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# Technology Forecast of United States Geothermal Energy Resource Development

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## ABSTRACT

This forecast defines the nature of the technology on which this industry depends, the technological impediments which, if uncorrected, might block its growth, the means available to overcome the impediments, and the range of energy production levels which might possibly be expected from this source. A complete relevance tree for geothermal energy technology was first constructed, and was followed by designed interviews with industrial and scientific authorities. The results of these two steps were analyzed in a series of energy system diagrams synthesizing the overall judgments about technologically feasible levels of development, unconstrained by economic and institutional considerations. In the accelerated case, U.S. geothermal electricity capacity results for 1985 are (MWe): vapor, 3500; liquid, 17 000; hot dry rock, 5000; geopressured, 10 000. The results for the year 2000 are: vapor, 10 000; liquid, 500 000; hot dry rock, 200 000; geopressured, 54 000.

After this analysis we developed an electric utility simulation model of the decision mechanism involved in the choice and construction of new central-station generating capacity. In effect, this system-dynamics model simulated the introduction of geothermal energy into the utility fuel choice for the U.S. The model incorporates economics, construction time, reliability, fuel availability, environmental factors, and technology. These forecasts simulate the real geothermal energy electricity capacity development and their results were as follows: for 1985, normal development 7000 MWe, accelerated development 19 500 MWe; for 2000, normal development 188 000 MWe, accelerated development 249 000 MWe.

## INTRODUCTION

In August 1973 we began a technology assessment of geothermal energy resource development for the U.S. National Science Foundation. As part of this assessment we made an overall technology forecast of the development of geothermal energy in the U.S. to the year 2000.

In making such a technology forecast for the development of geothermal energy, several phases must be considered. First of all, geothermal energy is a natural resource. Therefore, it was necessary to estimate the amount of resource residing in the earth, and in our case, in the U.S. After this was done, it was necessary to estimate the rate of discovery with time. Finally, even though estimates of the amount of resource and discovery were made, this did not tell us anything about the utilization of the geothermal energy. Therefore, it was necessary to estimate the feasible limits of utilization of geothermal energy with time.

The estimates described in the preceding paragraph represent the upper limit of what is technologically feasible in the development of geothermal energy in the U.S. The next step in our technology forecast was to estimate what would actually be developed and consumed in the USA until the year 2000. This type of estimate, of course, is very different from the preceding one. In this estimate, we take what has been established as technically possible and superimpose the limitations of (1) time; (2) rate of planning; (3) growth of energy demand; (4) education time among decision makers; (5) time for development of industrial machinery and systems; (6) time for exploration; (7) construction time of geothermal fields and power plants; and (8) time required to mitigate all the social, economic, and political problems which come into the development of energy systems. This second technological forecasting step was handled by a simulation decision model and will be discussed later in this paper. The results of this two-step technological forecast are power estimates for the amount of geothermal energy converted into electricity for the USA by year from 1973 to 2000. This is shown in curves coordinated with the development of the competing energy forms: coal, natural gas, oil, nuclear, and solar energy.

## LOCATION OF GEOTHERMAL RESOURCES

By far, most of the geothermal resources are located in the western and southwestern parts of the U.S. The presently identified recoverable water-steam geothermal resources in the U.S. are estimated at $10^{16}$ Btu; this is specifically defined by the U.S. Geological Survey (U.S. Department of the Interior, 1973). Undiscovered recoverable and submarginal resources to a depth of 10 km are estimated at $4 \times 10^{19}$ Btu (Peck, 1972). This is believed contained in about 97.8 million acres of land more or less evenly spread out over the western part of the U.S. About 1.8 million acres of land in the western states have now been classified as being within a known geothermal resource area (KGRA) according to the U.S. Geological Survey. This might be compared to the oil "reserves and resources" concept. The as yet unidentified water-steam geothermal resources are believed to be much greater. Many experts believe them to be greater than the U.S. coal or oil-shale resources. An additional 96 million acres are listed as having "prospective value" for geothermal resources. It is interesting that about 60 to 70% of all of this land is owned by the federal government. However, "the distribution, extent, and magnitude of geothermal resources are not well known" at present (U.S. Department of the Interior, 1973). There is a great pressing need for a good, large exploration program.

On the basis of the small amount of known information, the geopressure geothermal resource is believed to underlay about 150 000 square miles of the Gulf Coast area, extending from Texas through Louisiana and touching Mississippi (Durham, 1974). This resource is very unusual in that besides containing hot water it contains dissolved natural gas. It has been estimated that the energy potential of the Gulf Coast geopressured zone is 45 000 MW of power and $8 \times 10^9$ $ft^3$ of gas per day (Maasberg, 1974). This is based on a 20-yr production period.

The areas indicated above do not include all of the possible dry hot rock sites. The possible dry hot rock area with hot-rock reservoir temperatures in excess of 290°C, at a depth of 5 km, has been estimated at 95 000 square miles broadly distributed throughout the western U.S. by the Los Alamos Laboratory (Brown, 1973). This estimate is based upon geologic heat-flow data surveys. The amount of heat stored in the hot rock at depths of 10 000 to 30 000 ft is immense. Smith (1973) has estimated that all of the U.S. energy requirements for 1970 ($6.8 \times 10^{16}$ Btu) may be extracted from such basement hot granite by cooling 40 cubic miles by 200°C.

In summary, the total geothermal resource which may be available for technically feasible development is immense. There is a possible resource capability to supply a significant portion of the total U.S. energy demand in the next generations.

## GEOTHERMAL ENERGY CHARACTERISTICS

There are several major characteristics of geothermal energy which are more or less peculiar to this resource and set it apart somewhat from other fuels. These are discussed below.

1. The geothermal energy resource is spread out all over the western part of the U.S. and over a giant crescent of the Gulf Coast extending from Texas through Louisiana and into Mississippi, as well as offshore on the continental shelf. Thus, a vast part of the country is blessed with a geothermal energy resource. It should be noted that this part of the U.S. is the most thinly populated, except, of course, for California. Also, Alaska and Hawaii (U.S. Congress, Senate Committee on Interior and Insular Affairs, 1973) have large potential geothermal resources.
2. From 60 to 70% of the geothermal resource is estimated to be on federal land. Thus, most of the geothermal resource will be directly subject to U.S. Government regulations in development. The environment impact statement for these lands was approved in December 1973 and the competitive leasing of the first 50 000 acres of government lands occurred on 22 January 1974. Besides this land, over 7 million acres have been claimed for geothermal energy exploration and exploitation in the western states (R. B. Hurlbert, 1974, personal commun.).
3. The potential geothermal energy resource available and which is technically feasible for development by the year 2000 is huge, as is shown by the results of this study. In one case the maximum, as predicted, could reach over 700 000 MWe by the year 2000. This would be about 20 to 30% of a predicted total U.S. demand for electricity. Therefore, potentially, the geothermal energy resource can be developed to be one of the major energy entities in the total fuel mix of the U.S. by the year 2000.
4. The environmental effects of utilizing geothermal resources are quite mild. Even though a considerable amount of surface land is required for geothermal plants, most of this surface land can be simultaneously used for such pursuits as farming.
5. The economic size of individual geothermal power stations is small, ranging from 50 to 250 MWe (Armstead, 1973). This may be contrasted to nuclear power plants which are now being built in the range of 1000 to 1500 MWe.
6. The geothermal energy capital and manufacturing costs appear to be approximately equal or lower than those for other fuel-electric combinations, although uncertainties exist at these beginning stages of the technology.
7. The basic geothermal energy resource, hot-water or steam, cannot be transported very far economically. The present range now practiced is 1 to 15 miles.
8. Finally, there is a very interesting characteristic of geothermal wells which should be noted. Once a well has been drilled and opened, it has been found the wiser course of action to leave it wide open unless long periods of shutdown are required. For short periods of time (days), the practice is to leave the well wide open. Frequent shutdowns of wells for short periods of time can lead to permanent damage to the wells. Such factors as stones and gravel stopping up the well, salts precipitating in the rock pores, salts precipitating and completely blocking the well, and condensate completely filling the well, have been found to occur. In many cases when wells have been shut down, the permanent damage has been so great as to require drilling a completely new well. Therefore, when the hot water or steam is not required for power production, wells are generally allowed to run free. Noting these technical operating characteristics, the operators of electricity power plants in the U.S., New Zealand, Japan, and Italy, prefer to base-load the geothermal power and not use it for peaking purposes.

## TECHNOLOGIC FEASIBILITY

The assessment of technologically feasible levels of development in the geology of the geothermal resources, in reservoir development technology, and in conversion technology, are indispensable to the appraisal of geothermal energy resources as a contributor to the U.S. energy picture. In this part of the project the main intent was to investigate the technological potential of geothermal energy rather than to consider questions related to economic feasibility. Therefore, the definition of crash program used in the analysis excluded monetary constraints, and the associated technology forecasts produced are technological feasibility upper limits on expected geothermal energy resources development. Because electric power is a universal energy form irrespective of specific energy end use and thus represents a logical framework for the evaluation of geothermal energy potential, the study focused specifically on the contribution of geothermal energy resources development to domestic electric power production.

## Background of Existing Forecasts

At the beginning of the study, existing estimates of geothermal resources of the U.S. and of the impact of the utlization of these resources on the nation's energy needs differed by as much as six orders of magnitude (U.S. Geological Survey, 1973). Resource estimates quoted in congressional hearings range from an equivalent of 5 GWe for 50 yr to 75 000 GWe for 100 yr (U.S. Congress, Senate Committee on Interior and Insular Affairs, 1972). Although the impact of geothermal resources on future domestic energy requirements is theoretically very large, the feasibility of large-scale commercialization largely remains unknown. A recent investigation forecasts that at least 19 GWe of generating capacity could be installed by 1985 using technology currently available or under development, and that more than 75 GWe probably could be installed by the year 2000, if a successful research and development program of moderate size were implemented (Hickel, Denton, and Dunlop, 1972). If a larger research and development program is developed quickly and is successfully executed, the same source estimates that the nation's geothermal resources could be supplying 132 GWe by 1985 (20% of total electric power generating capacity) and 395 GWe by 2000. In contrast to these forecasts, the National Petroleum Council (1972) estimates that by 1985 only 3 to 19 GWe could be installed, depending on various development emphasis assumptions. The national energy research and development plan recently published (1 December 1973) estimates commercial geothermal power of at least 20 GWe by 1985, 80 GWe by 2000, and 200 GWe by 2020 (Ray, 1973). In 1985 and 2000 this is equivalent to 0.7 and 3 million barrels of oil per day, respectively. The Project Independence Geothermal Energy Task Force Report (November 1974) estimates that 20 to 30 GWe by 1985 and 200 GWe by 2000 can be developed by a coordinated national program.

The wide range in estimates of the amount of geothermal power that may be produced in the form of electric power reflects a number of factors, the primary ones being the lack of factual knowledge of the resource itself and the differences in the assumptions concerning future technology.

Table 2. Relevance interrogation.

| | |
|---|---|
| Level 1. | What natural resources are available? |
| Level 2. | What primary energy forms can be developed from these natural resources? |
| Level 3. | What major technologies are associated with the development of these energy forms? |
| Level 4. | What applied technological areas are involved in these major technologies? |
| Level 5. | What systems, processes, or methods are involved in these applied technological areas? |
| Level 6. | What major components comprise these systems and processes, or what specific techniques are used in these methods? |

## Methodology

The methodology developed in this study consists of consideration of technologically feasible levels of geothermal resources utilization through the mechanism of individual evaluations of the availability of various technological subsystems, the lack of any one of which could impede this utilization. The technological subsystems considered are categorized under the general headings of resource exploration and appraisal, reservoir development, energy conversion, and environmental technologies.

The technology forecasts of the development of geothermal energy, information about the constraints to technological progress, and suggestions for means of removing these restraints were obtained in a four-phase methodology (Table 1).

1. First it was necessary to make a careful description and identification of the total content of geothermal technology down to the component level. This was done by developing a geothermal energy relevance tree. A relevance tree is a hierarchical structure in which the lower levels, in the aggregate, completely describe the upper levels to which they are connected. The first two levels of the relevance tree are given in Figure 1. Table 2 gives the relevance interrogation for all six levels. The complete tree is 84 pages long.
2. A complete list of impediments to the evolution of geothermal technology was drawn up. This list was carefully checked and extended later by comparing it to the completed technology relevance tree.

Table 1. Flow chart of methodology.

| | Phase | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| Major effort | Systematic description of present status of geothermal technology | Develop list of technological impediments to development | Obtain forecasts of impediments | Integrate forecasts |
| Method | 1. Relevance tree<br>2. Energy system approach | 1. Relevance tree<br>2. "Brainstorming"<br>3. Technical consultation | Interview | Energy system diagrams |
| Results | A. Decomposition of:<br>(1) geothermal technology into 4 subsystems<br>(2) resources into 5 types<br>(3) time into 3 time frames<br>B. Description of current status of geothermal technology | Preliminary list of 37 impediments to serve as starting point for Phase 3 | Forecasts on future status of all impediments, including broad subsystem impediments | Forecasts of technically feasible levels of geothermal energy resources development as functions of time, resource type, and research and development program. |

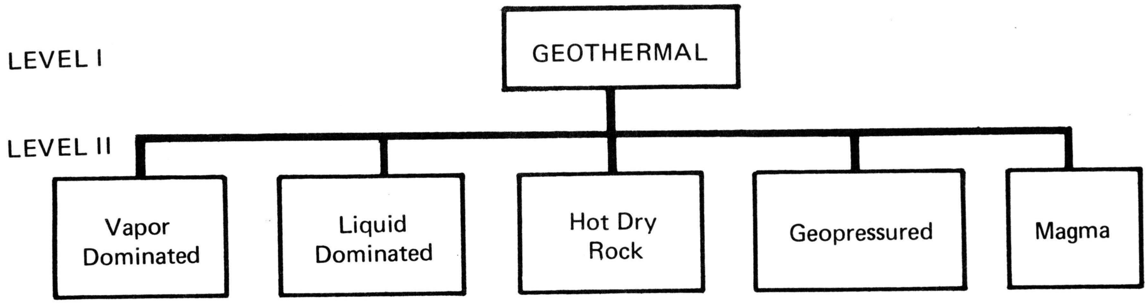

Figure 1. Geothermal relevance tree: the first two levels.

3. A carefully structured interview sequence was drawn up based on Steps 1 and 2. A group of respondents with the expertise needed to span the spectrum of disciplines from geology to rotation machines relevant to the development of geothermal technology was identified and invited to participate in a series of individual interviews. In all, 28 experts participated.

Information produced by this interview sequence included independent assessments of technologically feasible levels of identified resources and of industry capacity to bring identified resources to the earth's surface and convert them to electricity. Also, information was obtained on the nature of the associated technology impediments, and how and under what conditions the impediments could be removed, for each of the five types of geothermal resources and for the two research and development program scenarios. The results of these interviews were synthesized into energy system flow diagrams (Fig. 2) which integrated independent evaluations of: (1) the level of identified geothermal resources, (2) the capability of industry to develop the reservoirs, and (3) perform the thermal-electric energy conversion.

The systematic decomposition into smaller building blocks (subsystems) of geothermal energy systems has a dual advantage: (1) experts versed in one or more specific subsystems can describe the status of the subsystem, whereas very few persons are knowledgeable about the entire spectrum of technological impediments to geothermal technology; and (2) a breakdown of this nature is essential to policymakers charged with devising a research and development program that will enhance geothermal resources development in a cost-effective and timely manner.

In a further attempt to make a systematic assessment, geothermal energy resources have been categorized by five discrete types of resources and have been evaluated independently for various time periods. These are:

1. Vapor-dominated resources: naturally occurring, single-phase flow of thermodynamically saturated or superheated steam (no liquid).
2. Liquid-dominated resources: a naturally occurring, two-phase mixture of liquid (usually brine) and steam at an elevated temperature.
3. Hot dry rock: a geologic formation with very high heat content but which does not contain waters that would otherwise act as heat transport media.
4. Geopressured zones: extensive deep zones of pressurized brine with fluid temperatures in the 100 to 375°F range.
5. Magma: molten rock within the earth.

Technologically feasible levels of geothermal energy resources development have been evaluated under assumptions of a normal and a crash research and development program. The normal program was defined as a research and development program whereby geothermal technology continues to be developed on the same basis that is currently (1973) being developed, without additional, externally applied stimuli. The crash program is a research and development program whereby geothermal technology is developed under the stimulus of a declared national policy and massive government support, in which case cost is virtually no impediment.

## Results of a Technical Feasibility Study

Table 3 summarizes the results. The forecasted values for geothermal energy resources development represent what various geothermal experts consider to be technologically feasible levels of geothermal energy supply, and therefore are upper limits on the actual contribution of geothermal energy to electric power generation capacity.

The present installed geothermal electric generating capacity is 0.396 GWe. The technically feasible level of

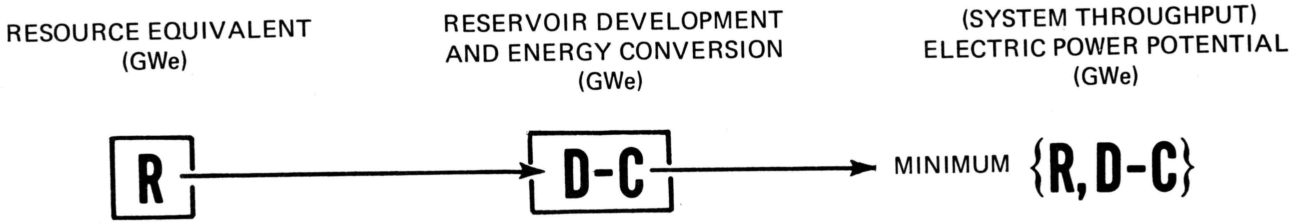

Figure 2. Sample energy system flow diagram. *R* is the forecast for resource equivalent, amount of electrical generating capacity which can be supported by forecasted level of identified resources for 25 yr, assuming a 10% overall conversion efficiency, for resource type program time. *D-C* is the forecast for reservoir development and energy conversion capability for resource type program time.

Table 3. Geothermal technology forecasts (all resources).

| Year | Level of development program | Technologically feasible electric power capacity (GWe) Range (all data) | Midrange | Median* |
|---|---|---|---|---|
| 1973 | — | 0.396 | — | 0.396 |
| 1985 | Normal | 5–24 | 9–11 | 10 |
|  | Crash | 12–142 | 27–40 | 35 |
| 2000 | Normal | 25–600 | 55–200 | 200 |
|  | Crash | 55–3430 | 270–800 | 770 |

* Median values are given here for convenience. The range of forecasts reflects better the present state of knowledge.

geothermal energy resources development is forecasted to be 10 GWe in 1985 and 200 GWe (median forecasts) in 2000 under normal program conditions. If a crash program is implemented, the corresponding values are 35 GWe in 1985 and 770 GWe in 2000. In reality, legal, institutional, and economic constraints will limit the amount of resource actually developed to a considerably smaller value.

As can be seen from the range forecasts in Table 3, considerable uncertainty exists among experts, a fact that is attributable both to the lack of factual knowledge of the resource itself and, more importantly, to the differences in assumptions one makes concerning future technology. Because of this uncertainty, the reader is cautioned against use of the median forecast out of the context of this paper; the range or midrange forecasts are a better reflection of the available information regarding technically feasible development of geothermal energy resources.

The potential relative contribution of each of the various types of geothermal resources to electric power supply is illustrated by Figures 3 and 4, which show the median forecasts for each resource type for 1985 and 2000, respectively. Analysis indicates that hot dry rock and liquid-dominated resources are relatively abundant, whereas vapor-dominated and, to a lesser degree, geopressured zone resources are relatively scarce. Accordingly, results for the year 2000 indicate small contributions from the two resource-limited types. On the other hand, it is the technology associated with the development of the hot rock resources, rather than a resource limitation, that will cause development of this resource to lag behind that of the liquid-dominated resources, according to most experts. The technological problems associated with development of magma resources restrict utilization of magma resources to negligible amounts.

The rather low forecasts for the 1985 level of feasible geothermal energy resources development indicate a rather insignificant role for geothermal energy in the U.S. fuel mix for some years to come. This is because the gestation time for commercialized geothermal energy will be 5 to 10 yr. After that, geothermal energy utilization may spread rapidly.

Forecasts for 2000 indicate a possible significant role for geothermal energy in the U.S. fuel mix by the end of the century, with a median forecast of 770 GWe under a crash development program, which would be approximately 40% of the total U.S. electric power supply. In this time frame, there is uncertainty among experts as to whether the levels of identified resources or the industrial capability for reservoir development and energy conversion will be more limiting. In the case of liquid-dominated resources, inadequacies in the level of identified resources and those of development/conversion capability appear to be approximately equal as limiting constraints.

Results of the analysis also indicate that the greatest impact of a crash development program, in terms of potential additions to the national fuel supply mix, will be to increase development of liquid-dominated and hot dry rock resources, due primarily to the fact that resources for these two types

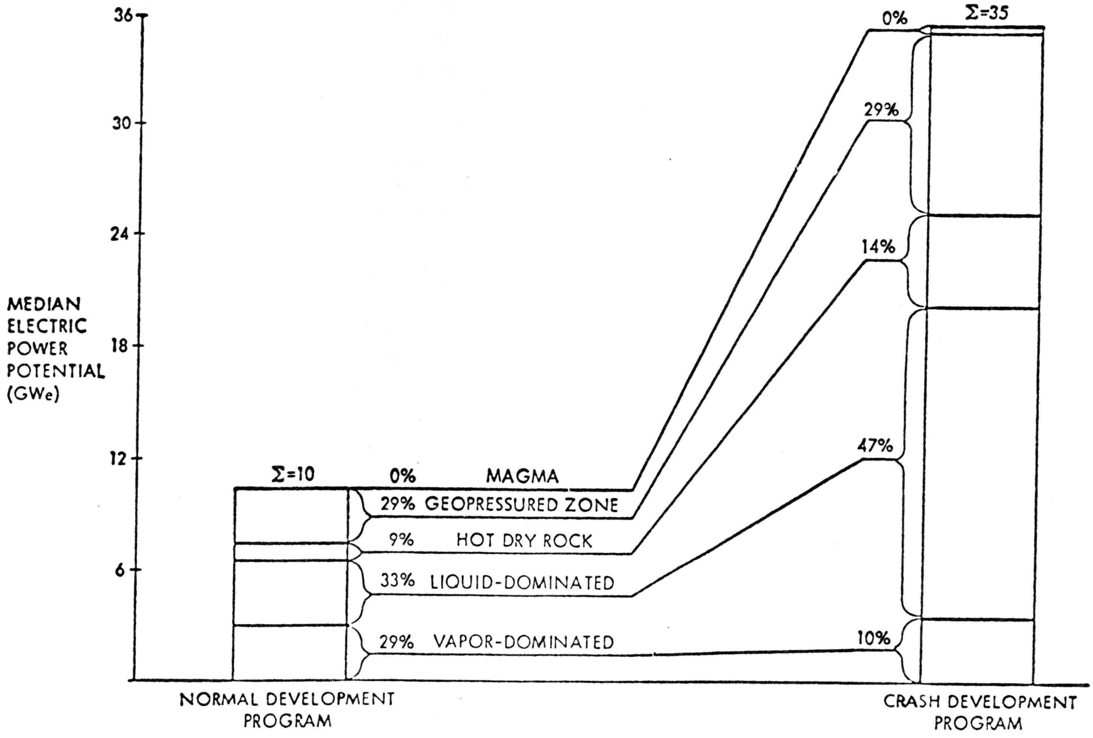

Figure 3. Median forecasts of geothermal potential for the year 1985.

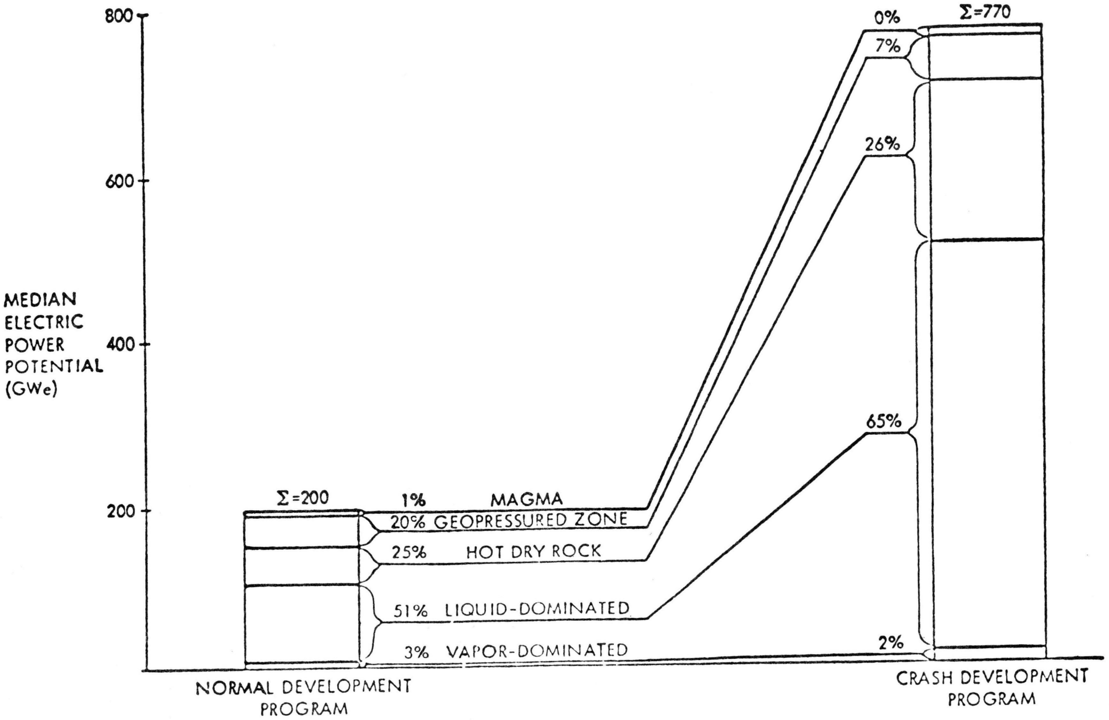

Figure 4. Median forecasts of geothermal potential for the year 2000.

are abundant and can support greater exploitation. One possible research and development strategy for a crash program would be to concentrate on the development of liquid-dominated and hot rock resources. However, the energy potential of geopressure and vapor geothermal resources are so large in absolute terms that their development should be pushed also.

The methodology that was used to obtain these forecasts of technologically feasible levels of geothermal energy resources development resulted in narrower ranges of development levels than previously existed in the literature. Some possible reasons for these results are:

1. Questions asked of respondents were phrased at the level of major subsystems and were restricted to the field of expertise of a given interviewer.
2. The forecasts refer to the levels of technically feasible geothermal developments and are thus upper limits on the amount of geothermal-based electric power capacity that actually could be installed. The question of technical feasibility includes fewer uncertainties, as opposed to economic, political, and social feasibility, than does the question of predicting actual developments.

## Economics

The capital costs and the manufacturing costs of electric power from geothermal energy may tend to be locally lower than any of the conventional power generating methods (coal, oil, natural gas, and nuclear) for the future. Collected data are given in Table 4. The year of the estimate and the reference are as indicated. Present capital costs per kilowatt for nuclear plants are \$350 to \$615 and for coal plants, \$250 to \$550 for start-up in the period 1975 to 1980 (Stanford Research Institute, 1973; Weinberg, 1973).

In these times of very rapidly increasing fuel costs and construction costs, it is difficult to get good comparative estimates as we are dealing with moving targets. Nevertheless, the figures in Table 4 clearly show the possible economic advantages of geothermal over conventional power plants; geothermal requires less dollars per kilowatt hour and has a lower manufacturing cost. The geothermal power plant also includes the costs for obtaining the fuel, hot water or steam, as well as the cost of the fuel-gathering system and the power plant. In this, the geothermal capital cost is unique. For all the conventional fuels, the capital cost is only that for building the power plant. The capital required for obtaining the fuel is in addition to that shown, and is reflected, of course, in the fuel price and in the manufacturing cost for the electricity. Since in the future capital will be scarce and expensive (high interest rates), it is very important to realize that geothermal energy may require a low total amount of capital for the total energy system.

## WESTERN U.S. ENERGY DEMAND

Since the greatest potential for the development of geothermal energy exists in the western part of the U.S., it is necessary to examine the electrical requirements in this region, which encompasses the Mountain and Pacific power generating regions. Table 5 shows the capacity requirements from 1971 as projected through the year 2000 based on the National Power Survey of 1970 (Federal Power Commission, 1971). The total requirements in the year 2000 are projected at 480 000 MWe. This may be compared to the maximum case found in this study for geothermal energy development of 770 000 MWe as being technically feasible. Since it seems logical to assume that the future development of electrical plants in the western U.S. will be based on a rational fuel mix, it should be expected that geothermal energy will only supply a portion of the western requirements.

Table 4. Power cost comparisons—geothermal.

| Power plant type | Plant size (MWe) | Capital cost ($/kWe) | Cost of thermal heat | Generating cost (mill/kWh) |
|---|---|---|---|---|
| Dry steam, operational | | | | |
| The Geysers, California | | | | |
| Unit No. 11 under construction | 106 | 132 | 2.7 mill/kWh | 5.71 |
| Unit No. 14 on line 1976 | 110 | 148 | 4.8 mill/kWh | 8.35 |
| Larderello, Italy | 25 | — | 3.2¢/$10^6$ Btu | 2.96 |
| Hot water brine, operational | | | | |
| Cerro Prieto, Mexico, 1973 | 75 | 264 | - | 8.00 |
| Otake, Japan, 1970 | 30 | 288 | - | 6.50 |
| Wairakei, New Zealand, 1970 | 192 | — | 6.9¢/$10^6$ Btu | 5.14 |
| Rotorua, New Zealand, district heat, 1970 | — | — | 3.36¢/$10^6$ Btu | — |
| Reykjavik, Iceland, district heat, 1970 | — | — | 7.5 to 14¢/$10^6$ Btu | — |
| Hot water brine, estimates | | | | |
| Armstead (1970) | 100 | 270 | 4 to 5¢/$10^6$ Btu | 3.90 |
| Green and Laird (1973) | 20 to 42 | 330 to 297 | - | 12.77 to 4.77 |
| Austin, Higgins, and Howard (1973) | 220 | 180 | - | 3.20 |
| Stanford Research Institute (1973) | 215 | - | - | 7.75 to 9.35 |
| Kaufman (1973) | 260 | - | - | 9.00 |
| Hot rock, estimates | | | | |
| Brown, Smith, and Potter (1973) | | | | |
| 300°C, dual cycle | 100 | 186 | — | 4.70 |
| 175°C, isobutane cycle | 100 | 316 | - | 8.00 |
| American Oil Shale Corp., et al. (1971) | 200 | — | — | 6.87 |
| Geopressure, estimates | | | | |
| Durham (1973) | 45 | 380 | 1.25 mill/kWh | — |

## Export East of the Rocky Mountains

Geothermal energy logically will be developed in parallel with a complete fuel mix in the West based on all the aforementioned basic fuels. Therefore, it is probable that there will be excess geothermal energy over the energy requirement in the West. This means that very large amounts of geothermal electricity may be available for export east of the Rockies. This amount may be as high as 50 000 MWe according to the crash program case in the year 2000. Export of such huge amounts of electricity may be practical in the future. High-capacity, high-voltage, long-distance electricity transmission lines are now being built and planned in several places in the U.S. In fact, recently an 800-kV-dc, 1400-MWe electric transmission line was constructed from Oregon to Los Angeles, 840 miles. The estimated transmission cost for such lines is 3 to 3.5 mill/kWh per 1000 miles for 1000-MWe capacity at 70% load factor (Federal Power Commission, 1971). Putting transmission lines west to east instead of north to south will allow the exportation of geothermal electricity to such cities as Chicago. Over a distance of 3000 miles, this places the cost range of delivered power at 15 to 20 mill/kWh; whether this will be competitive remains to be seen.

Table 5. Capacity requirements, western United States (MW).

| Year | Mountain region* | Pacific region† | Total |
|---|---|---|---|
| 1971 | 19 010 | 47 974 | 66 984 |
| 1973 | 24 400 | 70 600 | 95 000 |
| 1980 | 35 200 | 100 800 | 136 000 |
| 1985 | 49 600 | 141 200 | 191 000 |
| 2000 | 120 000 | 360 000 | 480 000 |

Source: National Power Survey, Federal Power Commission. Twenty percent reserve requirements assumed (U.S. Department of the Interior, 1973).

*The Mountain region consists of Arizona, Colorado, Montana, Nevada, New Mexico, Utah, and Wyoming.

†The Pacific region consists of California, Oregon, and Washington.

## ELECTRIC UTILITY MODEL

At this point in the study, while the forecasts for technologically feasible geothermal power development were satisfactory as upper-limit guidelines, a more quantitative structured approach was felt necessary in order to synthesize the available data and to provide a systematic basis for comparing the consequences of impacts and policies. It was desirable to answer the question: what will the growth of the geothermal power industry really be in the next 25 years in the context of competition from all of the other forms of energy?

Since the major use of geothermal energy in the U.S. will probably be to generate electricity, a simulation model was constructed to describe the rate of growth of geothermal electricity production in the U.S. Further, the model was based on a simulation of real-life electric utility company decision-making. The general concept behind the mathematical model is simply that the model can serve as a surrogate for the real system.

Imagine a situation in which a utility company executive is faced with a decision about what type of generation capacity to add to his system. He sees a gap between presently available generation capacity and projected demand. Suppose there are several alternative systems from which he might choose. What factors would enter his decision process? The literature in the field and discussion with a number of utility company executives suggest that competing systems might be compared on the basis of: Reliability (Is the rate of unplanned repair and maintenance likely to be higher for one than the other?); Environmental problems (Clearly, systems must comply with environmental regulations; nevertheless, it may be easier to do so with one than with the other.); Fuel availability (Is fuel likely to be equally available for the power systems over their anticipated life?); Capital costs (Is one system likely to be less expensive than the other?); Operating costs (Is the manufacturing cost of electricity greater for one system than the other?); and Construction time (Is the planning and construction process more lengthy for one system than the other?).

Decision-making in the utility industry has been the focus of a recent study (Gray, 1973) which shows that plant choice and investment have usually been guided by a judicious evaluation of the previously listed factors.

The electric utility simulation model developed in this study is primarily a model of the decision mechanism involved in the construction of new central-station generating capacity. Given a certain level of future demand and information concerning future costs and other characteristics of the various generating alternatives, the model calculates on-line capacity for each alternative through the year 2000. Separate calculations are made for the western region of the U.S. (as defined by the Federal Power Commission) and the remainder of the country, because almost all geothermal resources are in the West. System dynamics modeling as developed by Forrester (1961) was the method used in building this model.

Figure 5 illustrates the calculation of the need for new capacity. Demand for electricity is supplied to the model as an input. Federal Power Commission projections have been used through 1990 and extrapolations of those trends have been used to simulate demand projections through 2010. In the model, projected demand is read from the table 10 years in the future.

The need for new capacity is the difference between projected demand and expected capacity, the capacity that will be on-line in 10 years if no new capacity is planned. Expected capacity is found by subtracting capacity of plants that will be retired during the next 10 years from present capacity and adding the capacity of plants that are already planned or under construction. The amount of new capacity that is needed to meet projected demand is then allocated among the various generating alternatives as planned capacity which, after construction and planning delays, becomes on-line capacity.

Table 6. Key assumptions of the simulation model

Total geothermal resources identified equal the technologically feasible levels given in Table 3.

Demand for electric generating capacity increases by the year 2010 to 2532 × $10^3$ MW in the East and 600 × $10^3$ MW in the West.

Lifetimes for coal, oil, and nuclear generating plants are assumed to be 40 yr.

Plant construction times (yr) are:

| | |
|---|---|
| Coal | 6 |
| Oil | 5 |
| Nuclear | 10 in 1973, decreasing to 6 in 2000 |
| Solar | 8 |
| Geothermal | 3 |
| Transcontinental transmission line | 6 |

The decision of what type of plant to build is determined by the following factors with the weights shown:

| | |
|---|---|
| Reliability of service | 0.5 |
| Fuel availability | 2.0 |
| Cost of electricity | 1.0 |
| Environmental considerations | 0.6 |
| Plant construction time | 0.1 |
| Capital investment | 1.0 |

Solar energy first becomes commercially available on a large scale to electric utilities in 1987 (Little, Arthur D., Inc., 1974).

Geothermal energy first becomes commercially available on a large scale to electric utilities in the East in 1985.

Initial conditions for geothermal power in 1973 include:

| | |
|---|---|
| Available resources | 1200 MW |
| Number of wells drilled | 150 |
| Developed resources | 396 MW |

Planned capacities ($10^3$ MW):

| | East | West |
|---|---|---|
| Coal | 49.7 | 9.7 |
| Oil | 33.5 | .4 |
| Nuclear | 183.6 | 15.7 |
| Geothermal | 0 | 1.1 |

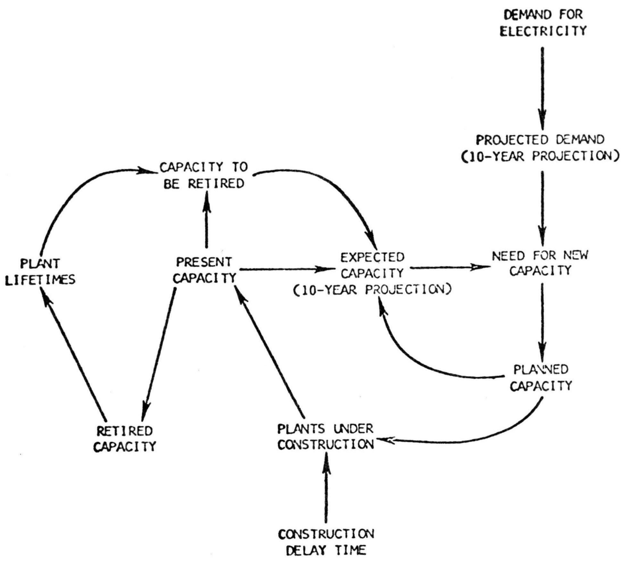

Figure 5. Determination of present capacity and need for new capacity.

The process by which needed capacity is allocated to the various alternatives is shown in Figure 6. The alternative generating plants included in the model are coal, oil, nuclear, geothermal, solar, natural gas, hydroelectric, and, for the East only, imports of geothermal energy from the West via a transcontinental grid. Natural gas and hydroelectric capacities are input to the model, following National Electric Reliability Council (1974) and Federal Power Commission projections, and do not enter into the allocation process.

The decision value for each alternative is a measure of the perceived desirability of that alternative to the utility. It is assumed that the desirability is based on the six criteria previously listed. The selection of the factors themselves, the weights accorded them, and the other judgmental inputs to the model were provided by a panel of experts familiar

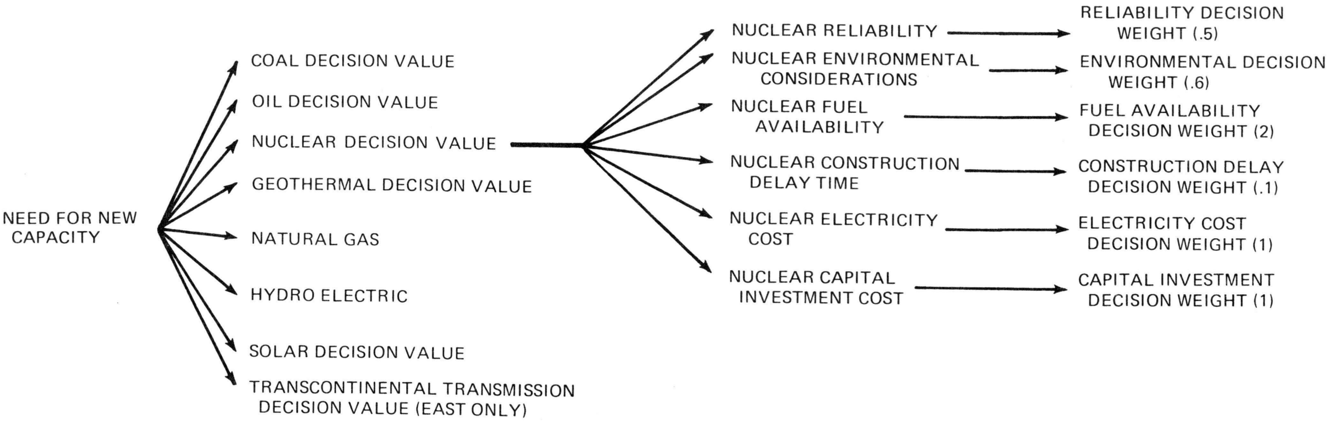

Figure 6. How allocation of new capacity is determined. Decision factors are shown for nuclear only; considerations are similar for coal, oil, geothermal, solar, and transcontinental transmission; hydro and natural gas capacities are exogenous inputs.

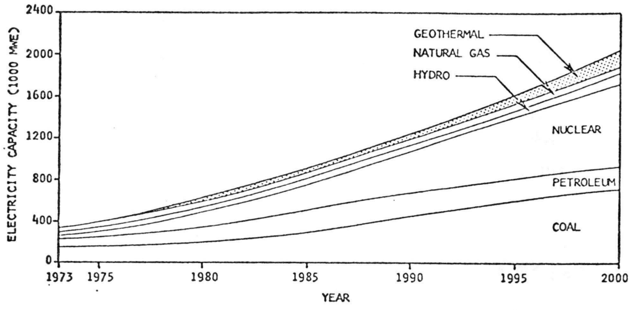

Figure 7. Electricity fuel mix—total U.S.

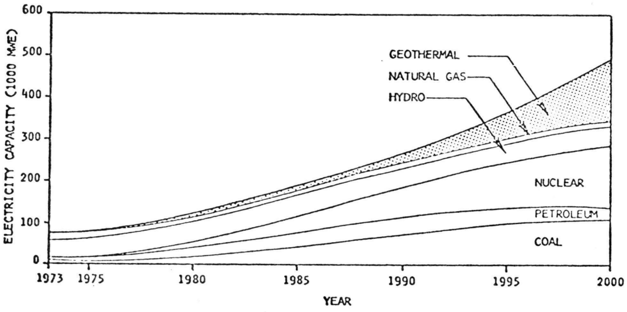

Figure 8. Electricity mix—western U.S.

with or involved in utility company decision-making. The key assumptions used in the model are listed in Table 6. The major parametric outputs are shown in Table 7 and Figures 7 and 8.

Using the model, it was possible to explore and illustrate the effects of certain policies designed to control the rate of introduction of geothermal energy, within the limits of accuracy of the simulation. A systematic attempt was made to define a range of activities designed to influence geothermal development and to understand their significance and

Table 7. Forecast generation capacity obtained from simulation model.

| | | 1985 | | | | 2000 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | West | | Total | | West | | Total | |
| Case | Fuel | ($10^3$ MWe) | (%) | ($10^3$ MWe) | (%) | ($10^3$ MWe) | (%) | ($10^3$ MWe) | (%) |
| No geothermal | Coal | 47 | 25.5 | 307 | 34.8 | 147 | 34.5 | 787 | 38.5 |
| | Petroleum | 36 | 19.6 | 202 | 22.9 | 33 | 7.8 | 183 | 9.0 |
| | Nuclear | 41 | 22.3 | 258 | 29.2 | 181 | 42.5 | 959 | 47.0 |
| | Geothermal | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Hydro | 47 | 25.5 | 72 | 8.2 | 58 | 13.6 | 90 | 4.4 |
| | Natural gas | 13 | 7.1 | 43 | 4.9 | 7 | 1.6 | 23 | 1.1 |
| | Total | 184 | 100.0 | 882 | 100.0 | 426 | 100.0 | 2042 | 100.0 |
| Base | Coal | 44 | 24.0 | 305 | 34.6 | 112 | 22.7 | 695 | 34.4 |
| | Petroleum | 34 | 18.6 | 201 | 22.8 | 30 | 6.1 | 181 | 9.0 |
| | Nuclear | 39 | 21.3 | 255 | 28.9 | 139 | 28.2 | 841 | 41.7 |
| | Geothermal | 6 | 3.3 | 6 | .7 | 147 | 29.8 | 188 | 9.3 |
| | Hydro | 47 | 25.7 | 72 | 8.1 | 58 | 11.8 | 90 | 4.5 |
| | Natural gas | 13 | 7.1 | 43 | 4.9 | 7 | 1.4 | 23 | 1.1 |
| | Total | 183 | 100.0 | 882 | 100.0 | 493 | 100.0 | 2018 | 100.0 |
| Accelerated | Coal | 43 | 22.4 | 303 | 34.0 | 95 | 19.0 | 671 | 33.3 |
| | Petroleum | 32 | 16.0 | 200 | 22.5 | 28 | 5.6 | 177 | 8.8 |
| | Nuclear | 38 | 19.8 | 254 | 28.5 | 119 | 23.8 | 808 | 40.0 |
| | Geothermal | 19 | 9.9 | 19 | 2.1 | 192 | 38.5 | 249 | 12.3 |
| | Hydro | 47 | 24.5 | 72 | 8.1 | 58 | 11.7 | 90 | 4.5 |
| | Natural gas | 13 | 6.8 | 43 | 4.8 | 7 | 1.4 | 23 | 1.1 |
| | Total | 192 | 100.0 | 891 | 100.0 | 499 | 100.0 | 2018 | 100.0 |

Table 8. Policies studied using simulation model.

| Policy | Method of simulating |
|---|---|
| 1. Geothermal resources not developed | Geothermal option removed from model decision simulation |
| 2. Geothermal resources not exported from West to East | Importation option removed from model East decision simulation |
| 3. Base run | Technologically feasible generation capacity (from technological interviews) per "normal" program |
| 4. Incentives created to reduce perceived risk associated with field depletion rate | Perceived availability factor for geothermal increased to 1. |
| 5. Government-funded hot dry rock development program | Technologically feasible generation capacity (from technological interviews) for hot dry rock "crash" program used with "normal" capacity estimates for other resource types |
| 6. Technical "crash" program | Technologically feasible generation capacity (from technological interviews) per "crash" program |
| 7. Accelerated (technical and nontechnical "crash") program which included: | As in (4) and (6) above, plus: |
| Steam cost subside | Steam cost reduced to 25% of its initial level |
| Demonstration plants | Perceived geothermal reliability factor increased to unity |
| Environmental programs | Perceived environment factor increased to unity |

power by testing them with the model. Table 8 lists the policies considered and the means employed to stimulate them. In essence, the model output can be considered a quantitative scenario in which assumptions and projections are consistent (Table 9).

Some observations about these policies are:

1. If all of the simulated technical and nontechnical policies designed to expedite geothermal development are implemented simultaneously, the amount of electricity produced from this source could be increased about 30% over a "normal program" of geothermal development (249 000 MWe versus 188 000 MWe in 2000).
2. The policies which seem most effective in stimulating the development of geothermal energy are those which improve the level of available resources.
3. As the amount of geothermal energy is increased by various policies, the other electricity sources which are most affected are nuclear energy and coal. Generating sources using petroleum are limited by uncertainty about the continued availability of oil, and, thus, are little affected by geothermal growth. Solar energy from central generating plants becomes available too late in the simulation to be much affected by geothermal before 2000.
4. The amount of geothermal energy exported from the West to the East is not affected significantly by the policies considered.

## CONCLUSION

This combination of forecasting techniques has yielded a series of forecasts for the development of the U.S. geothermal energy resources. The second set of forecasts simulate the real goethermal energy electricity capacity development and their results are: for 1985, 7000 MWe with normal development, 19 500 MWe with accelerated development; for 2000, 188 000 MWe with normal development, 249 000 MWe with accelerated development.

## ACKNOWLEDGMENT

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Table 9. Effect of selected policies on the level of geothermal development in the year 2000. Amounts listed are thousands of megawatts electric.

| | No geothermal | No imports to east | Base run | Depletion uncertainties removed | Hot dry rock development | Technical crash | National accelerated program |
|---|---|---|---|---|---|---|---|
| Geothermal East | 0 | 43.4 | 41.3 | 40.2 | 41.3 | 54.8 | 57.0 |
| Geothermal West | 2.2 | 90.04 | 146.8 | 148.2 | 155.6 | 181.1 | 192.2 |
| Imported by East | 0 | 0 | 56.4 | 56.0 | 57.5 | 57.5 | 57.5 |

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