geysers steam field in northern California (Anderson, 1986). The well was 249 m (817 ft.) deep, produced 18.9 kg/s (150,000 lbm/h) of dry steam at a wellhead pressure of 790 kPa (114 lbf/in^2), and had the capability to generate about 7 MW of electric power. Although it had been known since 1925, when a few shallow wells were drilled at The Geysers, that this was an excellent resource, Magma 1 really marked the beginning of its commercial phase of development.

First Commercial Plant at a Liquid-Dominated Reservoir

In 1958, the first turbine-generator unit, rated at 6.5 MW, was commissioned at the Wairakei power plant on the North Island in New Zealand. It was followed by 12 more units over the next 5 years, bringing the total installed capacity to 192.6 MW. Since the geofluid was a mixture of steam (and other gases) and liquid (mostly water but with a number of dissolved solids), an elaborate fluid gathering system was required to process the mixture in order to separate the steam from the rest. An array of separators, flash vessels, holding tanks, silencers and pipelines were designed and constructed for this purpose. These designs became accepted as industry standards for numerous other plants around the world and established the New Zealanders as among the chief geothermal experts (Thain and Stacey, 1984).

First Geothermal Power Plant in the United States

On 25 September 1960, the PG&E commissioned its Geysers Unit 1, an 11 MW dry-steam plant (Bruce, 1964). The capital cost was $182/kW; the plant is still in operation. Although the technology needed to tap the steam field was not highly sophisticated, the significance of Geysers 1 lay in establishing confidence among utilities in geothermal energy as a reliable and inexpensive source of electricity. This pathfinder power plant was recognized by the American Society of Mechanical Engineers in October 1985 as a National Historic Mechanical Engineering Landmark. Today, PG&E operates 19 units at The Geysers, having a combined installed capacity of 1,361 MW. Furthermore, there are five other utilities or companies involved at The Geysers either operating or constructing plants, with a total capacity of 557 MW.

First Large Binary Geothermal Plant

In September 1979, the Magmamax Power Plant (now named the B.C. McCabe Unit 1) began operating at the East Mesa geothermal field in California's Imperial Valley. The plant uses a process developed and patented by the Magma Power Company (U.S. Patent No. 3,757,516) which involved pumping the hot geofluid out of the reservoir, maintaining pressure to prevent flashing, passing the liquid through a bank of heat exchangers in which a secondary working fluid (isobutane) is evaporated, and then returning the cooled geofluid to the reservoir by means of injection wells. The secondary fluid passes through a more-or-less conventional, closed Rankine cycle. The plant was rated at a nominal 10 MW. Although the original design was not entirely successful (subsequent modifications have significantly improved performance, Hinrichs, 1984), this plant served as proof of concept, proof of engineering viability, and led to a variety of types of binary plants, both larger and smaller, which are now in operation at many sites. The chief advantages of a binary-type plant

Table 1. GEOTHERMAL POWER PLANTS ON LINE AS OF 1987

Country	Type of Power Plant								Totals	
	Dry Steam		1-Flash		2-Flash		Binary			
	NPU	MWe	NPU	MWe	NPU	MWe	NPU	MWe	NPU	MWe
United States	28	1918	4	45.5	5	136.5	55	111.85	92	2211.85
Philippines	0	0	23	894	0	0	0	0	23	894.0
Mexico	2	10	9	175	5	470	0	0	16	655.0
Italy	41	499.7	1	4.5	0	0	0	0	42	504.2
Japan	1	22	6	88.1	2	105	0	0	9	215.1
New Zealand	0	0	1	10.0	9	157.2	0	0	10	167.2
El Salvador	0	0	2	60	1	35	0	0	3	95.0
Indonesia	3	85.25	1	2	0	0	0	0	4	87.25
Kenya	0	0	3	45	0	0	0	0	3	45.0
Iceland	0	0	4	11	1	28	0	0	5	39.0
Nicaragua	0	0	1	35	0	0	0	0	1	35.0
Turkey	0	0	1	20.6	0	0	0	0	1	20.6
China	0	0	6	4.886	3	9	6	0.7	15	14.586
Soviet Union	0	0	1	11	0	0	0	0	1	11.0
France (Guadeloupe)	0	0	0	0	1	4.2	0	0	1	4.2
Portugal (Azores)	0	0	1	3	0	0	0	0	1	3.0
Greece	0	0	1	2	0	0	0	0	1	2.0
TOTALS:	75	2534.95	65	1411.586	27	917.9	61	106.55	228	5003.986

NOTES: NPU = Number of Power Units; MWe = Installed Megawatts-electric
Totals include plants under construction and scheduled for completion in 1987.

Table 2. GEOTHERMAL POWER PLANTS UNDER CONSTRUCTION OR IN ADVANCED PLANNING

Country	No. Units	Total MWe
United States	49	435.74
Philippines	3	147.5
Mexico	15	370
Italy	19	555
Japan	4	138
New Zealand	4	116.2
El Salvador	5	75
Indonesia	5	275
Nicaragua	1	35
Soviet Union	4	80
Portugal (Azores)	1	10
Costa Rica	1	55
Guatemala	1	15
Romania	1	1
India	1	1
TOTALS:	114	1754.44

TABLE 3. GEOTHERMAL POWER PLANTS IN THE UNITED STATES

Plant Location	No. Units	Total MWe
The Geysers/CA	28	1918.0
East Mesa/CA	27	36.5
Salton Sea/CA	2	44.5
Heber/CA	2	94.0
Mammoth/CA	2	7.0
Wendel/CA	2	0.6
Coso/CA	1	27.0
Puna/HI	1	3.0
Wabuska/NV	2	1.2
Beowawe/NV	1	17.0
Brady/NV	1	6.0
Steamboat/NV	10	19.0
Desert Peak/NV	1	9.0
Soda Lake/NV	3	2.75
Empire Farms/NV	4	3.6
Milford/UT	1	20.0
Cove Fort/UT	4	2.7
TOTALS:	92	2211.85

are its ability to use relatively low-temperature fluids (thereby increasing the number of geothermal fields that may be considered for electric power generation) and the very low impact on environmental quality (owning to the closed-loop nature of the operation).

First Plant to Operate Successfully on Hypersaline Brines

In July 1982, the Salton Sea Geothermal Electric Project, a 10 MW flash plant, started producing electricity from brines that contained about 230,000 ppm of dissolved solids (Moss and others, 1982). These brines has been nortorious for causing severe and rapid scaling of pipes and other equipment. Although these brines were hot, roughly 246°C (475°F), they had resisted exploitation until the Salton Sea plant came along. The milestone development that led to the success of this plant was the adoption of flash-crystallizer and reactor-clarifier technology to the handling and treatment of the brines (Featherstone and Powell, 1981). It now appears technically feasible to exploit the vast resource, estimated at 3,000 MW, at the Salton Sea geothermal field. Larger plants are now in operation and under construction utilizing the new technology (Hodgson, 1985).

State of Geothermal Development Worldwide

Table 1 summarizes the state of geothermal power development around the world as of this writing (mid-1987). Table 2 shows where plants are either under construction or in the advanced planning stage. Detailed listings of plants, country by country, are given in Tables 3-18. The geographical distribution of plants and promising sites are depicted on Figures 2-19.

These tables and figures are self-explanatory and require no further elaboration.

Power Plant Performance

By "performance" we mean: efficiency and reliability. The former is a measure of how well the plant converts the available energy in the geofluid to electricity; the latter is a measure of the amount of time the plant is up and producing or ready to produce power. In general, geothermal plants score very well on both counts.

It is not possible to present performance figures on all the plants listed under the previous section in this article (even if data on all plants were available); however, a few plants merit special attention.

With regard to **dry steam plants**, we may focus on those at The Geysers. The efficiency of the plants is often characterized by a specific steam consumption of about 8 kg/kWh (18 lbm/kWh). This measure may serve a purpose at a particular field (where steam conditions are reasonably uniform), but is a poor measure when plants at different fields are compared. A consistent and thermodynamically correct method is to use the **utilization efficiency** based on the Second Law of Thermodynamics (DiPippo and Marcille, 1984). On this basis, PG&E Geysers Unit 14, for example, has an efficiency of 56.3 percent; it consumes 7.45 kg/kWh (16.4 lbm/kWh) of saturated steam at 179°C (355°F). The efficiency is relative to a dead state at 18.3°C (65°F). These figures are typical for PG&E units.

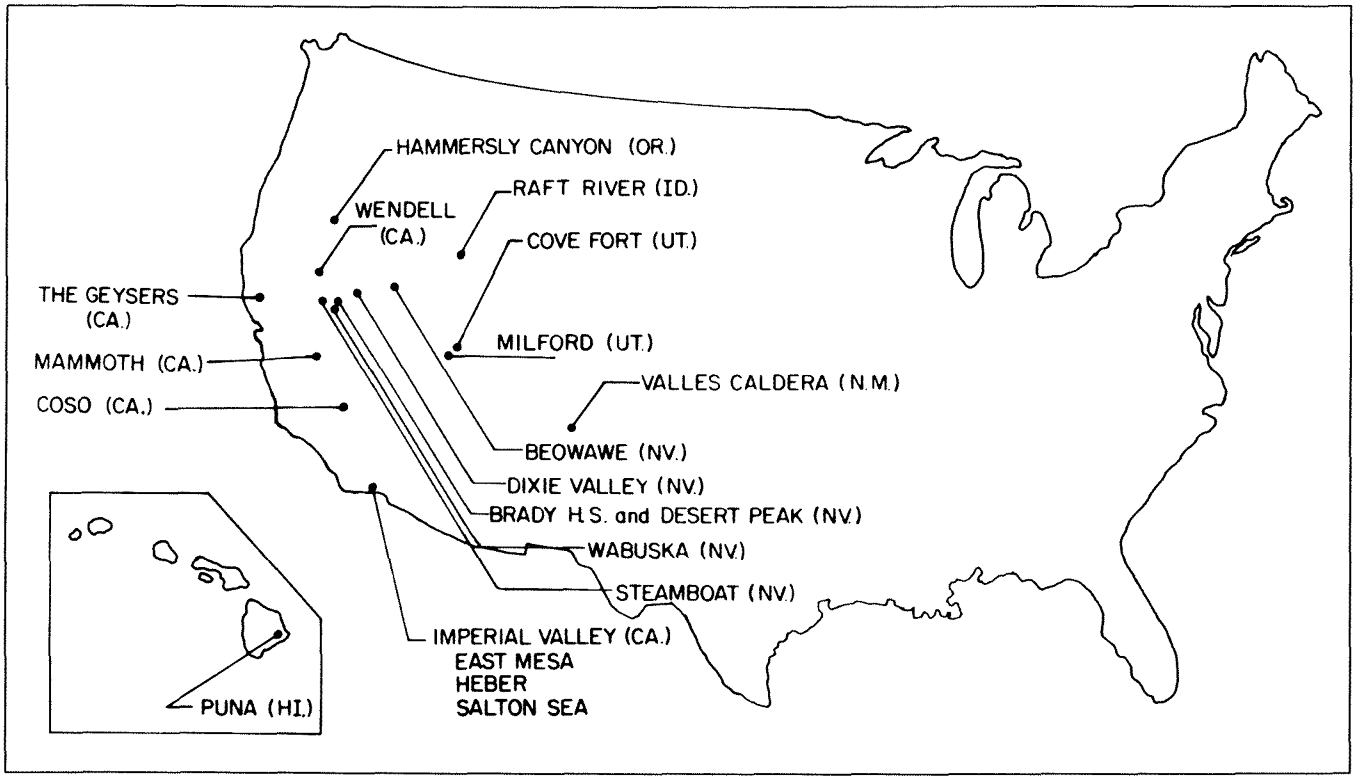

Figure 2. Geothermal plant sites/prospects in the United States. General note for Figures 2-19: Geothermal sites are denoted by filled-in circles; cities by open circles.

Table 4. GEOTHERMAL POWER PLANTS IN THE PHILIPPINES

Plant/Location	No. Units	Total MWe
Tongonan/Leyte	4	115.0
Tiwi/Luzon	6	330.0
Mak-Ban/Luzon	6	330.0
Palimpinon/S. Negros	7	115.0
TOTALS:	23	894.0

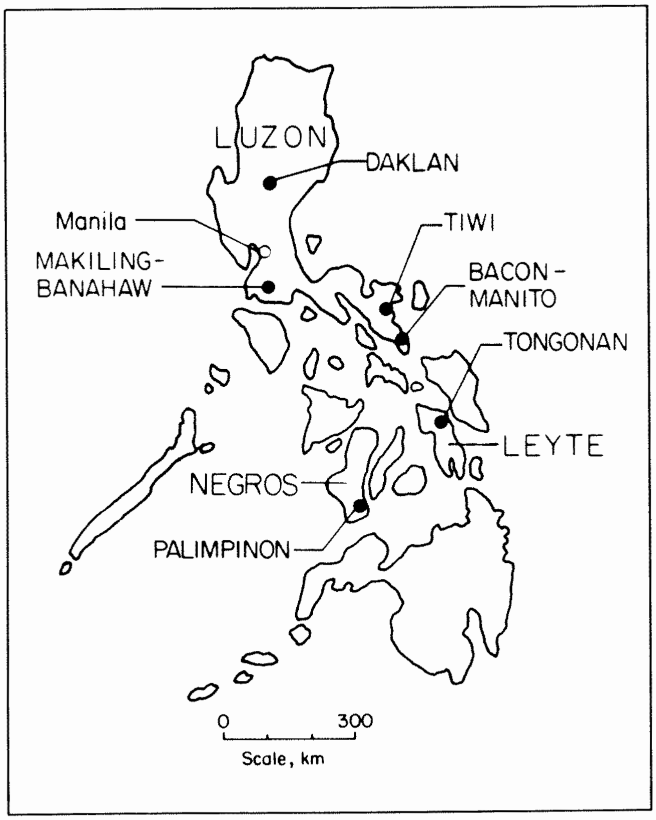

Figure 3. Geothermal plant sites/prospects in the Philippines.

Table 6. GEOTHERMAL POWER PLANTS IN ITALY

Plant/Location	No. Units	Total MWe
Larderello/Tuscany	34	429.7
Travale/Tuscany	3	48.0
Mt. Amiata/Tuscany	3	22.0
Latera/Latium	1	4.5
TOTALS:	41	504.2

TABLE 5. GEOTHERMAL POWER PLANTS IN MEXICO

Plant/Location	No. Units	Total MWe
Cerro Prieto I/Baja CA	5	180.0
Cerro Prieto II/Baja CA	2	220.0
Cerro Prieto III/Baja CA	2	220.0
Los Azufres/Michoacan	7	35.0
TOTALS:	16	655.0

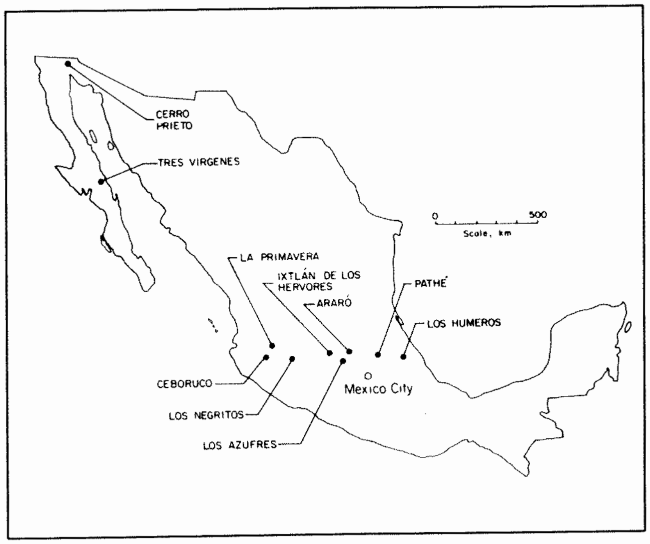

Figure 4. Geothermal plant sites/prospects in Mexico.

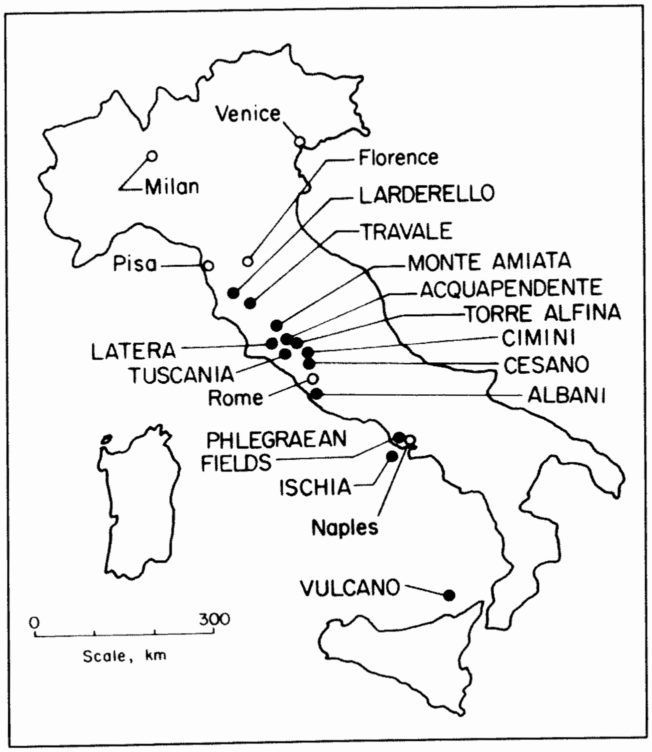

Figure 5. Geothermal plant sites/prospects in Italy.

It is interesting to compare these results with those of the SMUDGEO No. 1 plant, owned and operated by the Sacramento Municipal Utility District (SMUD), also located at The Geysers. This plant has an efficiency of 70.2 percent and consumes 6.17 kg/kWh (13.6 lbm/kWh) of slightly superheated steam. The SMUDGEO unit is designed for high efficiency because the price SMUD pays for its steam is commodity based, i.e., dollar/mass of steam, and therefore SMUD can afford to build a more efficient (and more costly) plant so as to extract a higher fraction of the available energy of the steam. As mentioned earlier, PG&E pays for its steam on a dollar/kWh-generated basis which leads to a different optimum plant cost and a different (less efficient) design.

Table 7. GEOTHERMAL POWER PLANTS IN JAPAN

Plant/Location	No. Units	Total MWe
Matsukawa/Honshu	1	22.0
Otake/Kyushu	1	12.5
Onuma/Honshu	1	10.0
Onikobe/Honshu	1	12.5
Hatchobaru I/Kyushu	1	55.0
Kakkonda I/Honshu	1	50.0
Suginoi/Kyushu	1	3.0
Mori/Hokkaido	1	50.0
Kirishima/Kyushu	1	0.1
TOTALS:	9	215.1

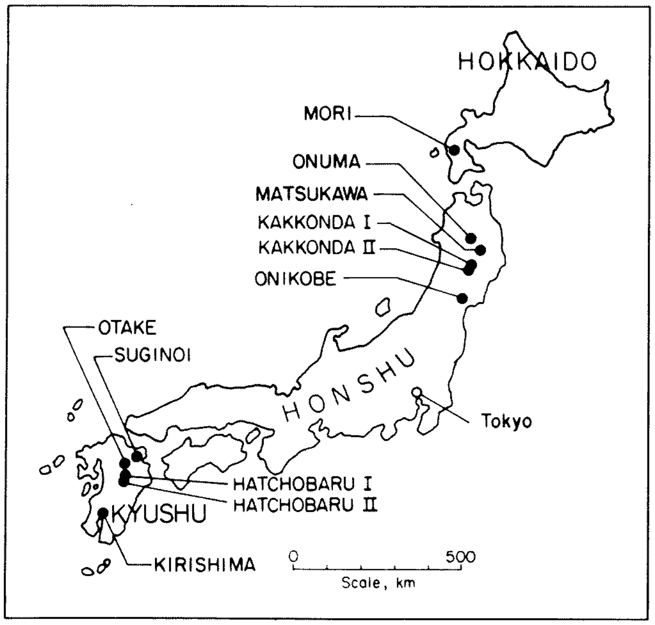

Figure 6. Geothermal plant sites/prospects in Japan.

Table 9. GEOTHERMAL POWER PLANTS IN CENTRAL AMERICA

Plant/Country	No. Units	Total MWe
Ahuachapan/El Salvador	3	95.0
Momotombo I/Nicaragua	1	12.5
TOTALS:	4	130.0

The entire PG&E geothermal power plant complex (19 units, 1,361 MWe) recorded an adjusted capacity factor of 81.4 percent for the year 1985 (Williams, 1986). In the first year of its operation (Dec. 1983 - Nov. 1984), the SMUDEGO No. 1 plant achieved an adjusted capacity factor of 93.6 percent. This "adjusted" capacity

Table 8. GEOTHERMAL POWER PLANTS IN NEW ZEALAND

Plant/Location	No. Units	Total MWe
Wairakei/North Island	9	157.2
Kawerau/North Island	1	10.0
TOTALS:	10	167.2

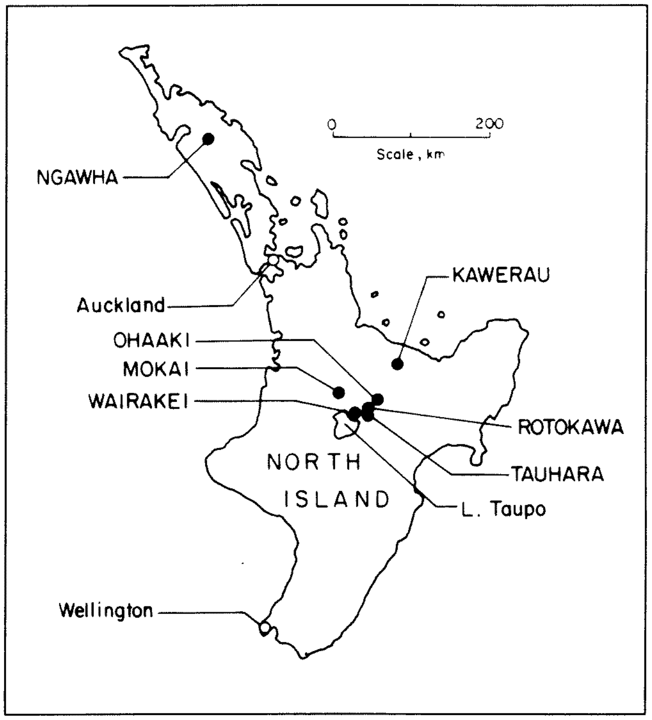

Figure 7. Geothermal plant sites/prospects in New Zealand.

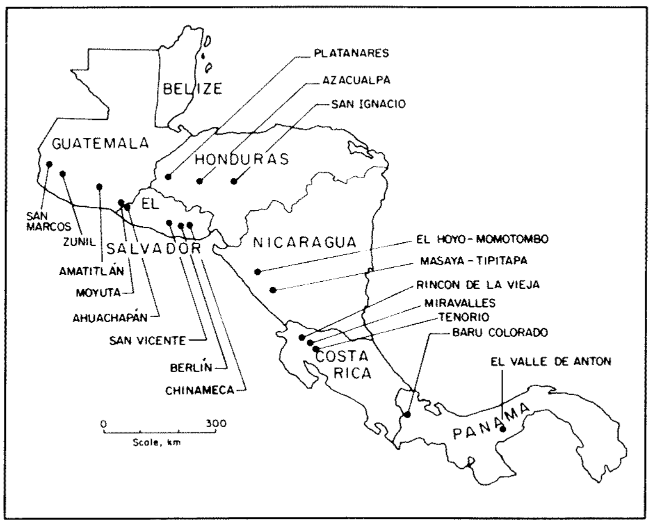

Figure 8. Geothermal plant sites/prospects in Central America.

factor takes into account curtailments ordered because of excess hydroelectricity generation in the system.

With regard to **flash-steam plants**, the slate of plants in Japan makes for an interesting study. There are nine plants on line (See Table 7), eight of which are flash plants (six single-flash, two double-flash). The six single-flash plants have a combined capacity of 88.1 MW; the two double-flash plants generated 600,697,167 kWh, yielding a capacity factor of 77.8 percent; the double-flash plants (Hatchobaru and Mori) produced 637,134,000 kWh, for a 69.3 percent capacity factor. The Hatchobaru plant operated 100 percent of the time and had a capacity factor of 94.2 percent (Mori, 1985). Thermodynamically, the Kakkonda single-flash plant operated at 50 MW and required 70 kg/kWh (154 lbm/kWh) of geofluid, 14 percent (wt) of which is steam. The utilization efficiency is 20.7 percent. The Hatchobaru double-flash plant operated at 55 MW, required 17 kg/kWh (37.5 lbm/kWh) of geofluid, 33 percent (wt) of which is steam, and had an efficiency of 53.8 percent.

Table 10. GEOTHERMAL POWER PLANTS IN INDONESIA

Plant/Location	No. Units	Total MWe
Kamojang/Java	3	85.25
Dieng/Java	1	2.0
TOTALS:	4	87.25

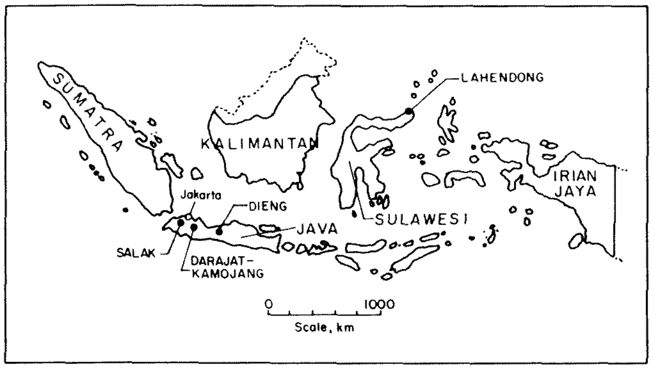

Figure 9. Geothermal plant sites/prospects in Indonesia.

Table 11. GEOTHERMAL POWER PLANTS IN KENYA

Plant/Location	No. Units	Total MWe
Olkaria/Rift Valley	3	45.0

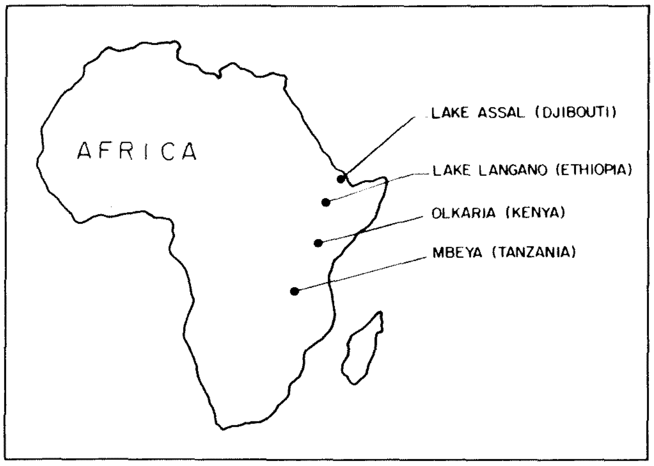

Figure 10. Geothermal plant sites/prospects in Africa.

Table 12. GEOTHERMAL POWER PLANTS IN ICELAND

Plant/Location	No. Units	Total MWe
Namafjall/Myvatn	1	3.0
Krafla/Myvatn	1	28.0
Svartsengi/Reykjanes	3	8.0
TOTALS:	5	39.0

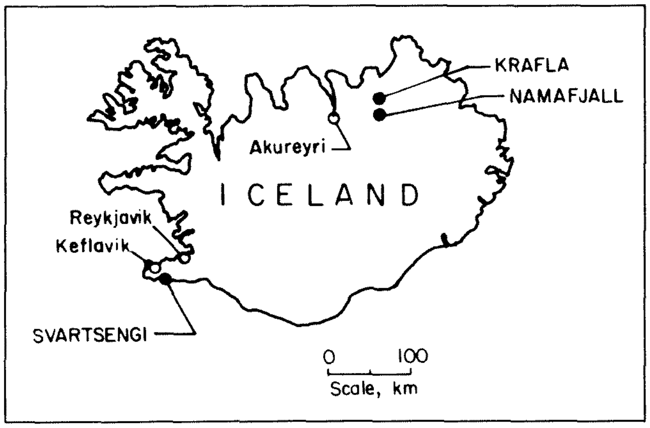

Figure 11. Geothermal plant sites/prospects in Iceland.

Table 13. GEOTHERMAL POWER PLANTS IN TURKEY

Plant/Location	No. Units	Total MWe
Kizildere/W. Anatolia	1	20.6

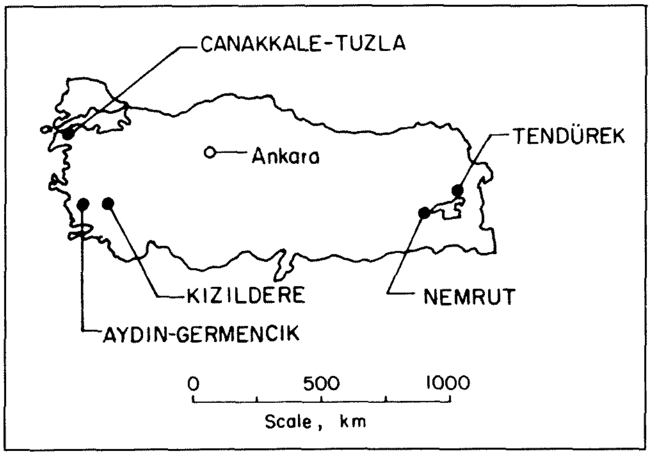

Figure 12. Geothermal plant sites/prospects in Turkey.

Table 14. GEOTHERMAL POWER PLANTS IN CHINA

Plant/Location	No. Units	Total MWe
Dengwu/Guangdong	3	0.586
Huailai/Hebei	1	0.20
Wentang/Jiangxi	2	0.10
Huitang/Hunan	1	0.30
Chingshui/Taiwan	1	3.0
Xiongyue/Liaoning	2	0.20
Yangbajing/Xizang	4	10.0
Zhaoyuan/Shandong	1	0.20
TOTALS:	15	14.586

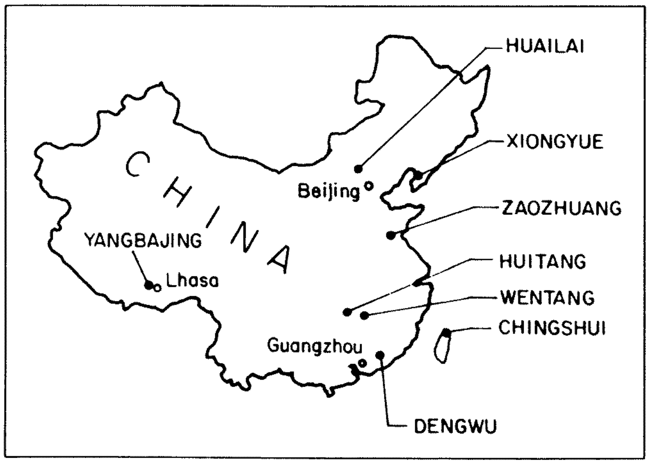

Figure 13. Geothermal plant sites/prospects in China.

Table 16. GEOTHERMAL POWER PLANTS IN GUADELOUPE

Plant/Location	No. Units	Total MWe
La Bouillante/Basse Terre	1	4.2

With regard to **binary plants**, there are fewer to examine as to performance. The world's largest plant, the Heber Demonstration Plant, has yet to achieve full output due to lack of brine supply. The specifications indicate that the plant should run at 75 kg/kWh (165 lbm/kWh) of brine at 182°C (360°F) and produce 46.6 MWe (net) from 70 MW (gross). This would represent a utilization efficiency of 33 percent (net). To date, the maximum reported output was as follows: 22 MW (gross), 10 MW (net), on a brine flow of 441 kg/s (3,500,000 lbm/h) at 181°C (358°F),(Solomon and Berning, 1987); this corresponds to an efficiency of 15.8 percent (net).

At the other end of the size spectrum, we may examine the 600 kW unit at Wabuska, NV. Data have been reported for the period August 1985 through March 1986 (Culver, 1987). The system (i.e., plant, well and auxiliaries) was available for 4,999.4 hours out of a total time of 5,832 hours, for an availability factor of 85.7 percent. The plant produced 2,117 MWh, for a capacity factor of 60.5 percent. A performance test conducted on 6-7 March showed the plant generating 0.755 MW (gross), 0.513 MWe (net), consuming 363 kg/kWh (800 lbm/kWh), and having a utilization efficiency of 19.3 percent (net).

It is worth noting that the overall utilization of a resource can be improved by the use of hybrid plants. Such plants may combine geothermal and fossil energy sources (Kestin and others, 1978), may integrate single- and double-flash plants (DiPippo, 1978), or may combine direct-heat uses with electric power production (DiPippo, 1987). While plants of this sort will always be advantageous thermodynamically, practical considerations may restrict their application.

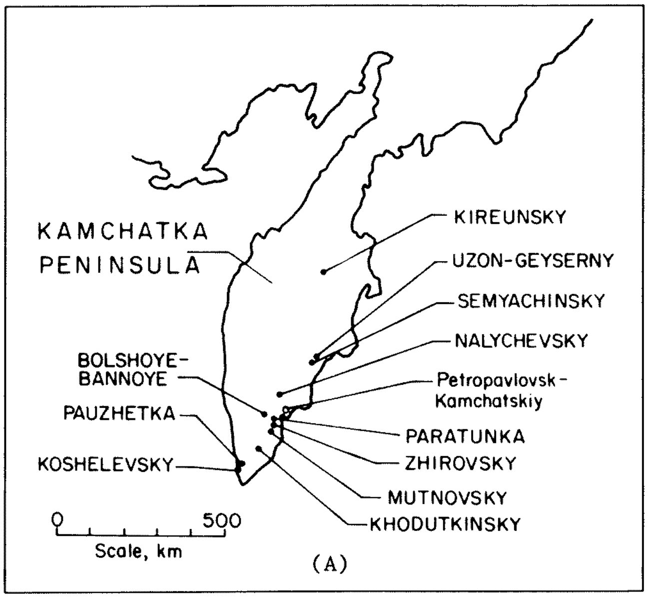

Figure 14a. Geothermal plant sites/prospects in the Soviet Union: Kamchatka Peninsula.

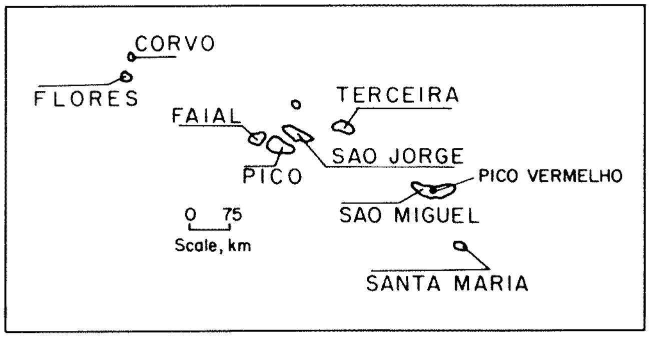

Figure 15. Geothermal plant sites/prospects in the Azores.

Table 15. GEOTHERMAL POWER PLANTS IN THE U.S.S.R.

Plant/Location	No. Units	Total MWe
Pauzhetka/Kamchatka	1	11.0

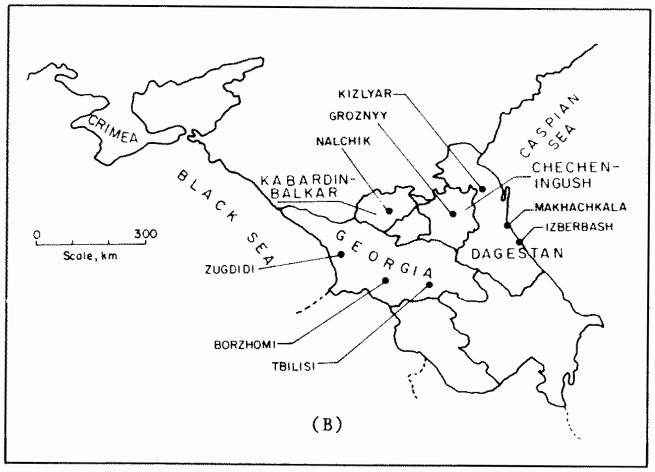

Figure 14b. Geothermal plant sites/prospects in the Soviet Union: Caucasus region.

Table 17. GEOTHERMAL POWER PLANTS IN THE AZORES

Plant/Location	No. Units	Total MWe
Pico Vermelho/Sao Miguel	1	3.0

Table 18. GEOTHERMAL POWER PLANTS IN GREECE

Plant/Location	No. Units	Total MWe
Milos	1	2.0

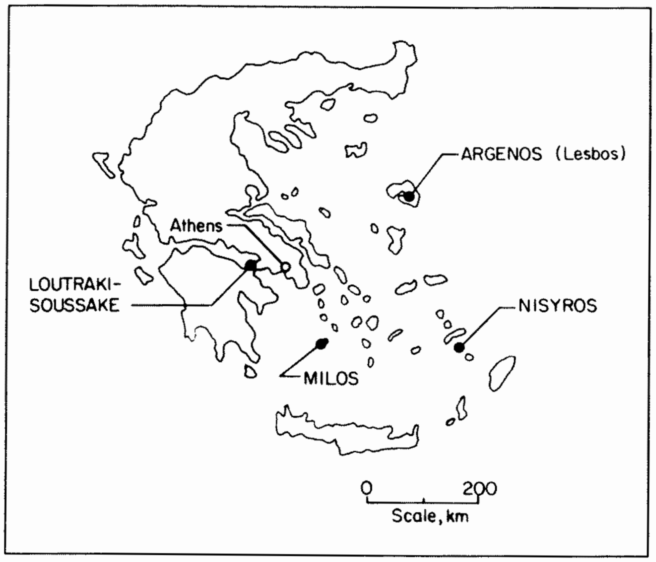

Figure 16. Geothermal plant sites/prospects in Greece.

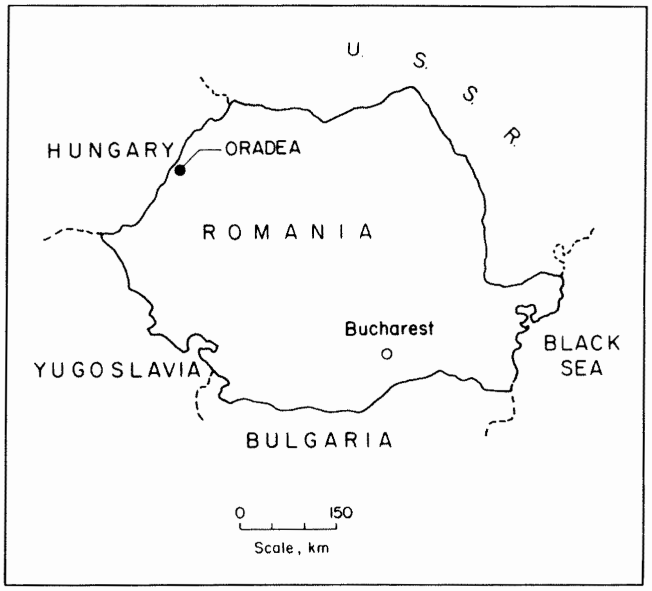

Figure 17. Geothermal plant sites/prospects in Romania.

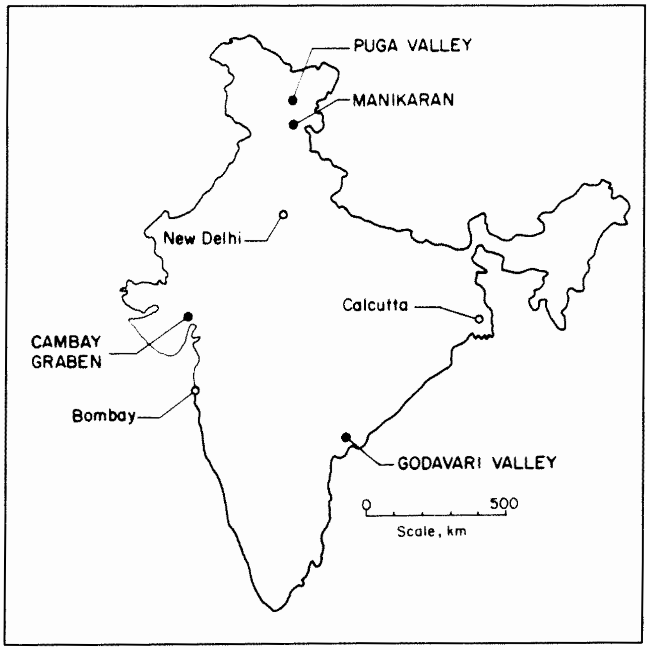

Figure 18. Geothermal plant sites/prospects in India.

The Future For Geothermal Power

We may estimate the growth of geothermal electricity over the next 5 years with the help of Table 2. The plants listed there should be on line within the next 5 years in most cases. If we allow for the usual delays and take only 75 percent of the expected new capacity, then about 1,315 MWe should be added by the year 1992. That would bring the total installed worldwide capacity to roughly 6,320 MW by then. The average annual growth rate over the next 5 years would thus be about 4.8 percent. The actual growth rate will depend on the world price of oil. If the price remains relatively low, i.e., $15-18/bbl, then the rate is likely to be less than 4.8 percent. If the price jumps abruptly to, say, $25-30/bbl, then there might be economic justification to accelerate construction of geothermal capacity, and the rate could climb to over 6 percent. If all the new capacity listed in Table 2 were to come on line in 5 years, the growth rate would be 6.2 percent.

Over the next 5 years, the ranking of the countries involved in geothermal power will change. Using Table 2 as a guide, the United States will retain its leadership with about 140 units on line producing roughly 2,650 MW. This will account for nearly 40 percent of the total geothermal power on line in the world, down 4 percentage points from the present. Italy may return to the second position, closely followed by the Philippines and Mexico. These four leaders will account for roughly 85 percent of all geothermal power capacity and 76 percent of all geothermal power units. There should be 21 countries on the list in 5 years, the four new additions being Costa Rica, Guatemala, Romania and India.

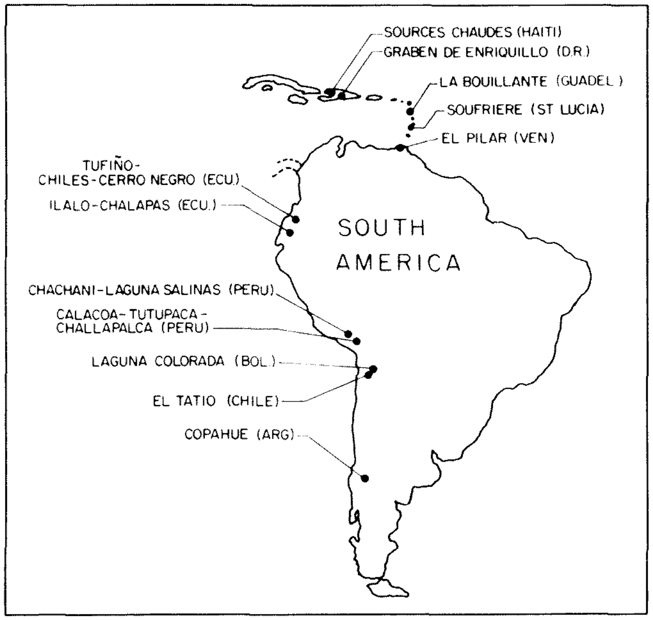

Figure 19. Geothermal plant sites/prospects in South America and the Caribbean.

Concluding Remarks

In conclusion, geothermal energy has developed as a reliable source of generating electricity wherever in the world thermal anomalies are found. There are many types of energy conversion systems proven for use with low-, medium- and high-temperature fluids, including ones with extremely high concentrations of impurities. In many cases, the performance of geothermal plants far exceeds industry norms for conventional plants. Geothermal energy is sure to continue to play an important role in meeting the generation requirements of many countries, particularly in a world of uncertain oil prices and supply.

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