Geothermal Energy Prospects for the Next 50 Years

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ABSTRACT

The material in this report was compiled for use in a report on unconventional energy resources prepared by the Conservation Commission of the World Energy Conference (WEC). Because of the necessity for brevity in the WEC report, much of the material was condensed. This report is being published for the benefit of those who may wish more detailed information.

Three facets of geothermal energy--resource base, electric power potential, and potential nonelectric uses--are considered, using information derived from three sources: (1) analytic computations based on gross geologic and geophysical features of the earth's crust, (2) the literature, and (3) a worldwide questionnaire. None of these sources either individually or in combination fully satisfy the need for information about the geothermal potential, but it is hoped that a more comprehensive assessment can be evolved as more data become available.

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SUMMARY

The penetration of any natural resource into the marketplace is a function of dynamic economic relationships that are sometimes difficult to determine in advance. The concept of reserves is intimately linked to these relationships, where reserve is that portion of the resource base known to exist and to be producible and marketable in competition with other resources. In the case of geothermal energy, neither the reserves nor the resource base is well known at this time. For the purpose of this report the prospects for worldwide geothermal energy utilization were investigated from two approaches. The first was based on projections made by professionals and organizations in various countries of the world, as reported in the literature and as reported in response to the EPRI questionnaire that was sent to member nations of the World Energy Conference and to many nonmember nations. The second approach was to estimate the potential for utilization based on geothermal, geologic, and geophysical parameters and engineering estimates of recovery and conversion efficiencies. The resulting data on potential geothermal energy utilization throughout the world are summarized in tables 1 and 2.

The geothermal resource base underlying the continental land masses of the world to a depth of 3 km and at temperatures higher than 15°C was calculated to be 1.2×10^{13} GWh (th). The sum of the estimates reported by individual countries was 5.8×10^{11} GWh (th). The difference lies in the gross assumptions of the general method used in the first approach, the general incompleteness of detailed assessments of geothermal potential, and conservative estimates of specific resources in individual nations. Only about 2% of the resource base is high enough in temperature to be considered for electric power generation, and only about 1 part in 10,000 can be converted to electric energy with present technology. Although the overall recovery and conversion efficiencies are very small, the electric energy potential with current technology is substantial, roughly 1.2×10^3 GW cen(e) (gigawatt-centuries, electric). The present worldwide, installed electric-power generating capacity is 1.325 GW (e).

Table 1

WORLDWIDE GEOTHERMAL ENERGY USE

<i>Source</i>	<i>Electric Capacity (GW)</i>			
	<i>1977</i>	<i>1985</i>	<i>2000</i>	<i>2020</i>
Literature and questionnaire	1.3	12	90	Not available
Calculation		170	500	1000
	<i>Thermal Capacity (GW)</i>			
	<i>1977</i>	<i>1985</i>	<i>2000</i>	<i>2020</i>
Literature and questionnaire	7.0	33	76	210
Calculation		25,000	80,000	120,000

Table 2
WORLDWIDE GEOTHERMAL RESOURCE BASE

<i>Class</i>	<i>Temperature (°C)</i>	<i>Resource Base^a (GWh [th])</i>	<i>Thermal Potential^b (GWh [th])</i>	<i>Electric Potential^b (GWh [e])</i>
1	< 100	1.05×10^{13}	7.3×10^{11}	0
2	100–150	1.07×10^{12}	7.5×10^{10}	0
3	150–250	2.7×10^{11}	1.9×10^{10}	4.8×10^9
4	> 250	1.4×10^{10}	9.7×10^8	2.5×10^8
Totals		1.2×10^{13}	8.2×10^{11}	5.1×10^9

^aResource base is the energy stored at temperatures above 15°C at depths to 3 km. The sum of individual country estimates is 5.8×10^{11} GWh (th).

^bIt is assumed that only about 20% of these quantities can be produced with current technology.

The potential for nonelectric uses is much greater than the potential for electric power generation in terms of total heat; but the growth of nonelectric applications may be slower than that of electric applications because of the necessity for compatible industries and for populations to be near the resource. However, geothermal energy is a truly international energy resource because it is present in all countries on earth. Thus, it should be carefully considered in the evaluation of alternative energy sources throughout the world.

Section 1

INTRODUCTION

Geothermal energy is the natural heat of the earth and is a truly international source of energy, available as an indigenous source of energy in all countries on earth. At present, geothermal energy is being sought primarily for the production of electric power, but its utilization in other forms, such as space and industrial heating, may be of great value in the economy of many nations seeking development of alternative energy sources and conservation of fossil and nuclear fuels.

Geothermal energy has been used for centuries. Early uses included space heating and therapeutic baths (balneology). Current applications include agriculture, municipal and industrial heating, and the generation of electric energy.

Attempts to harness geothermal energy to produce electric power date back to the beginning of this century. The first experimental electric power generator was operated at Larderello, Italy, in 1904, using natural geothermal steam that seeped through rock fractures to the surface. The first power plant was completed in 1913 in Italy, the pioneer in developing geothermal energy for power generation. In a number of other countries, including Japan, the United States, and Indonesia, attempts to develop geothermal energy for power production were made in the early 1920s. Geothermal energy developments have since occurred in a number of countries, reaching a total world electric capacity of about 1.3 GW in 1976. However, the incentive for developing geothermal energy was small when fossil fuel was inexpensive and presumed in abundant supply. Furthermore, energy planners have traditionally been reluctant to depend on an energy resource when its quantity could not be precisely predicted or its cost was not known well in advance. After the energy crisis of 1973, when fossil fuel costs rose markedly compared with the period immediately preceding the crisis, a reexamination of all existing energy resources brought about a renewed awareness and interest in geothermal energy for both electric and nonelectric uses.

This very large energy resource, available in one form or another in every country on earth, could play an increasingly important role in the overall energy supply. Some countries fortunate enough to be in the major geothermal belts of the world may be able to provide a significant portion of their energy requirements from geothermal resources. However, even countries in areas of normal temperature gradients may find that certain geologic, climatic, and economic circumstances may combine to create a favorable economic setting for utilizing hot subsurface water.

The purpose of this report is to review the prospects for geothermal energy over the next fifty years and to summarize its practical uses and future potential. The source material for the report includes information published in the open literature; responses to a questionnaire sent to member countries of the World Energy Conference and many nonmember nations; and a generalized analytic estimate of national resources, using uniform criteria. A comprehensive assessment of worldwide geothermal potential was prepared. The potential includes such factors as total stored energy above a specified temperature and depth (the resource base), actual utilization (to the extent reported), ongoing development, and prospects for the future.

Our knowledge about geothermal energy is still very limited. The information used in the compilation of this report was incomplete in many instances; an effort has therefore been made to indicate the sources as being either the survey questionnaire, the literature, or analytic derivation, including the underlying assumptions. It is hoped that this initial assessment will be of use to the nations of the world in their specific investigations of how geothermal energy can play a role in meeting world energy requirements.

Section 2

GEOHERMAL RESOURCES

Temperatures of the earth's crust increase with depth at varying rates, depending on location. The normal temperature gradient is about 25°C/km depth. Thus, in a region where the ambient surface temperature (mean annual temperature) is 15°C, it is expected that a random hole drilled to a depth of 1 kilometer will encounter a temperature of 40°C (the ambient temperature plus the temperature increase due to the normal temperature gradient in the region). However, in some regions of the world the temperature gradient is much greater than normal, increasing in places to a gradient as high as 1°C/m. In those areas associated with recent volcanism, relatively high temperatures may be encountered at shallow depth.

GEOHERMAL ENERGY RESOURCE TYPES

Geothermal resources are divided into three basic types: liquid-dominated and vapor-dominated hydrothermal systems; hot dry rock systems; and geopressed systems. These types are characterized by their thermodynamic and hydrologic properties, as discussed below.

Liquid-Dominated Systems

Liquid-dominated geothermal resources are those controlled by the presence of circulating liquids (water or brine) that can transport the thermal energy of the rock from deep regions to near-surface regions by natural circulation. The temperature of known liquid-dominated geothermal systems varies from ambient or slightly above to as high as 360°C. Most investigators agree that liquid-dominated resource types are far more abundant than the vapor-dominated ones. Certainly far more liquid-dominated systems have been discovered than vapor-dominated systems.

Usually the temperature in the best liquid-dominated geothermal regions increases rapidly with depth until the temperature reaches the boiling point of water. Further increases in temperature with depth will be slight until a depth is reached where liquid domination ceases. Temperatures seldom exceed the boiling point of water at prevailing hydrostatic pressures.

Vapor-Dominated Systems

Vapor-dominated systems, sometimes referred to as dry steam fields, are relatively rare. However, the most important and successful geothermal power developments in the world today are associated with the development of vapor-dominated systems (Larderello, Italy; The Geysers, California; and Matsukawa, Japan). In such systems the continuous phase within the pore space in the near-surface region is that of steam, while in the deeper regions water is presumed to be present. Temperatures are typically in the range of 220-150°C. Production of steam from this type of reservoir is relatively simple, and quite often a slight superheating of the steam occurs during production.

Hot Dry Rock Systems

Since temperatures increase with depth independent of hydrothermal convection, it is reasonable to assume that much more heat is stored in the rock matrix than in the circulating water. Since porosity generally decreases with depth, it may be further assumed that vast volumes of hot dry rock exist at greater depths within the earth's crust. Research efforts are under way to develop methods of introducing cold surface waters into such hot dry rock systems with natural or artificially induced fractures and extracting heated water through a pattern of holes drilled in the vicinity of the injection holes. Calculations suggest that the heat reserve in known geothermal systems is much larger than the heat contained in the fluids only. It is conceivable that many of the hydrothermal systems known today could become depleted of geofluids long before the heat reserve itself has been exhausted. Thus, it is possible that today's liquid-dominated geothermal systems may be further exploited as hot dry rock systems at some time in the future.

Geopressured Systems

Geopressured reservoirs are generally located in deep sedimentary strata in geologic regions where sediment compaction has taken place over geologic periods of time and where an effective shale cap has formed. Under conditions of shale compression, in which water is squeezed out of the shale matrix into adjacent sand bodies, an internal pressure greater than the ordinary hydrostatic pressure at that depth is imparted to the water. In extreme cases of geopressure, water pressures approach those of the overall weight of the overlying rocks (close to lithostatic pressure). This overpressured water system, known as a geopressured geothermal resource, is often characterized by higher-than-normal temperature gradients because of the increased specific heat capacity of the overpressured

rock-water system. Temperatures as high as 237°C have been encountered in some geopressured zones in the Gulf Coast of the United States, with wellhead pressures in excess of 7.6×10^7 Pa (11,000 psi). In addition, geopressured fluids typically contain anomalously high concentrations of dissolved methane gas. Practically all large synclinal basins of the world contain some geopressured zones. In the United States alone, geopressured geothermal resources cover an area of more than 200,000 km² in the states of Texas and Louisiana.

GEOGRAPHIC DISTRIBUTION OF GEOTHERMAL RESOURCES

Geothermal energy resources are concentrated to a large extent along certain well-defined belts, shown in Figure 1. These belts of higher geothermal potential are associated with earthquake activity and recent volcanism. These belts of high volcanic activity, seismicity, and hot spring activity are associated with geologic plate boundaries and cover approximately 10% of the earth's surface. The most outstanding geothermal belt of the world is the Circum-Pacific Belt (the so-called Belt of Fire). One branch of the belt extends through Central America to the western portion of South America and then to Antarctica. Another branch of the belt runs through the East Pacific region through New Zealand, New Guinea, and Indonesia and then branches out north, running through the Philippines, Japan, and Eastern Siberia; it then turns eastward through the Aleutians back to northern Canada. Another outstanding geothermal belt runs through East Africa, Ethiopia, Kenya, Tanzania, and gradually weakens southward. The western branch of the Circum-Pacific Belt extends through northern India, Iran, Turkey, and Greece. A continuation of that belt runs through Italy and probably through North Africa. The Mid-Atlantic Ridge Belt usually runs underwater. However, where islands have formed following volcanic eruptions associated with the separation of the major earth plates, considerable geothermal activity is to be found, as in Iceland or in the Azores chain. Geopressured resources are also abundant in many major sedimentary regions of the world, including the Gulf Coast of the United States, the North Sea, western India, and the Persian Gulf.

Source: Geonomics, Inc.

Figure 1 Geothermal regions of the world

GEOTHERMAL RESOURCE BASE

Analytic Estimates

Active geothermal exploration is proceeding in practically all countries that are crossed by the major geothermal belts. In many countries where fossil fuel resources are not known to exist or are in short supply, exploration of hot water resources for direct heat purposes is currently under way. Estimates of the geothermal resource base for member nations of the World Energy Conference and many nonmember nations were derived by a simple analysis involving a number of assumptions with respect to heat content and volumes of thermal resources. The results are given in Table 3.

Notation E in Table 3 represents the power of 10. For example, 2.4 E6 is equivalent to 2.4×10^6 . It is noted that the resource base in the $<100^\circ\text{C}$ class is by far the largest quantity. Although this class is too low in temperature for electric power generation, it may be useful for space heating and other direct heat uses, provided the economics of drilling and producing this portion of the resource is favorable in some particular regions of the world. The resource in the $100\text{--}150^\circ\text{C}$ class is not likely to be economical for electric power generation in many nations. However, this part of the resource can be used for direct heat uses. The total worldwide resource base (in the continental masses to 3 km depth) for these two temperature classes is 3.8×10^{25} and 3.8×10^{24} J, respectively. The resources in the $150\text{--}250^\circ\text{C}$ and $>250^\circ\text{C}$ classes are currently competitive with fossil fuels for electric power generation; the higher the temperature, the better are their thermodynamic and economic efficiencies. The resource bases in these two classes are 9.6×10^{23} and 5.0×10^{22} J, respectively. Assuming a commonly accepted average net electric power conversion efficiency of 3% of the gross heat, the total electric energy stored under these two classes is estimated as 9.6×10^3 GW cen (gigawatt-centuries).

Assumptions. The following assumptions were used in calculating the resource base:

1. All "normal" areas of the world have a vertical temperature gradient of $25^\circ\text{C}/\text{km}$ depth.

Table 3
CALCULATED WORLDWIDE GEOTHERMAL RESOURCE BASE
(joules)

<i>Country</i>	<i>Area (km²)</i>	<i>X</i>	<i>Resource Base in Temperature Classes (°C)</i>				<i>Total</i>
			<i><100</i> <i>(Class 1)</i>	<i>100-150</i> <i>(Class 2)</i>	<i>150-250</i> <i>(Class 3)</i>	<i>>250</i> <i>(Class 4)</i>	
Algeria*	2.4 E6	0.007	6.7 E23	3.6 E21	9.6 E20	5.9 E19	6.7 E23
Angola*	1.3 E6	0	3.5 E23	0	0	0	3.5 E23
Argentina*	2.8 E6	0.03	8.0 E23	1.8 E22	5.0 E21	2.9 E20	8.4 E23
Australia	7.7 E6	0	2.2 E24	0	0	0	2.2 E24
Austria	8.4 E4	0	2.4 E22	0	0	0	2.4 E22
Bangladesh	1.4 E5	0	4.0 E22	0	0	0	4.0 E22
Barbados*	4.3 E2	1.00	9.2 E19	9.6 E19	2.5 E19	1.5 E18	2.1 E20
Belgium	3.1 E4	0	8.8 E21	0	0	0	8.8 E21
Bolivia*	1.1 E6	0.30	2.9 E23	7.1 E22	1.9 E22	1.2 E21	3.8 E23
Brazil*	8.5 E6	0.05	2.4 E24	9.2 E22	2.5 E22	1.5 E21	2.5 E24
Bulgaria	1.1 E5	0	3.1 E22	2.4 E20	6.3 E19	4.0 E18	3.2 E22
Burundi*	2.8 E4	1.00	5.9 E21	6.3 E21	1.6 E21	1.0 E20	1.4 E22
Cameroon*	4.8 E5	0.10	1.3 E23	1.0 E22	2.8 E21	1.7 E20	1.5 E23
Canada*	1.0 E6	0.20	2.7 E24	4.6 E23	1.2 E23	7.1 E21	3.3 E24
Chad*	1.3 E6	0.10	3.5 E23	2.8 E22	7.5 E21	4.6 E20	3.8 E23
Chile*	7.6 E5	1.00	1.6 E23	1.7 E23	4.6 E22	2.7 E21	3.8 E23
China*	9.6 E6	0.25	2.6 E24	5.4 E23	1.4 E23	8.4 E21	3.2 E24

*Country is in conjectured geothermal belt, not yet proven by exploration.

Table 3 (continued)

Country	Area (km ²)	X	Resource Base in Temperature Classes (°C)				Total
			<100 (Class 1)	100-150 (Class 2)	150-250 (Class 3)	>250 (Class 4)	
Colombia*	1.1 E6	0.30	3.0 E23	7.5 E22	2.0 E22	1.2 E21	3.9 E23
Costa Rica	5.1 E4	1.00	1.1 E22	1.1 E22	3.0 E21	1.8 E20	2.5 E22
Cuba	1.1 E5	0	3.2 E22	0	0	0	3.2 E22
Cyprus	9.3 E3	0	2.6 E21	0	0	0	2.6 E21
Czechoslovakia*	1.3 E5	0.10	3.5 E22	2.8 E21	7.5 E20	4.6 E19	3.8 E22
Dahomey	1.2 E5	0	3.3 E22	0	0	0	3.3 E22
Denmark	4.3 E4	0	1.2 E22	0	0	0	1.2 E22
Dominican Rep.*	4.8 E4	0.25	1.3 E22	2.7 E21	7.1 E20	4.2 E19	1.6 E22
Ecuador	4.6 E5	1.00	1.0 E23	1.0 E23	2.6 E22	1.6 E21	2.3 E23
Egypt	9.5 E5	0	2.7 E23	0	0	0	2.7 E23
El Salvador	2.1 E4	1.00	4.6 E21	4.6 E21	1.2 E21	7.5 E19	1.0 E22
England	1.3 E5	0	3.7 E22	0	0	0	3.7 E22
Ethiopia	1.2 E6	0.60	3.0 E23	1.6 E23	4.2 E22	2.6 E21	5.0 E23
Fiji*	1.8 E4	0.20	5.0 E21	8.0 E20	2.1 E20	1.3 E19	5.9 E21
Finland	3.6 E5	0	1.0 E23	0	0	0	1.0 E23
France	5.5 E5	0	1.5 E23	0	0	0	1.5 E23
Germany, East	1.1 E5	0	3.1 E22	0	0	0	3.1 E22
Germany, West	2.5 E5	0	7.1 E22	0	0	0	6.7 E22

*Country is in conjectured geothermal belt, not yet proven by exploration.

Table 3 (continued)

Country	Area (km ²)	X	Resource Base in Temperature Classes (°C)				Total
			<100 (Class 1)	100-150 (Class 2)	150-250 (Class 3)	>250 (Class 4)	
Ghana	2.4 E5	0	6.7 E22	0	0	0	6.7 E22
Greece	1.3 E5	0.30	3.5 E22	8.8 E21	2.3 E21	1.4 E20	4.6 E22
Greenland	2.2 E6	0	6.3 E23	0	0	0	6.3 E23
Guadeloupe	1.8 E3	1.00	3.8 E20	3.9 E20	1.0 E20	6.3 E18	8.8 E20
Guatemala	1.1 E5	1.00	1.4 E22	2.4 E22	6.3 E21	3.9 E20	4.6 E22
Haiti*	2.8 E4	0.025	8.0 E21	1.5 E20	4.0 E19	2.5 E18	8.0 E21
Honduras*	1.1 E5	0.50	2.5 E22	1.2 E22	3.3 E21	2.0 E20	4.2 E22
Hungary	9.3 E4	0	2.6 E22	0	0	0	2.6 E22
Iceland	1.0 E5	1.00	2.2 E22	2.3 E22	5.9 E21	3.7 E20	5.0 E22
India*	3.3 E6	0.02	9.2 E23	1.4 E22	3.8 E21	2.3 E20	9.2 E23
Indonesia	1.9 E6	1.00	4.1 E23	4.2 E22	1.1 E23	6.7 E21	9.6 E23
Iran*	1.7 E6	0.20	4.6 E23	7.1 E22	1.9 E22	1.2 E21	5.4 E23
Iraq	4.3 E5	0	1.2 E23	0	0	0	1.2 E23
Ireland	7.0 E4	0	2.0 E22	0	0	0	2.0 E22
Israel*	2.1 E4	0.025	5.9 E21	1.2 E20	3.1 E19	1.9 E18	5.9 E21
Italy	3.0 E5	0.50	7.5 E22	3.3 E22	8.8 E21	5.4 E20	1.2 E23
Ivory Coast	3.2 E5	0	9.2 E22	0	0	0	9.2 E22
Jamaica	1.1 E4	0	3.2 E21	0	0	0	3.2 E21

*Country is in conjectured geothermal belt, not yet proven by exploration.

Table 3 (continued)

Country	Area (km ²)	X	Resource Base in Temperature Classes (°C)				Total
			<100 (Class 1)	100-150 (Class 2)	150-250 (Class 3)	>250 (Class 4)	
Japan	3.7 E5	1.00	8.0 E22	8.0 E22	2.1 E22	1.3 E21	1.8 E23
Jordan*	9.8 E4	0.025	2.8 E22	5.4 E20	1.5 E20	8.8 E18	2.8 E22
Kenya	5.8 E5	0.60	1.4 E23	7.5 E22	2.0 E22	1.3 E21	2.4 E23
Korea* (N & S)	2.2 E5	0.50	5.4 E22	2.4 E22	6.3 E21	3.9 E20	8.8 E22
Kuwait	2.0 E4	0	5.9 E21	0	0	0	5.9 E21
Liberia	1.1 E5	0	3.1 E22	0	0	0	3.1 E22
Libya	1.8 E6	0	5.0 E21	0	0	0	5.0 E21
Luxembourg	2.6 E3	0	7.5 E20	0	0	0	7.5 E20
Malawi*	9.5 E4	0.01	2.7 E22	2.1 E20	5.4 E19	3.4 E18	2.7 E22
Malagasy Rep.*	5.9 E5	0.005	1.6 E23	6.3 E20	1.7 E20	1.0 E19	1.6 E23
Malaysia	3.3 E5	0.02	9.2 E22	1.4 E21	3.8 E20	2.3 E19	9.2 E22
Mali	1.2 E6	0	3.4 E23	0	0	0	3.4 E23
Martinique	1.1 E3	1.00	2.4 E20	2.4 E20	6.3 E19	3.9 E18	5.4 E20
Mexico	2.0 E6	0.60	4.6 E23	2.6 E23	6.7 E22	4.2 E21	8.0 E23
Morocco	4.4 E5	0.04	1.3 E23	3.9 E21	1.0 E21	4.2 E21	8.0 E23
Nepal	1.4 E5	0.10	3.9 E22	3.1 E21	8.4 E20	5.0 E19	4.2 E22
Netherlands	3.6 E4	0	1.0 E22	0	0	0	1.0 E22
New Guinea	2.4 E5	0.60	5.9 E22	3.1 E22	8.4 E21	5.0 E20	9.6 E22

*Country is in conjectured geothermal belt, not yet proven by exploration.

Table 3 (continued)

Country	Area (km ²)	X	Resource Base in Temperature Classes (°C)				Total
			<100 (Class 1)	100-150 (Class 2)	150-250 (Class 3)	>250 (Class 4)	
New Hebrides	1.5 E4	1.00	3.2 E21	3.3 E21	8.8 E20	5.4 E19	7.5 E21
New Zealand	2.7 E5	0.50	6.7 E22	2.9 E22	8.0 E21	4.6 E20	1.0 E23
Nicaragua	1.5 E5	1.00	3.2 E22	3.3 E22	8.8 E21	5.4 E20	7.5 E22
Nigeria	9.2 E5	0	2.6 E23	0	0	0	2.6 E23
Norway	3.2 E5	0	9.2 E22	0	0	0	9.2 E22
Pakistan	8.4 E6	0.01	2.3 E24	1.8 E22	5.0 E21	3.0 E20	2.3 E24
Panama*	7.6 E4	1.00	1.6 E22	1.7 E22	4.6 E21	2.7 E20	3.8 E22
Paraguay*	4.1 E5	0.10	1.1 E23	8.8 E21	2.4 E21	1.5 E20	1.3 E23
Peru*	1.3 E6	1.00	2.8 E23	2.8 E23	7.5 E22	4.6 E21	6.3 E23
Philippines	3.0 E5	1.00	6.3 E22	6.7 E22	1.8 E22	1.1 E21	1.5 E23
Poland	3.1 E5	0	8.8 E22	0	0	0	8.8 E22
Portugal	9.2 E4	0.05	2.6 E22	1.0 E21	2.7 E20	1.6 E19	2.7 E22
Rumania	2.4 E5	0.01	6.7 E22	5.0 E20	1.4 E20	8.4 E18	6.7 E22
Saudi Arabia*	2.3 E6	0.02	6.3 E23	1.0 E22	2.6 E21	1.6 E20	6.3 E23
Senegal	2.0 E5	0	5.4 E22	0	0	0	5.4 E22
Sierra Leone	7.2 E4	0	2.1 E22	0	0	0	2.1 E22
South Africa	1.2 E6	0	3.4 E23	0	0	0	3.4 E23
Spain	5.1 E5	0.05	1.4 E23	5.4 E21	1.5 E21	9.2 E19	1.5 E23

*Country is in conjectured geothermal belt, not yet proven by exploration.

Table 3 (continued)

Country	Area (km ²)	X	Resource Base in Temperature Classes (°C)				Total
			<100 (Class 1)	100-150 (Class 2)	150-250 (Class 3)	>250 (Class 4)	
Sri Lanka	6.6 E4	0	1.8 E22	0	0	0	1.8 E22
Sudan	2.5 E6	0	7.1 E23	0	0	0	7.1 E23
Sweden	4.5 E5	0	1.3 E23	0	0	0	1.3 E23
Switzerland	4.1 E4	0	1.2 E22	0	0	0	1.2 E22
Taiwan	3.6 E4	1.00	7.5 E21	8.0 E21	2.1 E21	1.3 E20	1.8 E22
Tanzania	9.4 E5	0.03	2.6 E23	6.3 E21	1.6 E21	1.0 E20	2.6 E23
Thailand	5.1 E5	0	1.5 E23	0	0	0	1.5 E23
Trinidad & Tobago	5.1 E3	1.00	1.1 E21	1.1 E21	3.0 E20	1.8 E19	2.6 E21
Tunisia	1.6 E5	0.01	4.6 E22	3.6 E20	9.6 E19	5.9 E18	4.6 E22
Turkey	7.8 E5	0.50	1.9 E23	8.4 E22	2.3 E22	1.4 E21	3.1 E23
United States	9.4 E6	0.25	4.1 E24	5.0 E23	1.3 E23	8.4 E21	4.6 E24
Uruguay	1.9 E5	0.01	5.0 E22	4.1 E20	1.1 E20	6.7 E18	5.0 E22
USSR	2.2 E7	0.05	6.3 E24	2.4 E23	6.3 E22	4.0 E21	6.7 E24
Venezuela	9.1 E5	0.20	2.5 E23	0	1.0 E22	6.7 E20	3.0 E23
Vietnam (N & S)	3.3 E5	0.50	8.4 E22	3.7 E22	9.6 E21	5.9 E20	1.3 E23
Yugoslavia	2.6 E5	0	7.1 E22	0	0	0	7.1 E22
Zaire	2.3 E6	0.01	6.7 E23	5.0 E21	1.3 E21	8.4 E19	6.7 E23
Zambia	7.5 E5	0.10	2.1 E23	1.7 E22	6.7 E21	2.7 E20	2.3 E23

2. There are certain geothermal belts in the world where the vertical temperature gradient is higher than normal. Either part or all of any country may lie in a geothermal belt. Let A denote the total area of a country, of which a fraction X lies in a geothermal belt. X may range from 0 to 1.
3. Of the geothermal area (XA) in a country, 90% (0.9 XA) is assumed to have a temperature gradient of 40°C/km depth and 10% (0.1 XA) is assumed to have a temperature gradient of 80°C/km.
4. The average ambient atmospheric temperature of all countries is assumed to be 15°C.
5. For the purpose of this report, the geothermal resource base of a country is defined as the total heat contained in subsurface rocks and fluids to a depth of 3 km and at temperatures above 15°C.
6. Four temperature resource classes are considered:

Class 1: <100°C

Class 2: 100-150°C

Class 3: 150-250°C

Class 4: >250°C

7. Although the heat capacity of rock depends on lithology, porosity, and water content, an average volumetric specific heat (C_v) of 2.5 J/cm³ °C is an acceptable value for most areas.
8. The resource base, Q, associated with a particular temperature class is given by

$$Q = (A) (H) (C_v) (T-15) \quad (2-1)$$

where A denotes the area underlain by the resource, H the thickness (depth range) of the resource, C_v the volumetric specific heat of the subsurface material, and T the average temperature of the resource. Taking A in cm², H in cm, $C_v = 2.5 \text{ J/cm}^3 \text{ }^\circ\text{C}$, and T in °C,

$$Q = (2.5) (A) (H) (T-15) \text{ J} \quad (2-2)$$

9. In any temperature class, 20% of the total resource base is stored in the water and steam and the remainder is stored in the rock matrix. The rationale is as follows: Assuming the porosity range of subsurface material to be from 5 to 20%, the amount of water in 1 cm³ of porous rock varies from 0.05 to 0.2 cm³. Assuming an approximate volumetric specific heat capacity of from 0.21 to 0.84 J/°C, compared with 2.5 J/°C for the 1-cm³ rock-fluid system (assumption 7), the fraction of the resource base stored in water is from 0.21/2.5 to 0.84/2.5, or from 8.3 to 33.3%, with the average assumed to be 20%. The remaining 80% of the resource base is assumed to be stored in the rock.

Calculation Procedure.

1. Data on the surface area of each country were obtained from The Times Atlas of the World (1974) and converted to square centimeters.
2. The value X for each country was determined by estimating areal fractions in Figure 1 by expert, but subjective, judgment.
3. Resource base in normal areas:

$$\text{Area of normal gradient} = (A - XA) \text{ cm}^2$$

$$\text{Temperature gradient} = 25^\circ\text{C/km}$$

$$\text{Temperature (T) at any depth (h) is given by } T = 15 + 25h$$

(e.g., at 3 km, T = 90°C).

Thus, the entire resource in a normal area belongs to Class 1 (i.e., <100°C). The average temperature to a 3-km depth in the normal areas equals (15 + 90)/2, or 52.5°C. Using Q° to denote normal areas and Q₁, Q₂, Q₃, and Q₄ to denote the four resource temperature classes, the resource base of the normal areas can be calculated as follows:

$$Q_1^\circ = (2.5) (A - XA) (3) (52.5 - 15) (10^5) \text{ J}$$

or,

$$Q_1^\circ = (2.81 \times 10^7) (A - XA) \text{ J} \quad (2-3)$$

$$Q_2^\circ = 0 \quad (2-4)$$

$$Q_3^o = 0 \quad (2-5)$$

$$Q_4^o = 0 \quad (2-6)$$

The total resource base in normal areas = $Q_1^o + Q_2^o + Q_3^o + Q_4^o$. Of this resource base, 20% is classified as hot water or steam and 80% is in the dry rock category.

4. Resource base in geothermal areas (90%):

Area under consideration = 0.9 XA cm^2

Temperature gradient = 40°C/km

Temperature (T) at any depth (h) is given by $T = 15 + 40h$;

or $h = (T - 15)/40$.

The depth to the bottom of the Class 1 resource is $(100 - 15)/40$, or 2.125 km. The average temperature between the surface and this depth is $(15 + 100)/2$, or 57.5°C . Denoting these areas by Q_1^1 and using Q_1 , Q_2 , Q_3 , and Q_4 to denote resource classes, and using Eq. 2-2,

$$Q_1^1 = (2.5) (0.9 \text{ XA}) (2.125) (57.5 - 15) (10^5) \text{ J}$$

or,

$$Q_1^1 = (2.03 \times 10^7) (\text{XA}) \text{ J} \quad (2-7)$$

The depth to bottom of the Class 2 resource is $(150 - 15)/40$ or 3.38 km. Therefore, only part of the Class 2 resource falls within the 3-km depth range. The temperature at 3-km depth is $15 + 40 (3)$, or 135°C . The average temperature of the resource between depths 2.125 and 3 km is $(100 + 135)/2$, or 117.5°C , and the corresponding thickness $h = (3 - 2.125)$, or 0.875 km. Therefore, using Eq. 2-2,

$$Q_2^1 = (2.5) (0.9 \text{ XA}) (0.876) (117.5 - 15) (10^5) \text{ J}$$

or,

$$Q_2^1 = (2.02 \times 10^7) (\text{XA}) \text{ J} \quad (2-8)$$

$$Q_3^1 = 0 \quad (2-9)$$

$$Q_4^1 = 0 \quad (2-10)$$

The total resource base in 90% of the geothermal area in a country = $Q_1^1 + Q_2^1 + Q_3^1 + Q_4^1$. Of this resource 20% belongs to the hot water or steam classification and 80% is in the dry rock classification.

5. Resource base in geothermal areas (10%):

Area under consideration = 0.1 XA cm^2

Temperature gradient = 80°C/km

Temperature (T) at any depth (h), in km, is given by $T = 15 + 80h$;

or $h = (T - 15)/80$.

The depth to bottom of the Class 1 resource is $(100 - 15)/80$, or 1.063 km.

The average temperature between the surface and this depth is $(15 + 100)/2$, or 57.5°C . Denoting these areas by Q^2 and using Q_1 , Q_2 , Q_3 , and Q_4 to denote resource classes:

$$Q_1^2 = (2.5) (0.1 \text{ XA}) (1.063) (57.5 - 15) (10^5) \text{ J} \quad (2-11)$$

$$Q_1^2 = (1.13 \times 10^6) (\text{XA}) \text{ J}$$

The depth to bottom of the Class 2 resource is $(150 - 15)/80$, or 1.688 km.

The average temperature between 1.063 km and this depth is $(100 + 150)/2$, or 125°C , and the corresponding thickness $h = 1.688 - 1.063 = 0.625$ km. Using Eq. 2-2,

$$Q_2^2 = (2.5) (0.1 \text{ XA}) (0.625) (125 - 15) (10^5) \text{ J}$$

or,

$$Q_2^2 = (1.72 \times 10^6) (\text{XA}) \text{ J} \quad (2-12)$$

The depth to bottom of the Class 3 resource is $(250 - 15)/80$, or 2.938 km.

The average temperature between 1.688 km and 2.938 km is $(150 + 250)/2$, or 200°C , and the corresponding thickness $h = 2.938 - 1.688$, or 1.250 km. Using Eq. 2-2,

$$Q_3^2 = (2.5) (0.1 \text{ XA}) (1.250) (200 - 15) (10^5) \text{ J}$$

or,

$$Q_3^2 = (5.78 \times 10^6) (\text{XA}) \text{ J} \quad (2-13)$$

At 3 km, temperature is $15 + 80(3)$, or 255°C . Therefore the average temperature between 2.938 km and 3 km is $(250 + 255)/2$, or 252.5°C , the corresponding thickness h being $(3 - 2.938)$, or 0.062 km. Using Eq. 2-2,

$$Q_4^2 = (2.5) (0.1 \text{ XA}) (0.062) (252.5 - 15) (10^5) \text{ J}$$

or,

$$Q_4^2 = (3.56 \times 10^5) (\text{XA}) \text{ J} \quad (2-14)$$

The total resource base in 10% of the geothermal area of a country = $Q_1^2 + Q_2^2 + Q_3^2 + Q_4^2$. Of this resource 20% belongs to the hot water and steam classification and 80% belongs to the dry rock classification.

6. The resource base of a country, in different classes, is given as follows:

$$\text{Class 1: } Q_1 = Q_1^0 + Q_1^1 + Q_1^2 \text{ J} \quad (2-15)$$

$$\text{Class 2: } Q_2 = Q_2^0 + Q_2^1 + Q_2^2 \text{ J} \quad (2-16)$$

$$\text{Class 3: } Q_3 = Q_3^0 + Q_3^1 + Q_3^2 \text{ J} \quad (2-17)$$

$$\text{Class 4: } Q_4 = Q_4^0 + Q_4^1 + Q_4^2 \text{ J} \quad (2-18)$$

7. The total resource base of a country is given by

$$Q = Q_1 + Q_2 + Q_3 + Q_4 \text{ J} \quad (2-19)$$

The total hydrothermal (hot water and steam) resource of a country is $0.2Q \text{ J}$.

The total hot dry rock resource of a country is $0.8Q \text{ J}$.

Responses to Questionnaire

Only a few countries responded to the questionnaire with estimates of their resource base. The responses are shown in Table 4. In many cases the reported resource base is much lower than that estimated in Table 3 by the volumetric heat content method. Such discrepancies are inherent and are expected in estimates of this nature.

Table 4

GEOTHERMAL RESOURCE BASE ESTIMATES PROVIDED BY COUNTRIES IN RESPONSE TO QUESTIONNAIRES

<i>Country</i>	<i>Resource Base (J)</i>
Canada	1.7×10^{24}
England	8.4×10^{22}
El Salvador	1.9×10^{19}
Fiji	3.3×10^{18}
Germany, West	1.4×10^{23}
Hungary	5.4×10^{22}
India	8.0×10^{19}
Mexico	1.7×10^{20}
New Zealand	1.3×10^{20}
Nicaragua	5.4×10^{20}
Norway	1.3×10^{23}
Spain	5.0×10^{17}
Sweden	1.3×10^{18}
Taiwan	8.4×10^{16}
Total	2.1×10^{24}

Section 3

ELECTRIC ENERGY CONVERSION

Although the geothermal resource base computed in Section 2 is very large, only a small fraction is suitable for conversion to electric energy. The comparatively low temperature and the energy extraction difficulties result in an overall conversion efficiency that is small relative to that attainable with fossil fuels. The overall conversion efficiency is limited by the first and second laws of thermodynamics and by the inefficiencies associated with energy extraction and conversion to electric power.

To facilitate analytic estimates, the inefficiencies are grouped as follows:

F_a = available energy fraction. This factor includes an energy recovery component expressed as the ratio of recoverable energy to resource base, corrected for thermal efficiency.

F_w = wellhead fraction. This factor accounts for the friction, work, and heat flow losses associated with energy extraction.

F_p = power plant fraction. This factor accounts for losses between the wellhead and the power plant.

F_b = busbar fraction. This factor accounts for losses associated with the conversion from heat to electricity. It does not include the thermal conversion efficiency associated with the second law of thermodynamics, which was included in F_a .

The electric energy delivered to the busbar, E_b , is calculated by the equation

$$E_b = (F_a) (F_w) (F_p) (F_b) Q \quad (3-1)$$

where Q is the resource base.

For a given geothermal field of volume V, the geothermal resource base can be estimated in terms of the average specific heat and the difference between the initial reservoir temperature and the reference datum temperature:

$$\left(\frac{Q}{V}\right) = C_V (T_1 - T_0) \quad (3-2)$$

where C_V = volumetric specific heat ($2.5 \text{ J/cm}^3 \text{ }^\circ\text{C}$, from Section 2)

T_1 = initial reservoir temperature

T_0 = reference datum temperature (15°C , from Section 2)

ELECTRIC POWER POTENTIAL

The thermodynamic model of the typical geothermal system, assuming no heat recharge, is illustrated by the absolute temperature-entropy diagram of Figure 2. The nomenclature of Figure 2 is used in the derivation of equations in this section.

Energy Recovery

Assuming that T_2 is the temperature at which the geothermal reservoir production ceases to be economical, the ideal fraction of the energy per unit volume that can be produced is given by

$$\frac{E_{1-2}}{V} = C_V (T_1 - T_2)$$

Thus the fraction of the heat that can ideally be recovered is

$$\frac{E_{1-2}}{Q} = \frac{T_1 - T_2}{T_1 - T_0} \quad (3-3)$$

Thermal Efficiency

The thermal efficiency represents the fraction of the thermal energy, E_{1-2} , that can be converted to mechanical or electric energy under the second law of thermodynamics. In Figure 2, the shaded area represents the differential of ideal work, δW_{k_i} . The energy bounded by the same interval of the curve down to 0 K is δE . The Carnot efficiency is

Figure 2 Geothermal reservoir thermodynamics

$$\eta_{\text{Carnot}} = \frac{\delta W_{k_i}}{\delta E} = 1 - \frac{T_0}{T_H} \quad (3-4)$$

where $\delta E = C_V \delta T_H$. Integration of δW_{k_i} in Eq. 3-4 between the limits $T_1 \geq T_H \geq T_2$ results in

$$\frac{W_{k_i}}{E_{1-2}} = 1 - \frac{T_0}{T_{1-2,\ln}} \quad (3-5)$$

where $T_{1-2,\ln}$ is defined by

$$T_{1-2,\ln} = \frac{T_1 - T_2}{\ln(T_1/T_2)} \quad (3-6)$$

Available Energy Fraction

An expression for the fraction of the rock thermal energy that is available for conversion to electric energy, F_a , is obtained by combining Eq. 3-3 and 3-5.

$$F_a = \frac{W_{k_i}}{Q} = \left(\frac{T_1 - T_2}{T_1 - T_0} \right) \left(1 - \frac{T_0}{T_{1-2,\ln}} \right) \quad (3-7)$$

The available energy fraction may also be expressed as functions of the temperature ratios, $a = T_1/T_2$ and $b = T_1/T_0$ as

$$F_a = \left[\frac{b}{a} \left(\frac{a-1}{b-1} \right) - \frac{\ln a}{b-1} \right] \quad (3-8)$$

Figures 3 and 4 represent Eq. 3-7 and 3-8, respectively, for $F_a = f(a)$ for $b = T_1/T_0 = 600/288$. F_a is the product of the components E_{1-2}/Q from Eq. 3-3 and W_{k_i}/E_{1-2} from Eq. 3-5. These components are also graphed in Figure 3. Figure 4 shows F_a as a function of the initial resource temperature, T_1 , and the lower production limit temperature, T_2 . Both figures show the strong influence of a large T_1 on F_a and a small T_2 on the available energy fraction. For example, for $T_1 = 600$ K and $T_2 = 450$ K (177°C), the available energy fraction is $F_a = 0.215$. However, for $T_1 = 500$ K, F_a (from Figure 4) is reduced by a factor of 2.3 to only 0.093. Furthermore, if the minimum usable resource temperature T_2 can be reduced from 177°C to 150°C, Figure 4 shows for $T_1 = 500$ K that the fraction F_a increases from 0.093 to 0.136, improvement by a factor of 1.5.

Figure 3 Available energy fraction, F_a

Figure 4 Available energy fraction as a function of initial and final reservoir temperatures

One further factor affecting the "ideal" available energy fraction is the resource base reference temperature T_0 shown in Figure 2. If, because of local climatic conditions, the local sink or available coolant temperature, T_∞ , differs from T_0 , Eq. 3-7 is modified to

$$F_a = \left[\frac{T_1 - T_2}{T_1 - T_0} \right] \left[1 - \frac{T_0(T_\infty/T_0)}{T_{1,2} \ln} \right] \quad (3-9)$$

The sensitivity of F_a to the ratio T_∞/T_0 is noted in Figure 5. A reference point was selected corresponding to an initial reservoir temperature $T_1 = 227^\circ\text{C}$ (550 K) and a lower production limit temperature $T_2 = 127^\circ\text{C}$. For $T_\infty = T_0 = 15^\circ\text{C}$, (288 K), the available energy fraction F_a for the reference case is 0.168, as noted in Figure 4. The data in Figure 5 show the strong sensitivity of F_a to both T_1 and T_2 compared with the reference case, but a relatively low sensitivity of F_a to T_∞ .

Wellhead Fraction

The wellhead fraction, F_w , accounts for nonuniformity of rock temperature, T_2 , in a large-scale reservoir resulting from long conduction paths in impermeable rock masses that inhibit heat transfer to circulating fluids. It also accounts for fluid friction heat losses in the well bore during production. The wellhead fraction is thus related to the efficiency of mining the available energy, $(F_a)Q$. It can vary with the well and reservoir production techniques employed. Enhanced extraction may be achieved by explosive or hydraulic fracturing or by injection of colder fluids to "sweep" the thermal energy to the well bore. Thus the wellhead fraction, F_w , in contrast to the available energy fraction, F_a , which is determined by thermodynamic principles, is very much dependent on judgment and experience. It is also dependent on the type of geothermal reservoir and its porosity, permeability, and rock-size distribution. Based on expected values for these characteristics, values for F_w are given below.

<u>Reservoir Type</u>	<u>Wellhead Fraction, F_w</u>	
	<u>Range</u>	<u>Average</u>
Vapor-dominated	0.2 - 0.4	0.3
Liquid-dominated	0.2 - 0.6	0.4
Hot dry rock	0.01 - 0.15	0.08
Geopressured	0.2 - 0.8	0.5

Figure 5 Available energy fraction as a function of reservoir sink temperatures

Power Plant Fraction

The power plant input fraction, F_p , considers the piping from wells to power plant, the mode of generation, such as single or multiple flash, heat exchanger losses for binary cycle turbines, and other temperature or pressure losses. Based on experience with vapor-dominated systems at The Geysers (U.S.A.) and with liquid-dominated systems at Wairakei (New Zealand), the following values for the power plant fraction are used.

<u>Reservoir Type</u>	<u>Power Plant Input Fraction, F_p</u>
Vapor-dominated	0.95
Liquid-dominated*	0.6
Hot dry rock*	0.6
Geopressured	0.6

*For either flash steam or binary cycle operation

Busbar Fraction

The busbar fraction, F_b , reflects the efficiency of conversion of the net available energy delivered to a turbine (or other expander) to electric power at the busbar. At The Geysers and at Wairakei, the busbar fraction, F_b , is about 0.72. This is probably typical of most hydrothermal systems. Additional pumping power requirements will lower the expected value of F_b , whereas the additional hydraulic energy component of geopressured resources may increase the conversion efficiency. The following values of F_b are expected:

<u>Reservoir Type</u>	<u>Busbar Fraction, F_b</u>
Vapor-dominated	0.72
Liquid-dominated	0.72
Hot dry rock	0.65
Geopressured	0.75

Overall Efficiency

In summary, the overall efficiency for producing electric power from a given geothermal reservoir is given by:

$$\eta_0 = \frac{E_b}{Q} = (F_a) (F_w) (F_p) (F_b) \quad (3-10)$$

Typical values are given below for hydrothermal (and geopressured) reservoirs with $T_1 = 227^\circ\text{C}$ and $T_2 = 177^\circ\text{C}$, and for hot dry rock reservoirs with $T_1 = 302^\circ\text{C}$ and $T_2 = 177^\circ\text{C}$.

<u>Reservoir Type</u>	<u>F_b</u>	<u>F_p</u>	<u>F_w</u>	<u>F_a</u>	<u>η_0</u>
Vapor-dominated	0.72	0.95	0.3	0.09	0.018
Liquid-dominated	0.72	0.6	0.4	0.09	0.016
Hot dry rock	0.65	0.6	0.08	0.185	0.0058
Geopressured	0.75	0.6	0.5	0.009	0.020

These results show that the overall efficiency for producing electric power from hydrothermal systems is limited to about 2% of the resource base, primarily because of the small magnitudes of the factors F_a and F_w . Hot rock systems will have a smaller overall efficiency because of the smaller F_w . Although nature has placed a limit on the value of F_a , it is possible to increase the value of F_w through stimulation. Geopressured resources should have higher conversion factors for comparable operating temperatures T_1 and T_2 because of the larger wellhead fraction.

ESTIMATED WORLD POTENTIAL FOR GEOTHERMAL ELECTRICITY

For the purpose of estimation, only that portion of the geothermal resource base above 150°C is considered suitable for electric power production, and it is assumed that the overall conversion efficiency as derived herein applies uniformly. Since current technology is not adequate for the development of petrothermal (hot dry rock) geothermal resources, the estimates herein apply to hydrothermal resources only. For these calculations it is assumed that about 20% of the resource base is contained in hydrothermal systems. Estimates for countries having the greatest geothermal electric power potential are presented in Table 5.

Table 5
HYDROTHERMAL ELECTRICITY POTENTIAL
(calculated)

<i>Country</i>	<i>Electric Energy Potential E_b (MW cen)</i>	<i>Electric Power Potential (1000 MW)</i>		
		<i>1985</i>	<i>2000</i>	<i>2020</i>
China	160,000	23	70	140
United States	150,000	23	70	140
		(6)	(20)	
Indonesia	130,000	20	60	120
		(0.03-0.1)	(0.5-6)	
Peru	86,000	13	38	77
Mexico	77,000	12	36	72
		(0.4-1.4)	(0.5-20)	(4-20)
USSR	72,000	11	33	65
Chile	54,000	8	25	49
Ethiopia	50,000	8	23	45
Ecuador	30,000	5	14	27
Brazil	29,000	4	13	26
Turkey	26,000	4	12	24
		(0.4)	(1)	(1.5)
Japan	24,000	4	11	22
		(2)	(50)	
Kenya	24,000	4	11	22
		(0.03)	(0.06-0.09)	(0.09-0.15)
Colombia	23,000	4	11	21
Bolivia	22,000	4	10	20
Iran	22,000	4	10	20
Philippines	20,000	3	9	18
		(0.3)		

Note: Numbers in parentheses denote estimates by individual countries as presented in Section 5.

Table 5 (continued)

<i>Country</i>	<i>Electric Energy Potential E_b (MW cen)</i>	<i>Electric Power Potential (1000 MW)</i>		
		<i>1985</i>	<i>2000</i>	<i>2020</i>
Venezuela	12,000	2	6	11
Vietnam	11,000	2	5	10
Nicaragua	10,000	1.5 (0.2)	5 (0.35)	9 (0.8)
Italy	9,900	1.5	5 (0.8)	9
New Guinea	9,600	1.5	5	9
New Zealand	9,100	1.4 (0.4)	4 (1.4)	8 (2)
Chad	8,600	1.3	4	8
Zambia	7,500	1.1	3.4	7
Guatemala	7,200	1.1 (0.1)	3.2	6.5
Korea	7,200	1.1	3.2	6.5
Iceland	6,800	1 (0.15)	3 (0.5)	6 (0.8)
Total	1.1×10^6	169.5	502.8	998

Note: Numbers in parentheses denote estimates by individual countries as presented in Section 5.

Calculation Method

The following equation was used to calculate hydrothermal electric power potential for hydrothermal systems:

$$E_b = 0.2 Q \eta_0 \quad (3-11)$$

for which the terms have already been defined. The coefficient 0.2 is the 20% hydrothermal fraction assumed above.

Sample Calculation

Calculation of the national geothermal power potential for Iceland illustrates the method used. The resource base used for conversion to electric power is obtained from Table 3 as

$$Q = 5.9 \times 10^{21} (\text{Class 3}) + 3.7 \times 10^{20} (\text{Class 4}) = 6.3 \times 10^{21} \text{ J}$$

$\eta_0 = 0.017$ (overall efficiency, taken as the average of the estimates for liquid- and vapor-dominated systems).

The electric potential is given by Eq. 3-11 as

$$E_b = (0.2)(6.3 \times 10^{21})(0.017) = 2.1 \times 10^{19} \text{ J} = 6800 \text{ MW cen(e)}$$

Further assumptions were made to estimate the growth pattern of installed electric power capacity for the years 1985, 2000, and 2020: (1) By the year 2020, about 90% of E_b is assumed committed for use by the year 2100; (2) by the year 2000, one-half is assumed committed; and (3) by the year 1985, one-sixth is committed.

Thus, for the total $E_b = 6800 \text{ MW cen(e)}$ in the Iceland example, the installed-capacity timetable becomes:

<u>Year</u>	<u>Installed Capacity (MW [e])</u>
1985	1000
2000	3000
2020	6000

The use rate would essentially exhaust the hydrothermal-based $E_p = 6800$ MW cen(e) by the year 2100, requiring plant replacement after 2020 to maintain power capability, assuming there is no heat recharge to the reservoir. However, it is expected that technology to exploit the remaining 80% of the energy in the formation rock (the hot dry rock resource base), as well as to drill to deeper depths, will have become available by then.

Similar calculations of the potential for electric power capacity were made for the 28 countries listed in Table 5. Collectively, these countries contain more than 95% of the worldwide total of 1.2×10^6 MW (e). The worldwide potential for installed power capacity for the year 2020 is 1.2×10^6 MW (e). If only about 25% of this potential is used, perhaps limited by such constraints as local markets, competing energy sources, and site-specific difficulties, the capacity of 250,000 MW (e) would be very impressive, equivalent to a supply of 9×10^6 barrels of oil per day at a conversion efficiency of 42%. These estimates were derived for a conservative abandonment temperature, $T_2 = 177^\circ\text{C}$. The dependence of available energy on T_2 was noted in Figure 5. If conversion technology permits a lower T_2 (e.g., 150°C), the calculated capacity of 250,000 MW (e) would be increased by a factor of 1.45.

A further observation is of interest. Comparison of the estimated potential with the projections expressed in the questionnaires completed by the various responding countries shows a general expectation of utilizing only a small fraction of the estimated electric power potential. For the Iceland example, the comparison shows the following:

<u>Year</u>	<u>Questionnaire Estimate (MW [e])</u>	<u>Calculated Potential (MW [e])</u>
1985	150	1000
2000	500	3000
2020	800	6000

The sevenfold difference may reflect a conservative attitude toward the constraints that may limit the anticipated domestic market for electric energy due to the availability of other energy resources, such as hydropower, or site-specific considerations, such as inaccessibility. Japan, which has about four times the energy potential of Iceland ($E_D = 24,000 \text{ MW cen[e]}$), projects a much greater utilization factor.

PROJECTED UTILIZATION

The projections of electric power utilization as reported in responses to the questionnaire are shown in Table 6. Although the contrast between volumetric calculated and national estimates shown in Table 5 is evident, the growth shown in Table 6 is of the order of 25% per annum through 1985 and from 11% to 20% per annum through 2000. These growth rates could be considered good for this alternative energy source.

ECONOMICS OF GEOTHERMAL POWER

Since many factors affect the cost of geothermal power, and experience is still very limited, it is not possible to generalize about these costs. The major cost factors are:

- Exploration
- Reservoir development
- Geothermal fluid purity and temperature quality
- Site-specific considerations
- Power plant
- Waste geothermal fluid disposal
- Environmental protection
- Operation and maintenance
- Taxes
- Royalties
- Lead time from reservoir discovery to power generation

Many of these cost factors differ in individual countries, and other external factors, such as alternative energy sources, will affect the competitive position of geothermal power. Nevertheless, some observations with regard to experience in the United States may be useful.

Table 6
ELECTRICITY GENERATING CAPACITY
FROM GEOTHERMAL RESOURCES
(based on questionnaires)

<i>Country</i>	<i>1976 Installed Capacity (MW)</i>	<i>1985 Estimated Capacity (MW)</i>	<i>2000 Estimated Capacity (MW)</i>
United States	502	>3,000	>20,000
Italy	421	800	—
New Zealand	190	400	1,400
Japan	68	2,000	≈50,000
Mexico	75	400-1,400	1,500-20,000
USSR	5.7	—	—
Iceland	2.5	150	500
Turkey	0.5	400	1,000
Canada	—	10	—
Costa Rica	—	100	—
El Salvador	60	180	—
Guatemala	—	100	—
Honduras	—	100	—
Nicaragua	—	150-220	300-400
Panama	—	60	—
Argentina	—	20	—
Portugal	—	30	100
Spain	—	25	200
Kenya	—	30	60-90
Indonesia	—	30-100	500-6,000
Philippines	—	300	—
Taiwan	—	50	200
Total	1,325	8,335-9,335	14,775-100,000

Energy-Related Cost

In the United States, geothermal well drilling costs in 1976 dollars ranged from about \$150/m to \$300/m. The cost of geothermal heat delivered to the power plant at The Geysers (dry steam field) was about \$0.60 per million Btu. The cost of energy from other hydrothermal systems was projected to be in the range from \$0.60 to \$0.75 per million Btu. A better perspective of the relative value of geothermal energy can be gained by comparing it with oil-fired conventional plants. At \$13.50/bbl for oil, the energy cost would be \$2.50 per million Btu. Because of the difference in conversion efficiency of the conventional oil-fired plant compared with the geothermal plant, the oil-equivalent energy cost at The Geysers was about \$1.60 per million Btu, a little more than one-half the price of oil. For the other hydrothermal systems the oil-equivalent energy cost would range from about \$1.60 to \$2.50 per million Btu.

Power Plant Cost

Hydrothermal power plant costs are expected to be about the same as those for oil-fired plants; however, the plant cost for dry steam fields may be somewhat lower. Plant costs will vary depending on the conversion cycle and resource type (e.g., flashed steam, binary-cycle, geopressured) but will probably not exceed nuclear power plant costs unless the lower-temperature reservoirs are used.

Operating Cost

The annual power plant operating and maintenance cost is expected to be about 4.5% of the plant's capital costs. The operating and maintenance costs associated with reservoir operation are included in the estimated energy costs.

Section 4

NONELECTRIC USES

PRESENT USES

Geothermal energy applications other than for electricity generation are broadly categorized as nonelectric. Several factors make nonelectric applications at geothermal resource sites desirable.

- Electricity generation may not be economically feasible at geothermal resources with temperatures below 150°C.
- For higher-temperature resources where electricity generation is economic, thermal energy uses can reduce the cost of both the electricity and the nonelectric uses.
- Geothermal resources may contain economic quantities of minerals that may possibly be recovered.
- In special circumstances the geothermal resource can be either an important supply of water or an important supply of low-cost energy that can be used to purify water.

The most widespread interest and application of geothermal energy for nonelectric purposes has been as a supply of thermal energy. These thermal energy uses have been at temperatures near the lower end of the scale, which are not suited for economic electricity generation.

Mineral recovery and water purification, although not presently significant on a worldwide basis, could be of very great importance in local situations.

Nonelectric applications, either now or recently in operation, cover a wide spectrum. At one end is the age-old balneological use (therapeutic baths), while at the other end is the use of geothermal energy for cooling, as presently practiced in New Zealand. Applications range from the warming of water for washing livestock stalls to providing the thermal energy requirements of a modern

pulp and paper mill. Table 7 lists the main nonelectric applications throughout the world.

The estimated total energy use rate represented by Table 7 is about 7000 MW (th). This amount of power is not a large contribution to the total energy use rate of the world. But in some cases it is not an insignificant amount, since for a number of the countries with geothermal potential, it represents more than their total electric power requirements. It is evident that nonelectric applications have been receiving widespread attention, but not the concerted attention necessary for a substantial number of large-scale developments. The degree of utilization in any given country may be related to the availability of geothermal resources and the relative cost of obtaining energy from other sources.

The processes that are most developed with respect to their overall significance as nonelectric applications are space heating, industrial applications, and agricultural applications.

Space Heating

As illustrated in Table 7, space heating with geothermal energy is becoming widespread throughout the cooler regions of the world, with sizable applications in a number of countries. The two main classifications of space heating systems are district and individual. Most of the significant applications are in the district heating category. Two noted exceptions, which are individual systems, are at Rotorua, New Zealand; and Klamath Falls, Oregon, U.S.A.

The largest known, and probably the most economical, district heating system is in Reykjavik, Iceland. It supplies a total population of about 90,000 with space and domestic water heating from resources at temperatures varying from 80°C to 120°C. The geothermal water is pumped directly from well to pipeline, held in storage tanks to meet demand, circulated to the consumer at about 80°C, and then wasted to the municipal sewer system or reinjected. The city is divided into a number of districts, each served by its own pumping station. Water meters are used to determine individual consumer use for billing purposes. The present capacity of the geothermal system is 350 MW, with peaking energy demand met from a 35-MW oil-fired heating plant. The system is presently being expanded by about 25% to serve an additional 26,000 people. For consumers being supplied by this system, the average cost of heating is about 30% of what it would be if supplied from an oil-fired heating plant.

Table 7

PRESENT NONELECTRIC APPLICATIONS OF GEOTHERMAL ENERGY

<i>Country</i>	<i>Locality (where applicable)</i>	<i>Description of Application</i>	<i>Associated Power (J/d) *</i>	<i>Comments</i>	<i>Source</i>
Argentina		Total	Small	Space heating and drying	Questionnaire
Chile		Total	Small	Desalination pilot plant	Questionnaire
Czechoslovakia		Total	8.0×10^{12}	Space and water heating; mineral baths	Questionnaire
	Bohemian Massif		2.0×10^{12}		
	West Carpathinas		5.9×10^{12}		
France		Total	4.2×10^{10} to 2.1×10^{12}	Space and water heating	Questionnaire
Germany, West		Total	2.3×10^{10}	Miscellaneous use in 20–50°C range	Questionnaire
Hungary		Total	3.9×10^{12} to 9.1×10^{13}		Questionnaire
		Agriculture	4.6×10^{13}		Boldizsar (1974)
		District heating	5.0×10^{11}		
		Industry	2.1×10^{11}		
		Mineral baths and swimming pools	3.8×10^{13}		
	Szentes and various other localities	Greenhouse heating	1.4×10^{13}	Typical greenhouse vegetables plus paprika; typical horticulture; 800,000 m ² of greenhouse	UNESCO (1970)
	Various localities	Heating and cleaning animal shelters	1.8×10^{13}	Heating and cleaning milk rooms, cattle stalls, pigsties, chicken houses; 25 wells at 7×10^{11} J/d	UNESCO (1970)
	Szeged	District heating	—	University clinics and 1200 flats, 226,000 m ³	Einarsson (1973) Boldizsar (1974)

Note: Many of the entries on specific applications are from Howard et al., 1975, but original source is cited here.

*The associated power is as reported by the countries in the survey or by the reference. It may be either the power associated with the well flow or the power actually used in the application.

Table 7 (continued)

<i>Country</i>	<i>Locality (where applicable)</i>	<i>Description of Application</i>	<i>Associated Power (J/d) *</i>	<i>Comments</i>	<i>Source</i>
Hungary	Hódmezővásárhely	Individual space heating		Factory and hospital, 172,000 m ³	Einarsson (1973)
	Mako	Individual space heating		Hospital, 80,000 m ³	Einarsson (1973)
Iceland		Total	3.1×10^{13}		
	Reykjavik	District heating	2.8×10^{13}	The system's geothermal resources come from the Reykir area (3600 m ³ /h at 80°C, 170 MW [th]) and the Reykjavik area (1700 m ³ /h at 119°C, 155 MW [th]). Peaking is accomplished from the system's own fossil-fired peaking power plant. System started with 70-house pilot program in 1928.	Zoega (1974)
	Olafsfjörður	District heating	—	System serves the housing of 1000 inhabitants: built in 1944 using only 48°C water about 3 km away from the city. In 1961 deep drilling yielded additional water at 56°C.	Einarsson (1973)
	Selfoss	District heating	1.3×10^{12}	System serves 154,000 m ³ of housing and 75,000 m ³ of public, commercial, and industrial buildings (entire city of 2200). Boreholes are located 1.5 km away from the city. System started in 1948. 80 kg/s at 80°C.	Einarsson (1973)
	Hveragerði	District heating	—	System serves housing in entire city (820) and a therapeutic spa for 140 patients; it also supplies heating for 30,000 m ² of hothouses. The system was built in 1953 and utilizes a 180°C geothermal field.	Einarsson (1973)
	Saudarkrokur	District heating	—	This system serving the city of 2000 uses 70°C water from nearby boreholes.	Einarsson (1973)
	Various	Greenhouses	1.4×10^{12}	Glass greenhouses heated by natural steam and/or hot water, either directly or with heat exchangers.	UNESCO (1970)

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Table 7 (continued)

<i>Country</i>	<i>Locality (where applicable)</i>	<i>Description of Application</i>	<i>Associated Power (J/d)*</i>	<i>Comments</i>	<i>Source</i>
Iceland	Various	Greenhouses	—	1/3 flowers, 2/3 vegetables (tomatoes, cucumbers, lettuce); cost, \$0.91/GJ (1970)	UNESCO (1970)
	Various localities	Experimental salmon breeding station	8.8×10^{10}	Kollafjord experimental fish farm, rearing young salmon to the smolt stage; 7 l/s at 70°C.	Matthiasson (1970)
	Reykjavik	Drying fish in shelf dryers	Small	Uses excess water from commercial heating system in Reykjavik during summer in local stock-fish processing center	Lindal (1961a)
		Curing of light aggregate cement building slabs	Small	No details given; reported to occur in two or more countries	Lindal (1973)
	Reykholar	Drying seaweed	1.8×10^{12}	~80 l/s at 100°C; production of 3600 t/yr of dry seaweed	Matthiasson (1970)
	Hveragerdi (Hengill area)	Steam drying of wood	—	No details furnished; reported to occur in other places	Lindal (1961a)
	Namafjall	Production of dried diatomaceous earth recovered by wet-mining techniques	3.0×10^{12}	Dredging in the lake is done only in the summer, while the plant runs throughout the year; up to 50 t/h of steam at 183°C/10 ⁵ Pa	Lindal (1973) UNESCO (1970) Lindal (1970b)
		Total	2.1×10^{12}		Survey
Italy	Castelnuovo	Greenhouse	5.0×10^{10}	3000 m ²	Barbier (1975)
	Galzignano (Padua)	Greenhouse	3.5×10^{11}	20,000 m ²	
	Larderello	Geothermal steam used for processing imported ores (boric acid)	1.3×10^{12} to 1.6×10^{12}	30 t/h of steam	Lindal (1973)

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Table 7 (continued)

<i>Country</i>	<i>Locality (where applicable)</i>	<i>Description of Application</i>	<i>Associated Power (J/d) *</i>	<i>Comments</i>	<i>Source</i>
Italy	Larderello	Includes recovery of substances from the volatile components that accompany the geothermal steam (boric acid, ammonium bicarbonate, ammonium sulfate, and sulfur)	—	No longer in operation; large production before 1966	Muffler (1973) Mazzoni (1948) Garlado (1961) Lenzi (1964)
Japan		Total	2.5×10^{14}		Questionnaire
	Towada	District heating	1.8×10^{11}	System constructed in 1963 with 11.5-km transmission line from Sarukuro springs; 14 kg/s at 70°C	UNESCO (1970)
	Okawa	District heating	2.8×10^{11}	System provides heating for 3000 houses from a 12-km transmission line. 22 kg/s at 70°C.	UNESCO (1970)
	Ukiyama	District heating	2.2×10^{10}	Water is heated to 55°C in fossil-fueled boiler. 12 kg/s at 40°C.	UNESCO (1970)
	Aomori	District heating	2.0×10^{11}	Provides heating for 34 hotels and 140 houses, with water from the Asamushi hot spring area. 22 kg/s at 60°C.	UNESCO (1970)
	Kannawa, Beppu, Oita	Confectionery industry	—	Daily rice-processing capacity 180 kg; 98°C water, spring source	
	Ibusuki	Brewing and distilling	Small	No details given; one well used.	
	Various localities	Greenhouse heating	2.7×10^{11}	Horticulture (various species); vegetables (tomatoes, cucumbers, papayas, melons, bananas, eggplants); 3 types of greenhouse: glass, plastic, vinyl; 15,528 m ² of greenhouse	UNESCO (1970)

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Table 7 (continued)

<i>Country</i>	<i>Locality (where applicable)</i>	<i>Description of Application</i>	<i>Associated Power (J/d) *</i>	<i>Comments</i>	<i>Source</i>
Japan	Minami-Izu Shizuoka	Heating poultry houses, drying droppings	1.4×10^{11}	Yoshisawa poultry yard, heating below floor with pipes; drying droppings from 8000 chickens; 115°C water at 300 l/min	
	Ueda, Beppu, Oita	Heating poultry houses, drying droppings	Small	Nakamura poultry yard, 1600 chickens	
	Minami-Izu Shizuoka	Alligator and crocodile breeding	8.4×10^{11}	Alligators and crocodiles, 20 species; geothermal water mixed with cold to attain 28-32°C; water 105°C at 2000 l/min	
	Hokkaido and Kogashima prefectures	Eel breeding	Small	Uses water from hot springs	UNESCO (1970)
	Shikabe, Hokkaido	Experimental breeding station	8.8×10^{11}	Hokkaido hot-water hatching center, eels and carp; 70 l/s at 70°C	
	Shikabe, Hokkaido	Production of salt from sea water	—	No longer in operation, formerly about 150 t/yr. salt	UNESCO (1970)
		Extraction of sulfur from volcanic gases	—	Unsophisticated operation that has become uneconomical	UNESCO (1970)
New Zealand		Total	1.7×10^{13}		Questionnaire
	Kawerau	Pulp and paper processing and a small amount of electric power generation	8.8×10^{12} to 1.1×10^{13}	Geothermal energy delivered to mills by 36,287 kg/h of 1.4×10^6 Pa steam and 145,149 kg/h of 6.9×10^5 Pa steam, obtained by flashing wet steam at the well bore; 181,436 kg/h of steam	UNESCO (1970)
	Rotorua	Veneer factory	—	No details given	UNESCO (1970)
	Rotorua	Timber drying in kilns	—	No details given	UNESCO (1970)

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Table 7 (continued)

<i>Country</i>	<i>Locality (where applicable)</i>	<i>Description of Application</i>	<i>Associated Power (J/d) *</i>	<i>Comments</i>	<i>Source</i>
New Zealand	Rotorua	Individual space heating of homes plus space cooling of a business	—	Over 700 geothermal bores serving many individual applications. City consists of seven areas, three of which have approximately 80 bores at a useful average of 5.1×10^{10} J/d, 70 bores at a useful average of 6.3×10^{10} J/d, and 50 bores at a useful average of 2.0×10^{11} J/d, respectively.	UNESCO (1970) UNESCO (1974)
	Various localities	Greenhouse heating	—	Mushrooms (soil is sterilized and heated by using geothermal fluids directly); tree nursery (seedlings); tomatoes	UNESCO (1970)
	Taupo	Pig-farm heating, sterilizing; drying sheep crutchings; drying wool cuttings	Small	Geothermal steam is used to cook and sterilize garbage feed; warm piggy floors to 85° F; hose pens; sterilize and concentrate waste manure; dry sheep crutchings; boil sheet cuttings.	Keer et al. (1961)

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Table 7 (continued)

<i>Country</i>	<i>Locality (where applicable)</i>	<i>Description of Application</i>	<i>Associated Power (J/d) *</i>	<i>Comments</i>	<i>Source</i>
Nicaragua		Total	9.2×10^{12} to 16.7×10^{12}		Questionnaire
Peru		Total	Small	Desalination tests in progress	Questionnaire
Philippines		Total	4.2×10^{11}		
	Tiwi, Albay	Production of salt from seawater	$< 2.2 \times 10^{11}$	Seawater brought 3 km to plant; three grades of salt produced	Howard et al. (1975)
	Tiwi, Albay	Grain drying	$< 2.2 \times 10^{11}$	Palay drying time cut to 10 min from 4-8 h; model being tested	Howard et al. (1975)
Taiwan		Total	5.0×10^{10}		Survey
Turkey		Total	1.7×10^{10}		
	Kizildere	Greenhouse heating	1.7×10^{10}	Hot water passes through radiator; air forced through radiator heats greenhouse; 3.7×10^{12} J per 6 months.	Howard et al. (1975)
United States		Total	1.5×10^{12}		ERDA (1976)
	Boise, Idaho	District heating	8.0×10^{11}	This system, which continues to serve about 200 houses and 10-12 businesses (1970), is one of the oldest district heating systems. It was built during the 1890s. New system being expanded for space heating.	Wells (1971)

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Table 7 (continued)

<i>Country</i>	<i>Locality (where applicable)</i>	<i>Description of Application</i>	<i>Associated Power (J/d) *</i>	<i>Comments</i>	<i>Source</i>
United States	Klamath Falls, Oregon	Individual space heating of homes, businesses, space cooling, and miscel- laneous other uses	5.0×10^{11}	Space heating of homes is generally accomplished with several homeowners sharing a well and using downhole heat exchange systems. Presently 468 residences are heated geothermally. Some commercial installations with- draw the geothermal fluid, use it in heat exchangers, and discharge the waste water into the sewer system or a discharge area.	Lund et al. (1974)
	Oregon	Greenhouse heating	4.1×10^{10}	Steel-framed fiberglass greenhouse; 70° F year-round, automatic environmental control system; heat exchanger; tomatoes; 2415 m ² of greenhouse.	Head (1970)
	Imperial Valley, California	Recovery of potassium chloride from geo- thermal brine	Small		Muffler (1973)
	Imperial Valley, California	Production of dry ice from CO ₂ in the Salton Sea geothermal area	—		Muffler (1973)
USSR		Total	1.3×10^{13} to 4.2×10^{14}		
	Makhach-Kala	District heating	1.1×10^{12}	Several districts are supplied, one of which has 15,000 inhabitants. 23 kg/s at 63°C plus 70 kg/s, plus others	UNESCO (1970)
	Zgoudidi town, Georgia	District heating	5.0×10^{12}		UNESCO (1970)
	Mendji, Georgia	Heating of metero- logic station and agricultural uses	2.0×10^{12}		UNESCO (1970)
	Zaichi, Georgia	Heating of metero- logic station, hothouses, and baths	2.1×10^{12}		UNESCO (1970)

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Table 7 (continued)

<i>Country</i>	<i>Locality (where applicable)</i>	<i>Description of Application</i>	<i>Associated Power (J/d)*</i>	<i>Comments</i>	<i>Source</i>
USSR	Iserback town, Daghestan	District heating	6.3×10^{11}	Heating for 7500 inhabitants and industrial users	UNESCO (1970)
	Caspilsk town, Daghestan	District heating and hot water supply	5.0×10^{11}		UNESCO (1970)
	Paratounka, Kamchatka	Heating of apartments	5.4×10^{10}	Three apartment buildings of 48 apartments each	UNESCO (1970)
	Cherkesk, Stavropol	District heating, industrial uses, and hothouses	2.2×10^{12}	Heating for 18,200 inhabitants, plus industrial uses and hothouses	UNESCO (1970)
	Makhach-Kala and other localities	Greenhouse heating	1.1×10^{12} to 4.2×10^{14}	1,002,240 tons of tomatoes, cucumbers and other vegetables per year. Reported area varies from 5500 to 25,000,000 m ² of greenhouses.	UNESCO (1970) Peterson et al. (1975)
	Lorinsk	Animal husbandry	Small	Part of the Chukotsk collective farm	UNESCO (1970)
	Various localities	Animal husbandry	Small		
Yugoslavia		Total	4.2×10^{11}		Questionnaire
World Total			5.0×10^{14} J/d (7000 MW)		

Note: Many of the entries on specific applications are from Howard et al., 1975, but original source is cited here.

*The associated power is as reported by the countries in the survey or by the reference. It may be either the power associated with the well flow or the power actually used in the application.

A number of unique systems exist in one or more of the many geothermal space heating applications. For example, in Russia, France, and the United States, electrically powered heat pumps are used in conjunction with geothermal resources to provide either base or peak heating. In Rotorua, New Zealand, cooling with geothermal energy is accomplished using an absorption system.

Industrial Applications

The pulp, paper, and wood processing plant of Tasman Pulp and Paper Company, located in Kawerau, New Zealand, was the first major industrial development to utilize geothermal energy for heating purposes. The plant site was chosen because of the availability of geothermal energy. The geothermal energy was first used for timber drying in kilns and for wood preparation in 1957, then for the pulp and paper operation in 1962. Steam at pressures of 6.9×10^5 and 1.4×10^6 Pa is used for the various heating requirements of the plant. This system has been operating quite satisfactorily and has a power output of about 100-125 MW. A unique feature of the plant is the standby 10-MW noncondensing turbo-alternator, which is given priority for the geothermal steam in the event of a failure in the external electric power supply.

The production of diatomaceous earth at Namafjall, Iceland, is a significant development for geothermal energy in industrial applications. It is not only a large-scale application, it is also an example of the way in which geothermal energy can make a process economical, when it could not otherwise be justified.

Following the discovery of rich deposits of high-grade diatomite on the bottom of Lake Myvatn, technical and economic studies indicated that only by the use of potentially cheap geothermal energy from the nearby Namafjall high-temperature geothermal field could the recovery and drying of the diatomite be competitive with conventional diatomite production from comparatively dry land.

In late 1967 operation of the diatomaceous earth plant began with a production rate of 12,000 t/yr. In 1970 the plant expanded and production increased to 24,000 t/yr. The geothermal fluid, obtained from the wellhead at 250°C and a pressure of at least 3.9×10^6 Pa, is flashed to provide saturated steam at 1×10^6 Pa pressure that is transmitted to the plant. In the plant, the energy is used for drying, slurry heating, space heating, and de-icing storage reservoirs during winter. The total consumption during the winter amounts to about 50 t/h of the 1×10^6 Pa steam.

Another use that is indicative of the wide variety of applications for geothermal energy is the present use of relatively low-temperature waters to thaw large areas of ground to allow mining in certain regions of the USSR.

Agricultural Applications

The three primary agricultural applications of geothermal energy are greenhouses, animal husbandry, and aquaculture. By far the most extensive use of geothermal fluids is in greenhouses. This application is most common in regions where growing seasons are short and greenhouses are necessary to meet the local demand for vegetables. In Iceland most of the tomatoes, lettuce, cucumbers, and other fresh vegetables are grown with geothermal energy supplying the heating energy. Similarly, the USSR and Hungary have extensive greenhouse applications that use geothermal energy. The animal husbandry and aquaculture applications are much more restricted than are the greenhouses. Hungary has the only large application of geothermal energy for animal husbandry, and it is expected that this will not be a significant, widespread use for geothermal energy in the future. There are only a relatively few small aquaculture applications that use geothermal energy at this time.

POTENTIAL USES

Many other processes may be adapted to directly utilize geothermal energy. Because geothermal energy is thermal energy at a relatively low temperature (compared with that available from fossil fuels) and its direct use is limited to an area of several tens of kilometers surrounding the geothermal site, there are two main factors regarding the energy use in the particular process that must be considered when evaluating potential industrial uses. The first of these is the minimum temperature range of the geothermal fluid that can satisfy the potential use. The second is the energy-cost-intensiveness of the potential application (i.e., the energy cost to produce the product relative to the value of the product itself).

If the required temperature and the resource temperatures are compatible and the process is energy-cost-intensive, then there is a good chance that the use of geothermal energy in the process will be economical. The location of the raw materials with respect to the geothermal resource is also an important factor. If the process is not energy-cost-intensive, it probably will not be a good candidate for geothermal energy use, regardless of the temperature, unless the energy consumption in the particular industry is very high and there is an excellent

match in the location of the process, the raw materials, and the geothermal resource.

Figure 6 illustrates the approximate minimum required temperatures of geothermal fluids for a variety of applications. The figure shows the temperature requirements of both the present applications and a number of potential applications. In general, as the geothermal fluid temperature increases, the application heat transfer equipment costs decrease and the operation becomes more economical. Exceptions to this occur when the increased temperature is accompanied by increased corrosion and scaling in the system and when the increased temperature causes more complicated design problems, such as pressurization of the entire system.

Table 8 lists the energy-intensiveness of a variety of industrial processes, and Table 9 lists processes that have had detailed studies of their potential for use of geothermal energy. Production of heavy water and fresh water appear to be very good potential uses of geothermal energy, the first depending on the need, and the latter on the coincidence of the need and the geothermal resources. A number of the other energy-intensive uses in Table 8 have been examined for their potential for geothermal energy use. For many, the potential for geothermal use appears good. However, for a number of processes the electricity requirements are also quite large and the steam requirements could be generated quite cheaply in a combined system with electricity generation. For these, geothermal energy may not be competitive unless the resource is also adequate for electricity generation.

PROBLEMS IN NONELECTRIC USES

Although nonelectric uses are potentially feasible for a wide variety of resource qualities, these uses are not without problems. Some of the problems are due to the use itself, while others are due to the type of resource available. One of the most readily recognized problems with direct applications, and the one that most significantly separates nonelectric from electric applications, is the fact that direct uses are necessarily restricted to relatively small areas centering on the resource. Electricity generated from geothermal resources, remote from load centers, can be tied into a grid system. But in direct applications, the thermal energy cannot be economically transported more than a few tens of kilometers, depending on the nature and size of the energy requirement.

Source: The Unesco Press, 1973.

Figure 6 Approximate geothermal fluid temperatures for nonelectric applications

Table 8

**ENERGY REQUIREMENTS IN RELATION TO PRODUCT VALUE FOR
A WIDE VARIETY OF PROCESSES**

<i>Product and Process</i>	<i>Steam Requirements (kg steam/kg product)</i>	<i>Product Value (¢/kg)</i>	<i>Steam per Unit Product Value (kg steam/\$ value)</i>
Heavy water by hydrogen sulfide process	10,000	6,614	151
Ascorbic acid	250	551	45
Viscose rayon	70	165	42
Lactose	40	31	130
Acetic acid from wood via Suida process	35	22	159
Ethyl alcohol from sulfite liquor	22	15	142
Ethyl alcohol from wood waste	19	15	123
Ethylene glycol via chlorohydrin	13	29	45
Casein	13	123	10
Ethylene oxide	11	33	33
Basic magnesium carbonate	9	24	37
35% hydrogen peroxide	9	40	23
85% hydrogen peroxide from 35% H ₂ O ₂	4.75	—	—
Solid caustic soda via diaphragm cells	8	7	121
Acetic acid from wood via solvent extraction	7.5	22	34
Alumina via Bayer process	7	7	106
Ethyl alcohol from molasses	7	15	45
Beet sugar	5.75	22	26
Sodium chlorate	5.5	20	28
Kraft pulp	4.2	13	32
Dissolving pulp	4.2	—	—
Sulfite pulp	3.5	13	26
Aluminum sulfate	3.5	4	79
Synthetic ethyl alcohol	3	15	20
Calcium hypochloride, high-test	3.5	7	50
Acetic acid from wood via Othmer process	2.75	22	13
Ammonium chloride	2.75	13	21
Boric acid	2.25	11	20
Soda ash via Solvay process	2	3.3	60
Cottonseed oil	2	22	9
Natural sodium sulfate	1.8	3.3	54
Cane sugar refining	1.67	22	8
Ammonium nitrate	1.5	8	20
Ammonium sulfate	0.17	3.3	5
Fresh water from seawater by distillation	0.08	0.04	227

Source: B. Lindal (1973).

Table 9

POTENTIAL INDUSTRIAL USES OF GEOTHERMAL ENERGY

<i>Application</i>	<i>Description</i>	<i>Comment</i>	<i>References</i>
Production of heavy water	Production of heavy water by the hydrogen sulfide-water isotope exchange process	Good process for geothermal energy use since huge quantities of steam are required per dollar of product value; appears economical under proper conditions.	UNESCO (1970), Valfells et al. (1969), Valfells (1959)
Production of fresh water	Production of fresh water from either seawater or geothermal fluids	Promising process because of large quantities of energy required, but requires geographic coincidence of fresh water and geothermal sources. Use of geothermal fluid itself is interesting because of the already high enthalpy of the liquid.	Bodvarsson (1961), UNESCO (1970), Rex (1968, 1971), Barnea (1971), Guiza (1974)
Recovery of chemicals	Recovery of salt from seawater using geothermal energy	Found uneconomical. Also, novel scheme using glacial ice.	Lindal (1961b, 1967)
	Multiproduct recovery from seawater	Reference is largely a review of the possibilities and points out the more prominent candidates for recovery.	Ludviksson and Lindal (1966)
	Multiproduct recovery from seawater and/or geothermal brine	Reference discusses a sea-chemical complex and emphasizes extraction of common salt, calcium chloride, potassium chloride, and bromine from geothermal brine in the Reykanes peninsula of Iceland. Also considers magnesium chloride and soda ash production.	UNESCO (1970)
	Multiproduct recovery from geothermal brine	Production of minerals and fresh water from the geothermal brines in the Imperial Valley, U.S.A.	UNESCO (1970)
	Multiproduct recovery from geothermal brine	References discuss the possibilities of future chemical extraction from geothermal fluids in the USSR; bromine and iodine are emphasized but some reference is also given to alkaline metals, boron, lithium, and a few trace elements.	UNESCO (1970)

Table 9 (continued)

<i>Application</i>	<i>Description</i>	<i>Comment</i>	<i>References</i>
Production of alumina	Production of alumina from bauxite via Bayer process	Not in practice at time of study due to unfavorable market and raw material conditions.	Lindal (1961a)
Production of sulfur	Processing of sulfur ore with geothermal energy	Investigation still under way as of time of reference.	UNESCO (1970)
Mining	Use of geothermal energy in mining operations	Energy is required to ease mining operations and allow year-round mining in permafrost regions of USSR.	UNESCO (1970)
Refrigeration	Freeze-drying of foodstuffs using geothermal energy	Good potential use since the cost of conventional energy may be 45% of the processing cost in freeze-drying operations.	Ludviksson. (1970)
	Cooling with liquefied air	Process has been proposed a number of times, but no details have been given. Presumably, absorption refrigeration from geothermal energy would be used to decrease the power required in a conventional air liquefaction process.	

Source: Howard (1975).

In nonelectric applications a very significant factor, in addition to the size of the thermal energy demand and the distance between the resource and the market, is the annual load factor. Nonelectric geothermal systems are characterized by having substantially greater initial capital costs and lower operating costs than most conventional systems; consequently, when the annual load factor is low and the large capital investment is effectively used for only a small part of the year, the desirability of such a system markedly decreases. Space heating, one of the most potentially significant nonelectric uses, has quite low annual load factors in many of the heavily populated regions of the world. Iceland, which has enjoyed much success with geothermal space heating, requires space heating throughout the year and has a relatively high annual load factor of about 0.50 to 0.60. In comparison, a typical load factor for space heating systems operating in New York is about 0.2 to 0.3.

In addition, since geothermal energy requires large capital investments, it is very sensitive to interest-rate changes.

One technological problem may also substantially limit nonelectric applications at higher temperatures: as the geothermal fluid temperature increases, its tendency to cause corrosion and scaling also increases significantly. The usual surface heat exchangers that would normally be used in such applications are quite sensitive to corrosion and scaling, and an economical solution other than wasteful steam flashing has not yet been found.

Because nonelectric uses will almost exclusively utilize geothermal resources that are water-dominated and at the lower end of the temperature spectrum, the overall enthalpy drop per unit mass flow of geothermal fluid can be relatively small and the total flow rate of fluid can be very large. Often this fluid is not compatible with surface disposal and reinjection must be considered. Widespread experience with reinjection of the magnitude required in such applications does not exist, and substantial study and experimentation are required before the design for such disposal systems will be routine.

ECONOMICS

The economic feasibility of a nonelectric geothermal system depends on a number of factors. Hypothetical economic evaluations are open to question until all factors have been examined and practical experience provides realistic data. Economic data in the literature are most prevalent for space heating systems and show that geothermal systems can be economical relative to conventional systems under the right circumstances. The following two examples illustrate the comparison. Zoega (1974) reports the unit prices for heating in Reykjavik with different fuels as presented here in Table 10. Purvine (1975) reports that the cost of heating a college campus at Klamath Falls, Oregon, with geothermal energy is about one-tenth the cost that it would be if conventional fuel were used: 0.46 U.S. $\text{\$/m}^2$ of floor space for the geothermal system compared with 4.6 U.S. $\text{\$/m}^2$ of floor space for the conventional system. These costs may be on the low side, since the cost of capital was not included. The apparent inconsistency of greater economic advantage of geothermal energy in Klamath Falls compared with Reykjavik is a result of the college campus being a single concentrated load with small distribution charges, while about 60% of the Reykjavik heating cost results from distribution.

Table 10

**COST FOR SPACE HEATING WITH VARIOUS FUELS
IN REYKJAVIK, ICELAND**

<i>Source</i>	<i>Cost (U.S. ¢ /kWh)</i>
Geothermal district heating	0.53
Light fuel oil	2.18
Heavy fuel oil	1.04
Electricity (hydro)	1.44 to 2.91
Surplus electricity (night)	0.91

Source: Zoega (1974).

OUTLOOK FOR THE FUTURE

The total amount of geothermal energy contained in the geothermal resource base of the world was shown to be large. How rapidly this large resource will be developed throughout the various countries is not really evident at this time. However, recent price increases of fossil fuels in world markets should stimulate such development.

Since many of the nonelectric applications can use low-temperature resources, the total resource base given in Table 11 may be used for such applications. A large fraction of the energy requirements of most of the world's present societies could conceivably be satisfied with thermal energy from geothermal resources. There are, however, many factors that must be evaluated to determine the feasibility of application at each resource site. Although space here does not permit a full discussion of these details, there are a number of factors that generally indicate the desirability of applications:

Space Heating: The area to be heated must be close to the resource site; the higher the annual load factor the better; the institutional barriers of having district heating systems must be removed.

Industry: The energy use and/or energy-intensiveness of the process must be high; the raw materials source and resource location must be compatible; if large amounts of electricity are required in addition to thermal energy, the geothermal resource should also be able to produce electricity.

Table 11

**PROJECTED NONELECTRIC APPLICATIONS OF
GEOTHERMAL ENERGY
(calculated)**

<i>Country</i>	<i>Nonelectric Energy Potential, Classes 1 and 2 Resource Base (GW [th])</i>	<i>1985</i>	<i>Nonelectric Power Potential (GW [th]) 2000</i>	<i>2020</i>
USSR	22,000	3500	12,000	20,000
United States	17,000	3000	8,500	15,000
China	12,000	2000	6,000	11,000
Canada	12,000	2000	6,000	11,000
Brazil	8,000	1500	4,000	7,500
Pakistan	8,000	1500	4,000	7,500
Australia	7,000	1000	3,500	6,000
Mexico	3,000	500	1,500	3,000
Peru	3,000	500	1,500	3,000
India	3,000	500	1,500	3,000
Argentina	2,500	400	1,300	2,400
Sudan	2,500	400	1,300	2,400
Ethiopia	2,000	350	1,100	2,000
Zaire	2,000	350	1,100	2,000
Algeria	2,000	350	1,100	2,000
Saudi Arabia	2,000	350	1,100	2,000
Iran	2,000	350	1,100	2,000
Greenland	2,000	350	1,100	2,000
Chile	2,000	350	1,100	2,000
Indonesia	1,500	250	800	1,500
Colombia	1,500	250	800	1,500
Bolivia	1,500	250	800	1,500
Chad	1,500	250	800	1,500
Turkey	1,200	200	600	1,100
Angola	1,100	180	550	1,000
South Africa	1,100	180	550	1,000
Ecuador	1,100	180	550	1,000
Kenya	1,000	170	500	900
Tanzania	900	150	450	800
Japan	900	150	450	800
Egypt	900	150	450	800
Nigeria	800	140	400	700
Zambia	800	140	400	700
Venezuela	800	140	400	700
Philippines	700	120	350	650
France	500	80	250	450
New Zealand	400	70	220	390
Iceland	200	40	120	220
Hungary	100	15	40	75

Agriculture: The main applications are greenhouse heating and aquaculture. Both of these appear to be growing in significance and have very good potential applications in countries at higher latitudes. The main limitation to such applications will come from competition with the huge quantities of waste heat available from large fossil- or nuclear-fueled electricity generating plants. The geothermal systems might have a location advantage, and in many small countries they would not have the power stations to compete with.

Drilling depth required to recover the resource is also a very important factor. The maximum economically allowable depth is dependent on many variables, one of which is the resource temperature. In general, the maximum economically allowable depth increases as the resource temperature increases, and although the resource base for all classes was considered to extend to 3 km, only classes 3 and 4 could be expected to be economically recoverable at depths approaching 3 km.

An estimate of the worldwide nonelectric use potential that is limited by the resource can be made in a manner similar to that for electricity generation in Section 2. The estimate has an additional degree of uncertainty compared with that for electricity generation, however, because the overall conversion efficiency varies not only with the resource type and the other items considered for electricity generation but also with the particular type of process. For example, a specific process may extract a temperature drop of only 20 K from a geothermal fluid originally at 273 K (100°C), while an integrated process facility may extract 40-50 K. The estimate can be made by developing individual conversion factors similar to those developed in Section 3. However, since an estimate is to be made for the actual direct thermal use and not the thermodynamically maximum use, energy qualities rather than available energy quantities are of interest. With the nomenclature of Section 2, the factors are estimated as follows and denoted by ' to distinguish them from the values for electricity generation.

Available Energy Fraction, F'_a : The hot rock fraction is the energy obtained from cooling the resource from T_1 to T_2 relative to the resource base.

$$F'_a = \frac{E_{1-2}}{Q} = \frac{T_1 - T_2}{T_1 - T_0}$$

Wellhead Fraction, F'_w : The wellhead fraction is estimated to be the same for both electric and nonelectric applications.

$$F'_w \approx F_w$$

Heating Plant Input Fraction, F'_{hpi} : The pressure drops that occur in the piping and flashing represent very small losses for most direct thermal processes, and F'_{hpi} is estimated at 0.90 to 0.95.

Heating Plant Conversion Fraction, F'_{hpc} : The heating plant conversion efficiency depends very much on the type of plant. For an extensive district heating system with a large amount of distribution piping, F'_{hpc} may be slightly less than 0.8, while for a compact processing plant it might be 0.95.

With these factors and the data presented in Table 3, the geothermal nonelectric potential for the world is estimated at $4.2 \times 10^{23} \text{ J} = 1.45 \times 10^8 \text{ MW cen(th)}$. This estimate is based on the following:

- Only classes 1 and 2 of the resource base are considered for nonelectric uses (although some Class 3 resources are now being used for such).
- Only 20% of the total resource base will be considered as being convertible by present technology.
- On the average, $T_1 = 340 \text{ K}$ (67°C) and $T_2 = 330 \text{ K}$ (57°C) for the Class 1 resource; for the Class 2 resource, $T_1 = 400 \text{ K}$ (127°C) and $T_2 = 360 \text{ K}$ (87°C). (The T_2 values are different for the two resources because of differences in the processes that would use the resources.) With $T_0 = 288 \text{ K}$ (15°C), these yield $F'_{ic} = 0.19$ and 0.36 for classes 1 and 2 respectively.
- Mean values of $\eta_0 = (0.19)(0.4)(0.9)(0.9) = 0.05$ and $(0.36)(0.4)(0.9)(0.9) = 0.12$ will be used as averages for resource classes 1 and 2, respectively.

The estimate of worldwide potential for installed nonelectric capability for the years 1985, 2000, and 2020 becomes 25×10^6 , 80×10^6 , and 120×10^6 MW (th), respectively.

In comparison, Table 12 illustrates the questionnaire results for projections of nonelectric applications of geothermal energy in the years 1985, 2000, and 2020. Using the above methodology to estimate the potential for just the countries listed in Table 12 gives totals of 7×10^6 , 20×10^6 , and 30×10^6 MW (th) for 1985, 2000, and 2020, respectively. These values are two or three hundredfold larger than the estimates listed in Table 12 from the questionnaire, where the totals are about 2×10^4 , 6×10^4 , and 14×10^4 MW (th) for the same years. The large difference between the estimated potential and the estimated projected use is expected and reflects the following: (1) much of the Class 1 and Class 2 resource base may not be economically recoverable because of its occurrence at the greater depths (2 to 3 km) considered in the resource base, which is particularly true of the Class 1 resource; (2) limits on the anticipated domestic market for thermal energy near the resource; (3) availability of inexpensive low-temperature thermal energy (e.g., waste thermal energy from electric power plants and solar energy; and (4) site-specific difficulties such as mountainous terrain, land-use restrictions, and recreational use of the resource.

The estimates of the potential and projected uses reveal that a number of countries are planning substantial contributions from geothermal energy through nonelectric applications, but these contributions represent less than 1% of the total potential. The use estimates indicate roughly a two- to fourfold increase by 1985, a six- to tenfold increase by 2000, and up to a twentyfold increase by 2020, compared with the present use as illustrated in Table 12. It is evident that in the next several decades there will be significant progress, developments, and applications in this area. Countries that have promising geothermal resources but at present have not investigated nonelectric applications of geothermal energy would be well advised to consider this resource.

- Only classes 1 and 2 of the resource base are considered for nonelectric uses (although some Class 3 resources are now being used for such).
- Only 20% of the total resource base will be considered as being convertible by present technology.
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Table 12

**PROJECTED NONELECTRIC APPLICATIONS OF GEOTHERMAL ENERGY
IN THE YEARS 1985, 2000, AND 2020**
(results from questionnaires)

Country	Temperature Range of Expected Use ($^{\circ}\text{C}$)	Projected Nonelectric Use in Each Year (J/d)		
		1985	2000	2020
Canada	50-100	8.4×10^{11}	—	—
	20-50	4.2×10^{10}	—	—
England	Total	Small	$< 2.9 \times 10^{14}$	—
France	50-100	4.2×10^{13}	4.2×10^{14}	—
	20-50	—	Small	—
Hungary	100-150	—	$0-4.2 \times 10^{13}$	$0-8.4 \times 10^{13}$
	50-100	$2.8-4.2 \times 10^{11}$	$6.3-12.5 \times 10^{13}$	$1.1-2.9 \times 10^{14}$
	20-50	$1.5-2.5 \times 10^{13}$	$3.1-5 \times 10^{13}$	$5.9-8.4 \times 10^{13}$
Iceland	150-200	5.9×10^{12}	1.8×10^{13}	2.6×10^{13}
	100-150	1.3×10^{13}	2.9×10^{13}	5.0×10^{13}
	50-100	2.9×10^{13}	5.0×10^{13}	6.7×10^{13}
	20-50	1.0×10^{12}	2.0×10^{12}	4.0×10^{12}
Italy	Total	3.3×10^{12}	—	—
Japan	Total	2.7×10^{14}	—	—
Korea	50-100	3.6×10^6	—	—
	20-50	2.1×10^6	—	—
Mexico	Total	5.9×10^{13}	—	—
New Zealand	Total	3.3×10^{13}	5.0×10^{13}	—
Nicaragua	150-200	$< 4.2 \times 10^{14}$	$< 4.2 \times 10^{14}$	4.2×10^{14}
	100-150	1.3×10^{15}	2.5×10^{15}	4.2×10^{15}
	50-100	$< 4.2 \times 10^{14}$	$< 4.2 \times 10^{14}$	4.2×10^{14}
	20-50	—	—	—
Spain	Total	8.4×10^{11}	4.2×10^{12}	—
Sweden	50-100	—	$2.1-4.2 \times 10^{13}$	6.3×10^{13}
	20-50	—	2.1×10^{13}	4.2×10^{13}
Taiwan	150-200	1.7×10^{11}	4.2×10^{11}	8.4×10^{11}
	100-150	8.4×10^{10}	2.1×10^{11}	8.4×10^{11}
	50-100	1.3×10^{11}	4.2×10^{11}	1.3×10^{12}
	20-50	4.2×10^{10}	2.1×10^{11}	4.2×10^{11}
Yugoslavia	Total	5.0×10^{12}	2.1×10^{13}	4.2×10^{13}
United States	Total	2.9×10^{14}	$1.3-2.9 \times 10^{15}$	$8.4-16.8 \times 10^{15}$

Section 5

RECENT INTERNATIONAL DEVELOPMENTS

This section discusses the status of geothermal energy development in countries for which information is available from public documents or through responses to the questionnaire. It does not include estimates of the national geothermal resources calculated in Section 2, based on regional geology, volcanism, and other factors. Most of the data came from the responses to the questionnaire, although much information was obtained from literature sources such as the Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources.

In keeping with the World Energy Conference classification, the countries have been grouped by major geographic region in the following order: North America, Central America, South America, Western Europe, Eastern Europe, Asia, East Africa, and Oceania.

NORTH AMERICA

Canada

Geothermal development in Canada is in the preliminary stage and therefore does not provide sufficient information for a detailed assessment of the resource. Suffice it to say that the western part of Canada is in a geothermal region and it is therefore likely that intensive geothermal exploration will discover significant resources. At present, geothermal electric power capacity is estimated to reach 10 MW by 1985. Direct heat utilization would probably constitute the most important use of the resource in the near future, reaching perhaps 8.4×10^{11} J/d by 1985. The estimated total resource base of geothermal energy to a depth of 3 km and above 15°C is 1.7×10^{24} J.*

*All estimates given in this section are based on the questionnaires and available reports as distinct from our own estimates. See Section 2, Assumption 5, for the definition of resource base.

Mexico

A successful geothermal power plant of 75 MW (e) capacity has been in operation at Cerro Prieto since November 1973. The plant is presently being expanded through additional drilling and construction work to achieve a capacity of 150 MW in the near future. Informal estimates suggest that the Cerro Prieto field will support 500-1000 MW (e) capacity. Temperatures above 340°C have been recorded in some of the holes drilled most recently.

Extensive exploration is taking place in many other areas of Mexico, especially at Ixtlan, Los Negritos, and Los Azufres. It is estimated by the Comisión Federal de Electricidad that 400-1400 MW of geothermal electricity would be on stream by 1985 and 1500-20,000 MW by the year 2000. The ultimate geothermal potential of Mexico is variously estimated at 4000-20,000 MW (e).

United States

The largest geothermal power installations in the world at present are in the United States. By the end of 1976, 502 MW of installed electric capacity were in existence in the United States, all in The Geysers region of California. In that region a total geothermal power capacity of 2000-4000 MW is estimated to exist. The Geysers field is a high-quality vapor-dominated field that will increase in importance in years to come. The slow development of the field is primarily due to a variety of environmental and legal roadblocks.

Active exploration and drilling is presently going on in the United States in more than twenty separate areas (Figure 7). A major area of exploration is the Imperial Valley of California, just north of the successful geothermal power development at Cerro Prieto, Mexico. Four different geothermal fields have been discovered so far in the Imperial Valley: Niland, Brawley, Heber, and East Mesa. Estimates of the total geothermal capacity of the Imperial Valley for electric power production vary widely, ranging from 1500-20,000 MW (e) capacity. Severe salinity problems have been encountered in the Niland field near the Salton Sea, where dissolved solids concentrations of more than 25% have been encountered in a high-temperature field of large dimensions. The temperature range of the geothermal reservoirs encountered to date varies from 180°C in the Heber field up to 360°C in the Niland field.

Figure 7 Locations of geothermal drilling in the United States and northern Mexico

Successful discoveries have been reported in the Valles Caldera in New Mexico and the Roosevelt field in Utah. Both fields are reported to be high-temperature liquid-dominated geothermal reservoirs. It is informally estimated that the Valles Caldera field will support at least 100 MW (e) capacity. It is unknown as yet what the ultimate capacity of the Roosevelt field will be because only limited exploration has been completed. However, initial results have been encouraging inasmuch as one of the early exploration wells has produced a mass flow capable of supporting more than 15 MW (e) capacity.

It is the goal of the Department of Energy (DOE) to achieve a minimum geothermal power capacity of 6000 MW by 1985 and more than 20,000 MW of electricity by the year 2000. At the same time, considerable effort is being devoted to the study of direct heat uses since a large portion of the energy used in the United States is of the low-grade-heat type. The federal government, through DOE, will spend more than \$50,000,000/yr for the foreseeable future in an attempt to solve a variety of technical problems and stimulate private industry to explore and develop geothermal resources. As part of that effort, experiments are now being designed to exploit the geopressured resources of the Gulf Coast for the production of mechanical-pressure energy, geothermal heat, and methane gas.

Space heating is being implemented successfully in Klamath Falls, Oregon, and in Boise, Idaho, as well as in many other localities. The growing shortage of natural gas in the United States will no doubt cause an increase in the use of low-grade geothermal heat for both space heating and other direct heat uses such as greenhouses. The U.S. Geological Survey has estimated the recoverable heat in the United States to be about 3.5×10^{20} J of usable heat and up to 46,000 MW of electric energy.

CENTRAL AMERICA

Costa Rica

Active geothermal exploration is currently taking place in Costa Rica where the Las Pailas Hornillas area in the Guanacaste province is being investigated. Exploration drilling is scheduled to start by the end of 1977, and a geothermal power plant of 100 MW capacity is to be installed in 1982-1984.

El Salvador

Practically all of Central America is an intensely volcanic, highly active geothermal region. A 60-MW geothermal power plant has been in operation in the Ahuachapan field in El Salvador since 1976. That plant will soon be increased to 80 MW capacity through the development of a secondary flash system. It is the intention of the national electric authority in El Salvador (CEL) to develop at least 100 MW additional capacity from geothermal resources by 1985. Exploration efforts are currently proceeding at three promising geothermal fields: Chinameca, Berlin, and San Vicente.

Guatemala

In Guatemala, the national electric company (INDE), with the assistance of some outside consultants, is currently proceeding with geothermal exploration at the Moyuta field. No success has been achieved to date in proving geothermal steam for commercial power production capacity. However, simultaneous exploration through outside technical assistance is presently taking place at the Zunil prospect, and it is also likely that the Amatitlan geothermal area will be subjected to a closer examination in 1977. The objective of the present exploration in Guatemala is to achieve a minimum 100 MW capacity by the early 1980s.

Honduras

Honduras has just embarked on an aggressive geothermal exploration program. The national electric authority (ENEE) intends to explore two areas initially: the Pavana area near Choluteca in the southern part of the country and the San Ignacio area northwest of Tegucigalpa, the capital. The objective of that exploration program is to achieve a minimum of 50 MW capacity by 1982 and 100 MW by 1984-1985.

Nicaragua

Geothermal exploration is currently proceeding in Nicaragua, where active drilling is taking place at the Volcan Momotombo field. Sixteen exploration and development holes have been drilled to date. At present, the productive capacity of the wells is uncertain because of conflicting reports about their success. The national electric authority (ENALUF) hopes to achieve a 100 MW capacity from the Momotombo geothermal field by the early 1980s. It is estimated by ENALUF that 150-220 MW of geothermal power will be installed by 1985, 300-400 MW by 2000, and up to 800 MW by the year 2020.

Panama

Only minimal geothermal exploration has been carried out in Panama. Some attractive possibilities seem to exist in the region of Cerro Pando and Caldera-Chiriqui province. It is not possible at present to make a judgment on the ultimate potential of geothermal energy development in Panama. However, because Panama is in a major geothermal belt, it is likely that economically attractive geothermal possibilities would materialize in the course of exploration. Some projections suggest a probable installed geothermal capacity of 60 MW by 1985.

SOUTH AMERICA

Argentina

Geothermal exploration in Argentina has just been started under the auspices of the National Secretariat of Energy in cooperation with the Argentina Commission on Geothermal Energy. Geothermal activity is concentrated along the boundaries of the Andes range in the vicinity of recent volcanic activity. The principal area of investigation at present is the Copahue area in the Neuquen province. Detailed exploration will indicate the nature and quality of the geothermal resources in that area. Other areas, such as the Bahia Blanca and Rosario de la Frontera, are known to have hot water systems. It is hoped that 20 MW of geothermal power will be installed in the Copahue area by 1985. Only limited information about the ultimate potential of geothermal energy in Argentina is available.

Brazil

Geothermal exploration in Brazil has also just begun. At present there are at least 23 known hot springs, primarily in the state of Goias. There, two areas of hot springs--the Serra das Caldas, a well-known hot spring and resort area, and the Lagoa dos Peixes hot springs--indicate some potential and are presently being subjected to detailed investigation. Exploration is also planned for the regions of Bahia and Minas Gerais.

Chile

Exploration efforts in Chile, partially supported by the United Nations, have resulted in the discovery of the El Tatio geothermal field with a proven productive capacity of over 16 MW at present. Other regions of Chile show similar potential, notably the Puchuldiza and Pollo Quere in northern Chile.

Peru and Bolivia

No significant amount of geothermal exploration has been carried out as yet in Peru and Bolivia, but both countries are located in a region of active volcanism. Numerous hot springs and fumaroles are known to exist in these two countries. It is reported that discussions are under way between national authorities and some international organizations to assist in the exploration and development of geothermal resources.

WESTERN EUROPE

France

On the mainland, geothermal energy in France is likely to be used for direct heat purposes. In 1976 a geothermal heat installation near Paris provided heating for 10,000 apartments, resulting in an overall savings equivalent to 10,000 tons of petroleum. Other parts of France with the potential for geothermal heat applications include the Aquitaine Basin, Bresse, Limagne, and Alsace.

Extensive exploration of geothermal resources by the French government in Bouillante, Guadeloupe, have resulted in the discovery of a geothermal reservoir; it is expected that a small geothermal power plant of perhaps 10 MW will be installed on that island in the near future. It is expected that by 1985 the geothermal power plant at Bouillante might reach a 25 MW capacity. On the other hand, the direct heat utilization capacity in mainland France might reach 600-1700 MW (th) by 1985.

Greece

Geothermal exploration has been conducted in different parts of Greece since 1970. The most promising areas are the Ionian Islands, with the most outstanding potential existing on the islands of Milos, Santorini, and Nisiros. Some potential appears to exist also on the island of Lesbos, and there are warm springs in the regions of the Sperchios graben, Sousaki, Methana, and others. Geothermal drilling began on the island of Milos in 1972, and deep test drilling was done there in 1975-1976. Two deep test holes encountered temperatures higher than 250°C; however, both wells are reported to be characterized by relatively low flow rates.

Iceland

The chief use of geothermal energy in Iceland at present is for direct heating of homes in Reykjavik, the capital of Iceland. More than 340 MW (th) is presently being utilized for space heating in most of the homes in Reykjavik and neighboring towns. A small geothermal power plant is in operation at Namafjall, producing 2.5 MW (e). A 50-MW-capacity geothermal power plant is under construction at Krafla in an active volcanic zone. Subsequent to the start of construction the volcano became active, so the future of the power plant is somewhat uncertain at this moment.

It has been estimated that the high-temperature areas of Iceland have a production potential of 3200 MW (th) for fifty years and that the heat content of recoverable low-temperature resources may amount to the equivalent of 4 billion tons of petroleum. The estimated total capacity of geothermal electrical power in Iceland is expected to reach 150 MW by 1985, 500 MW by 2000, and perhaps as much as 800 MW by the year 2020. The chief use of geothermal energy in Iceland, however, is currently in direct heating. At present the total installed non-electric capacity is 3160 GWh/yr. The level of use is expected to increase to 10,000 GWh/yr (th) by the year 2000 and to perhaps 15,000 GWh/yr by 2020.

Italy

As of the first quarter of 1975, the total installed geothermal electric capacity in Italy was about 420.6 MW, of which 380 was in the Larderello region, 15 at Travale, and 22 in the Monte Amiata region (Figure 8). Italy pioneered the development of geothermal energy in the world when the first electric power generator was established at Larderello early in the 1900s. It is likely that a considerably accelerated geothermal exploration and development program will be taking place in Italy within the next few years. The total direct heat utilization (nonelectric) in 1976 was estimated at 2.1×10^{12} J/d. It has been estimated that the total geothermal power capacity in Italy might increase to perhaps 800 MW by 1985 and that direct heat utilization might increase by perhaps 60% over what it is at present. The total stored heat capacity in reservoirs of less than 100°C was estimated at 6.7×10^{21} J, and an approximately equivalent amount has been estimated for the reservoirs at a temperature range of 100-150°C.

Figure 8 Geothermal regions of Italy

Portugal

The chief exploration activity now taking place in Portugal is on the island of San Miguel in the Azores. There, geothermal exploration by the Institute of Geosciences, supported by an international contractor, is yielding initially promising results. Temperature gradients as high as $0.8^{\circ}\text{C}/\text{m}$ have been encountered in shallow test holes drilled in promising areas selected by prior geophysical investigations. The plans are to develop a 3-5 MW noncondensing geothermal power plant by 1978. In case of success, the geothermal exploration and development activity would continue, with the ultimate objective of developing at least 30 MW of geothermal electricity by the mid-1980s. Should a large geothermal reservoir be discovered, larger-scale development for industrial and other purposes might follow, with an ultimate objective of 100 MW or more by the year 2000.

Exploration in San Miguel is due to be followed in short order by exploration in the other islands, especially Terceira and Fayal. Exploration on the mainland of Portugal is under way, with the objective of developing hot water resources for nonelectric uses, mainly in the northern part of the country.

Spain

The main geothermal regions of Spain are located in the Canary Islands, especially at Lanzarote, where very high temperatures have been encountered at shallow depths. Intensive exploration is currently taking place at Lanzarote, with the objective of replacing the existing diesel power. Exploration in the mainland regions will revolve around the development of lower-grade geothermal resources for direct heating purposes. The objective of electric power development in Spain is to achieve a capacity of at least 25 MW (e) by 1985 and perhaps 200 MW by the year 2000. While it is difficult to estimate the nonelectric demand, it may range from 10 MW by 1985 up to 50 MW by the year 2000.

Sweden

At present there is no utilization of geothermal energy in Sweden. However, ongoing geothermal resource investigations suggest that some use will be made of hot water for direct heat purposes. It is estimated that by the year 2000 a total of $4.2\text{--}8.4 \times 10^{13}$ J/d will be yielded from geothermal water for nonelectric purposes. The estimated total stored heat to a depth of 3 km in Sweden is 4.2×10^{22} J.

West Germany

At present the only utilization of geothermal energy in West Germany is for non-electric purposes. At Urach and Wiesbaden the total installed capacity for non-electric purposes is approximately 4.5×10^{13} J/d. The estimated total energy resource base of West Germany appears to be approximately 1.4×10^{23} J to a depth of 3 km. The known hot water reservoirs in West Germany occur in the Rhine graben basin, the northern Germany basin, and the southern Germany (Molasse) basin.

United Kingdom

The United Kingdom appears to be a region of normal temperature gradient (25-30°C/km), with a few anomalous regions where temperature gradients reach 40-45°C/km (in southwest England). In the North Sea Basin, thermal gradients appear to be higher, at times exceeding 40°C/km. Electric power production from geothermal resources appears to be practicable only if technology for extracting geothermal heat from hot dry rock becomes successful (i.e., at the turn of the century or later). It is further estimated that direct heat utilization of geothermal energy may reach as much as 2.9×10^{14} J/d. The total resource base of geothermal energy to a depth of 3 km is estimated to be 5.4×10^{22} J on land and approximately 2.9×10^{22} J in the North Sea Basin.

EASTERN EUROPE

Hungary

Geothermal energy harnessed for direct heat uses is probably at its most advanced stage in Hungary. Extensive utilization is presently being made of low and intermediate geothermal heat for space heating, greenhouse heating, and industrial uses. It is estimated that present total utilization capacity of geothermal heat in Hungary is approximately 3.9×10^{13} J/d. Plans for further development suggest that the geothermal heat utilization will increase to 4.2-6.7 $\times 10^{13}$ J/d by 1985, 9.2-25 $\times 10^{13}$ J/d by 2000, and will ultimately reach as much as 1.7-4.6 $\times 10^{14}$ J/d by 2020.

In 1975 more than 430 wells were drilled in Hungary, which produced water at temperatures greater than 35°C at the wellhead and were utilized for direct heat. These wells produced over 460 m³/min of geothermal fluid, yielding over 1000 MW of thermal energy. The total usable heat in the recoverable water from the main reservoir in Hungary has been estimated to be 5×10^{19} J.

Soviet Union

Electric power is being produced on a small scale in the Soviet Union, mainly in the Kamchatka Peninsula. Two small power plants, one in Pauzhetska (producing 5 MW) and another at Paratunka (0.7 MW) have been operating for several years. At present geothermal energy in the USSR is primarily used as direct heat, including space heating, greenhouse operation, and industrial uses. More than 28 geothermal fields are now in use. Soviet scientists have estimated the potential yield of thermal water in the temperature range of 40-250°C to be $22 \times 10^6 \text{ m}^3/\text{d}$. The chief regions of geothermal exploration and development in the Soviet Union are in the Kuril Islands, Kamchatka, and the Caucasus belt. Some geothermal deposits appear to occur also in Siberia, Kazakhstan, and Middle Asia. It has been estimated that the hydrothermal deposits of Kamchatka alone have the capacity to support more than 350-500 MW (e) at present, although no specific plans for such utilization have been announced.

Yugoslavia

It is unknown whether any geothermal energy in Yugoslavia will be utilized for electric power production. However, it is assumed that geothermal heat will be used. The estimated utilization will be of the order of $5.0 \times 10^{12} \text{ J/d}$ by 1985, about four times as much by 2000, and about eight times as much by 2020. Not enough information is currently available in Yugoslavia on the potential of geothermal energy; however, reasonably steep temperature gradients of the order of 60°C/km are known to exist. The estimated reserve of geothermal energy below 100°C is $6.6 \times 10^{20} \text{ J}$.

Other Eastern European Countries

Limited exploration and use have been made of geothermal resources for non-electric uses in the rest of Eastern Europe. Geologic evidence suggests that the geothermal region of Hungary extends to Czechoslovakia and Rumania and that economically attractive temperatures may exist in regions of Austria as well. Some exploration in southwestern Poland suggests that temperatures up to 60°C may exist in depths of less than 1 km.

ASIA

China

Exploration in China is under way in the Himalayas, where 10 geothermal fields have been discovered to date. One of these, in the Ch'iang-T'ang region in the Tibetan highlands, will be developed to generate electric power in the near future. The recently discovered Ku-Tuë geothermal well near the Bhutan border has led investigators to conclude that the magma is very close to the surface along the Himalaya Range and that the geothermal potential is likely to be very great.

India

Geothermal exploration has been concentrated primarily in the northern regions of India. Exploration in the Puga Valley in the upper Himalayas close to the northern border of the country has found temperatures as high as 135°C at a depth of less than 100 m. Geochemical thermometry suggests that temperatures higher than 250°C may be encountered in deeper drilling in that region. Preliminary exploration in the Manikaran area suggests that reservoir temperatures of 200°C or higher may be encountered in this region. A series of intriguing hot springs runs along the entire northern and southern range of volcanic deposits in western India. At the northern end of that region, in the Cambay area, geopressured geothermal energy is likely to occur. There, in oil exploration wells, abnormally high wellhead pressures in excess of 100 kg/cm² have been encountered. A joint geothermal exploration program with the United Nations is now under way. It is likely to result in a rapid assessment of India's geothermal potential.

Israel

Exploration for geothermal resources in Israel was started in 1974. The Geological Survey of Israel conducted numerous field mapping and geochemical studies to identify geothermal resources in the Jordan rift valley and to compile a general heat flow map of the country. The hot springs in the Sea of Galilee region reach a temperature of 72°C. Chemical thermometry suggests that reservoir temperatures of at least 140°C may occur at depth in that region. Electrical resistivity surveys in the Jordan rift valley have detected a number of anomalously low resistivity areas that will be investigated more closely in the near future. Hydrogeological investigations of the central Negev region show that a warmer aquifer (approximately 40°C) underlies much of that region. Plans are now afoot to tap those aquifers for direct heat uses (greenhouse operations). A geo-

pressured system has been discovered in the Ashkelon region, but its pressure and temperature characteristics are not yet fully known. Hot springs in the Dead Sea region (Zohar and Ein Yesha) have been tapped for balneological purposes, and a thriving tourist industry is being developed around the springs. The Tiberius hot springs have been used since biblical times for therapeutic purposes and still have the remains of elaborate Roman spas.

Jordan

The outstanding geothermal springs in Jordan are the Zerka Ma'in Springs on the east side of the Jordan rift valley near the Dead Sea. The surface temperature of the Zerka Ma'in thermal springs is of the order of 64°C, and chemical thermometry suggests that reservoir temperatures may be higher than 180°C. At present, a preliminary evaluation of the Jordan geothermal potential is being conducted by a United Nations expert.

Turkey

Exploration drilling in the Kizildere field has resulted in the discovery of geothermal potential with a maximum temperature of approximately 207°C. However, because of serious calcium carbonate scaling problems, the field has not yet been used for commercial production. Instead, the geothermal fluid is presently being used for a pilot greenhouse operation. Extensive exploration activity by the Mineral Research and Exploration Institute of Turkey (MTA) has identified many other geothermal regions in the country. The MTA has estimated that geothermal energy is likely to supply 10% of the total Turkish electric energy requirements by the year 2000. Exploration activities in the Seferihisar and Tuzla regions of western Turkey have discovered areas of promising potential for the production of electricity from geothermal energy. Exploration activities elsewhere have suggested that in the regions near Kizildere and Ankara, significant geothermal energy potential does exist. At present the geothermal electric capacity in Turkey is only 0.5 MW. However, the exploration plans are to achieve a production capacity of 400 MW by 1985, 1000 MW by 2000, and perhaps 1500 MW by 2020. These are maximal estimates; other estimates are somewhat more conservative.

EAST AFRICA

Ethiopia

An active geothermal belt runs through the rift valley of eastern Africa, starting from the Red Sea to the north and continuing southward through the length of Ethiopia, Kenya, and Tanzania. Active volcanism is currently taking place in the Afar rift valley of northern Ethiopia, where the Erta-'Ale volcano has been boiling at 1000°C or more for over a century. It has been estimated that the amount of continuous heat flow necessary to keep the Erta-'Ale lava pool at its current temperature is equivalent to that of a 100-MW power plant at full capacity.

Three separate regions have been identified as potentially promising. The most attractive region for geothermal development appears to be the Danakil depression. In that region the Tendaho area seems to be particularly attractive, with geotechnical evidence suggesting the occurrence of high-temperature, low-salinity geothermal fields.

A number of favorable locations have been identified in the northern Afars area. At Dallol, geothermal springs with temperatures as high as 114°C at the surface have been measured. However, the problem confronting geothermal energy development in the Dallol area (other than the political instability of the area) is the very high salinity of the geothermal fluids. At present most of the geothermal exploration is centered on the lakes district north of Addis Ababa. Through a United Nations survey, a number of favorable geothermal prospects have been identified near Lake Langano and farther south.

The overall potential of geothermal energy in Ethiopia has been estimated from several thousand to perhaps as much as 20 GW. However, because of the small power demand in the country, the problem of developing high-quality geothermal resources, such as those at Tendaho, is associated with the cost of transmission from the remote prospect locations to the main grid of the country, sometimes more than 300 km away. Political factors have also caused a slowdown in developing the outstanding geothermal resources of the country. Therefore geothermal energy utilization has been restricted to minor balneological uses. However, there is no doubt that geothermal energy will eventually provide an important source of electricity in Ethiopia.

French Territory of the Afars and the Issas

Geothermal exploration in the region near Djibouti has encountered high geothermal reservoir temperatures (over 250°C at 1050 m); but because of the high salinity of the fluids, their utilization is fraught with problems.

Kenya

The geothermal exploration and development in Kenya is farther ahead than Ethiopia's. A successful exploration program at the Olkaria field about 50 km north of Nairobi has demonstrated the existence of a high-quality, low-salinity geothermal reservoir. Temperatures of up to 287°C have been encountered in drill holes less than 1.5 km deep. Further development drilling is due to take place at Olkaria, and exploration drilling is likely to take place in the near future in the Lake Hannington area to the north. Geophysical measurements of a third prospect, the Eburu Crater, have shown promising results.

The minimum installed capacity estimated by the East African Power and Lighting Company is 30 MW of electric power by 1985, 60-90 MW by 2000, and 90-150 MW by 2020. The stored energy in the Olkaria field has been estimated at 84 GW yr (gigawatt-years), of which 5% could be converted into electric energy.

Other East African Countries

Moderate exploration of the geothermal resources of Tanzania and Uganda has been carried out. On the basis of the limited exploration to date, it is too early to determine the ultimate potential of geothermal energy in those countries. Similarly, several geothermal indicators exist in Malawi and Burundi, but very little useful data are available to assess their commercial viability.

OCEANIA

Fiji

A number of hot springs, some at boiling point, suggest that geothermal potential may exist on Vanua Levu, the north island of Fiji. However, chemical thermometry indicates the base temperature of the reservoir to be quite low, of the order of 140°C. There are no immediate plans for development.

Indonesia

Indonesia is located along a major geothermal belt and is characterized by extensive volcanism and earthquake activity, common indicators of geothermal resources in the area. Extensive investigations of geothermal energy have been carried out at Java, Bali, and some other islands by the Geological Survey of Indonesia, by the PLN (the national electric authority), and by Petromina (the national oil company). In addition, technical assistance for the exploration of geothermal energy has been given by the governments of the United States and New Zealand. A 1927 exploration in the Kawah Kamojang near Bandung discovered that geothermal steam may be encountered at a very shallow depth. Renewed interest in the area spurred further exploration in 1973, with the assistance of the New Zealand government. As of May 1975, four holes had been drilled to depths of 500-800 m, and at least two have indicated the occurrence of dry steam underground. A small geothermal power plant is now being considered for the area, probably 15 MW initially.

The Dieng Plateau of central Java was investigated in the early 1970s by the Indonesia Power Research Institute with the assistance of the United States. Geophysical, geochemical, and drilling activities indicated the existence of a large, shallow geothermal system of the liquid-dominated type. Technical assistance missions by the United Nations and UNESCO have shown that many other geothermal areas in Java, such as Kawah Cibureum and Cisolok, are likely to be of interest. Informal estimates suggest that perhaps 20,000 MW of electric energy capacity occur in Java and as much as 60,000 MW in all of Indonesia.

The estimated minimum installed geothermal energy capacity in Indonesia will be 30-100 MW in 1985 and 500-6000 MW by the year 2000.

Japan

Japan witnessed a relatively slow growth of geothermal energy utilization for electric power production until the 1973 energy crisis. Prior to that only two electric generating plants using geothermal energy were in operation, in Matsukawa (22 MW) and Otake (13 MW). In 1976 the total installed geothermal power capacity in Japan was 68 MW. The energy crisis has stimulated the expansion of geothermal energy exploration. As a result it is anticipated that by the end of 1977 the installed geothermal power capacity will approach 150 MW (based upon the completion of a 50-MW power plant at Takinoue and the completion of a 50-MW plant at Hatchobaru). The current objective is to achieve an

installed geothermal electric capacity of 1000 MW or more by 1982 and about 2000 MW by 1985. In addition, ambitious geothermal investigations are currently taking place in Japan, with the goal of establishing as much as 50,000 MW electric capacity by the turn of the century.

More than 10,000 hot springs are known to exist in Japan. In the past they have been used primarily for balneological and religious purposes, with some minor uses such as fish breeding. Figure 9 shows the major regions of geothermal exploration in Japan at present. Approximately 2.5×10^{14} J/d are now being used for direct heat (nonelectric). The total geothermal energy resource of Japan, to a depth of 3 km, is estimated at 1.2×10^{21} J.

New Zealand

The presently installed geothermal plant at Wairakei has a capacity of about 190 MW (e). At Kawerau, geothermal energy is being used for the combined power production and direct heat needs of the Tasman Pulp and Paper Mill. In addition, geothermal energy is extensively used at Rotorua for space heating and, in one case, for air conditioning. A second geothermal field at Broadlands, to be commissioned in the early 1980s, is likely to be developed for power production, with an estimated capacity of approximately 150 MW. The total estimated geothermal power capacity of New Zealand is rated at approximately 2000 MW (e). It is estimated that 400 MW of geothermal electricity will be on stream by 1985, 1400 MW by the year 2000, and 2000 MW by the year 2020. The extent of direct heat utilization in New Zealand is expected to rise from 3.3×10^{13} J/d in 1985 to about 5.0×10^{13} J by the year 2000. The total resource base of geothermal energy in the explored areas of New Zealand is estimated to be 1.3×10^{20} J.

The Philippines

Extensive geothermal exploration has been taking place in the Philippines at the Tiwi, Leyte, and Los Banos areas. Successful exploration at Tiwi in southeastern Luzon has proved that sufficient geothermal steam exists for generating 100 MW electric power. The first 100-MW electric plant will be installed in 1977, to be followed shortly by another 100-MW plant in the same area. Promising exploration in the Los Banos area suggests that geothermal power may be developed there in a relatively short time. Plans in 1976 called for the installation of 300 MW of geothermal electricity by 1985. These plans are presently under review with the intent of increasing the number.

Figure 9 Major geothermal areas of Japan

Taiwan

No geothermal power plants are in operation in Taiwan, though significant geothermal potential does exist in the country. High-temperature reservoirs have been encountered in both the Tatun and Tuchang areas. In the Tatun area, temperatures are as high as 293°C, but because of the exceptionally high acidity of the water, no development was considered to be possible in that field. Current plans call for the development of 50 MW geothermal capacity by 1985, 200 MW by 2000, and perhaps 500 MW by 2020. The expected total capacity of direct heat utilization in Taiwan is 4.2×10^{11} J/d by 1985, three times as much by 2000, and five times as much by 2020.

Section 6

ENVIRONMENTAL CONSIDERATIONS

Geothermal energy promises to be less detrimental to the environment than energy derived from other sources; however, it is not environmentally benign and special consideration must be given to certain unique sets of possible problems. The amount of environmental control necessary will vary from country to country and region to region, depending on local air and water quality standards, on the characteristics of each geothermal reservoir, and to some extent on the power conversion process, whether it be flashed steam or some form of closed loop with reinjection.

Currently producing geothermal fields were developed with only the most rudimentary environmental controls, and several areas of concern have been identified as society has grown more environmentally aware. Not all fields will pose the same problems. A few of the more important considerations are as follows:

Waste brine disposal: If the geothermal fluid is partially or totally brine, the waste brine must be disposed of in a manner that will protect groundwater supplies needed for agricultural, domestic, or industrial uses. The methods of disposal thus far have consisted of surface streams, ponding and evaporation, and reinjection of the brine back into the reservoir. In some cases reinjection may be the preferred method, if there is a need to minimize ground subsidence or to replace the water in the reservoir to enhance production.

Noncondensable gases: Hydrogen sulfide and other noncondensable gases may affect air quality if the concentrations are sufficiently high and if they are vented to the atmosphere. Hydrogen sulfide appears to be the major offender, and present research is focusing on a solution to this problem. In some cases, the hydrogen sulfide concentration is so low that special controls may not be necessary. In others, stack disposal may suffice; and in some, sophisticated technology may be needed, depending on local factors.

Waste heat rejection: Geothermal power plants are less efficient than fossil fuel plants; roughly two to three times more heat must be rejected per unit of power. Where fresh water is in abundant supply, this may not be a problem, but in arid regions cooling water may be at a premium and could slow geothermal development unless suitable alternatives are available. One solution, if the plant is operated as a flashed steam facility, is simply to use the geothermal steam condensate as makeup water in the cooling tower. This approach could pose problems if the temperature of the resource is low and if binary cycles are used in which no steam is produced. It could also pose a problem where reinjection of all the fluids is desired. Some combination of alternative approaches may prove to be the best solution in the long run.

Subsidence: Withdrawal of fluids may result in subsidence if measures are not taken to minimize the effect. Some areas, such as low coastal zones, populated areas, and agricultural irrigation systems, may be especially sensitive to subsidence.

Noise: Vented wells or steam lines can create excessive noise. Muffler systems may be needed in noise-sensitive areas.

Other considerations: Toxic trace elements (such as arsenic and mercury), land use, cooling tower effluents, and seismicity may require consideration when assessing the environmental impact. However, these aspects appear to pose only minor problems.

Present environmental control technology will probably serve the geothermal industry's needs in the near term, and work is progressing on improved technology, particularly for the control of hydrogen sulfide emissions.

Section 7
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