Enhanced Geothermal Systems (EGS) R&D Program

EGS Report 2001-01

U.S. Geothermal Resources Review and Needs Assessment

Date: November 30, 2000

By: Dan Entingh, Princeton Energy Resources International, LLC, Rockville, Maryland

From: Enhanced Geothermal Systems Research Management Project
Princeton Energy Resources International, LLC, Rockville, Maryland
- Lynn McLarty, Project Director
- Dr. Daniel Entingh, Technology Development Director

For: U.S. Dept. of Energy Idaho Operations Office, Idaho Falls, ID
and
Office of Wind & Geothermal Technologies, U.S. Dept. of Energy, Washington, DC

Under: DOE Contract DE-AM07-97ID13517
Task DE-AT07-00ID60449

For more information contact Lynn McLarty, at 301-468-8442 or lmclarty@perihq.com

File: aadocs/9715/017/resource/assess02.doc

Preface

This report was written as background to discussions about planning for a possible new assessment of Enhanced Geothermal Systems and related hydrothermal and hot dry rock resources in the United States. Most of the material has been drawn from the author's memory of about twenty years of studying previous geothermal assessments and how information in them can be used to estimate how much geothermal energy might be economic in the near future. The author thanks especially Cliff Carwile, Lynn McLarty, and Joel Renner for insightful ideas and comments.

TABLE OF CONTENTS

PERI

January 12, 2001

Bob Creed, Project Manager
Laboratory Development Office
U.S. Department of Energy
Idaho Operations Office
850 Energy Drive, MS 1220
Idaho Falls, ID 83401-1563

Dear Bob:

Please find enclosed additional copies of the report, *U.S. Geothermal Resources Review and Needs Assessment,* prepared as a deliverable for Task DE-AT07-OOID60449 under contract DE-AM07-97ID13517. As we received no comments from DOE, the final report is unchanged from the original draft we sent to you on December 1, 2000.

If you have questions about this report please call me at 301-468-8442. Thanks.

Sincerely,

Lynn McLarty,
Project Manager

Enclosure

Cc: Elaine Richardson, Allan Jelacic, Joel Renner, Information Control & Accountability Branch of the Office of Scientific & Technical Information

1.0 SUMMARY

This is the general summary for this report. Not all of the statements in this section are repeated elsewhere in the report.

1.1 Purpose and Scope

The purpose of this report is to lay the groundwork for an emerging process to assess U.S. geothermal resources that might be suitable for development as Enhanced Geothermal Systems (EGS). Interviews of leading geothermists indicate that doing that will be intertwined with updating assessments of U.S. higher-quality hydrothermal resources and reviewing methods for discovering "hidden" hydrothermal and EGS resources.

The report reviews the history and status of assessment of high-temperature geothermal resources in the United States. Hydrothermal, Enhanced, and Hot Dry Rock resources are addressed. Geopressured geothermal resources are not.

There are three main uses of geothermal resource assessments.

1. They inform industry and other interest parties of reasonable estimates of the amounts and likely locations of known and prospective geothermal resources. This provides a basis for private-sector decisions whether or not to enter the geothermal energy business at all, and for where to look for useful resources.

2. They inform government agencies (Federal, State, local) of the same kinds of information. This can inform strategic decisions, such as whether to continue to invest in creating and stimulating a geothermal industry -- e.g., through research or financial incentives. And it informs certain agencies, e.g., Department of Interior, about what kinds of tactical operations might be required to support such activities as exploration and leasing.

3. They help the experts who are performing the assessment(s) to clarify their procedures and data, and in turn, provide the other two kinds of users with a more accurate interpretation of what the resulting estimates mean. The process of conducting this assessment brings a spotlight to bear on what has been accomplished in the domain of detecting and understanding reservoirs, in the period since the last major assessment was conducted.

1.2 Approach to Geothermal Energy Assessments

The methods used for the assessments take into account the different amounts of information and degrees of experience and knowledge about various U.S. areas (geothermal "prospects") that might contain useful geothermal energy.

In most cases, the hydrothermal assessments have been limited to estimating the energy potential for a number of Known Geothermal Resource Areas (KGRAs) for which a modest number of characteristics hint at the presence of relatively high temperature geothermal fluids (100 to 400 °C) relatively near the surface (depth of 0.5 to 4 km). Any cooler than that, or deeper than that, is not likely to produce economic electricity using today's technology. The Geothermal Steam Act defines KGRAs as areas that are reasonably likely to support commercial production of geothermal energy.

A distinction between Identified geothermal resources and Undiscovered (sometimes called "unidentified") resources is often made. Identified geothermal resources are known from surface shows of hot fluid (e.g., hot springs, mud pots, or geysers) or hot fluids encountered while drilling wells for petroleum (oil and natural gas) or minerals.

Most assessments concentrate on estimating the physical qualities of KGRAs, and from those qualities, estimating the total amount of electricity that might be produced if a certain fraction of the heat therein can be brought to the surface and converted to electricity. More details are presented in the text.

Economic assessments combine the physical information with knowledge of the cost and performance of technology that is used to bring geothermal energy to the surface, and convert it to electricity. The varying quality and amounts of energy in each KGRA results in a different cost and amount of electricity estimated as being producible at each. Those amounts are combined in an "economic supply curve" that offers a good representation of the general value of such geothermal resources as a whole

1.3 Status of Physical Assessments

a. Hydrothermal

The last comprehensive assessment of U.S. high-temperature geothermal resources was published in 1978, 22 years ago. That assessment covered four types of resources: (a) hydrothermal, (b) geopressured, (c) conductive, and (d) volcano-associated.

The hydrothermal part of the Circular 790 assessment focused on areas where evidence suggested there might be a substantial amount of hydrothermal resource underground. Most of those were identified based on "surface shows" of steam or warm water. A few (e.g., the Salton Sea, CA) were identified from evidence provided by exploration wells drilled to find minerals or petroleum. This assessment was done to meet the Department of Interior's responsibility, under the Geothermal Steam Act of 1970, to designate the "Known Geothermal Resource Areas" (KGRAs) of the U.S.

Note that KGRAs containing lands with Federal ownership are subject to competitive leasing of development rights through sales managed by the U.S. Department of the Interior (by its Bureau of Land Management). Other Federally-owned lands are subject to non-competitive leasing, where the impetus to lease originates in an industry application. Most of the Federal geothermal leases where plants are operating today are at KGRAs, under competitive leases.

Since USGS Circular 790, there have been three moderately-detailed partial updates of that work for specific regions, Southwest states (University of New Mexico, Las Cruces, circa 1980), the Pacific Northwest (Bloomquist et al., 1985) and California (the "Ebasco" assessment, 1991).

In addition, a small study funded by Sandia for the DOE Geothermal R&D program and the DOE Energy Information Administration in 1990-1991, updated results from USGS Circular 790 by interviewing industry experts (Petty et al., 1992.)

In early 2000, Wright, Reed, and Gawell interviewed U.S. sources to estimate totals (only) for geothermal-electricity capable resources, for current and "advanced" (un-specified) technology without regard to economics.

In mid-2000, Entingh and reviewed the Petty et al. data for impacts of results of exploration and land management decisions since about 1992. This also rectified some prior misinterpretations of the Petty et al.

data by accounting for potential capacity that Petty et al. had suggested to be encumbered by environmental or institutional issues. As of November 2000, this is an unpublished study that has been reviewed by one National Laboratory and one industry expert.

In general, there is a pretty steady trend for the estimate of amounts of identified hydrothermal resources to steadily decline over the past 22 years. The total has gone from about 23,000 MWe identified in USGS Circular 790 in 1978 to about 5,500 MWe identified in Entingh and Reed, 2000.

The amount of undiscovered geothermal resources remains very speculative, but also has declined a great deal over the past two decades.

Table 1-1 compares the estimates made in some of the more important studies.

Table 1-1. Comparison of U.S. Geothermal Hydrothermal Assessments, Nationwide

	MWe for 30 years		
Assessment Report	Identified	Undiscovered	Total
USGS Circular 726, 1975	26,700	126,700	153,500
USGS Circular 790, 1978	23,000	100,000 [a]	123,300
Bonneville 1985 [b]	318,000	--	318,000
Wright, 1991	--	4,800	4,800
Petty et al., 1992	27,400	22,600	50,000
Petty et al., 1993	--	--	49,300
Wright et al., 2000 [c]	6,520	12,360	18,880
PERI, 2000	5,520	10,460	15,980

Notes:
[a] Range of 72,000 to 127 MWe.
[b] Included Idaho, Montana, Oregon, Washington only. Two years later was reduced greatly.
[c] Here the high and low estimates are for current technology (6,520) and enhanced technology (total 18,880).

Identified Resources

The values estimated for identified resources have become quite a bit smaller over a period of about 20 years. They have changed from about 25,000 MWe (for 30 years) to about 6,000 MWe. The Ebasco values, for California only, are more or less consistent with the lower value.

The value of 318,000 from the Bonneville 1985 study essentially were retracted about two years later in Pacific Northwest power planning reports. The high values were caused by estimates of very large amounts of heat in two areas, which today are no longer viewed as useful hydrothermal areas.

The decline in amount of identified resources is almost predictable, in hindsight. Since the USGS team could not consider permeability in most of the sites they assessed, it is only natural that many of those sites would be found to be too impermeably to host hydrothermal systems.

Undiscovered Resources

Working estimates of undiscovered resources now have become controversial. PERI has interviewed a number of geologists and reservoir engineers who have broad familiarity with the U.S. geothermal scene for the past 20 years. Some of them believe that there are essentially no large undiscovered resources, after about 20 years of search for them by a few major firms (e.g., Unocal, Magma Power, Phillips, Chevron, CalEnergy.) Others believe that there may be a few quite large reservoirs out there, hidden, yet to be discovered.

This "gentlemen's disagreement" now needs to be brought out of the closet, aired out, and settled by some sort of rational process. Much discussion among the best technical experts in the U.S. is needed to achieve this.

b. HDR and EGS

Hot Dry Rock (HDR) and Enhanced Geothermal Systems (EGS) assessments are based on the scantiest of information.

Most of the published HDR assessments since about 1975 have been based on some estimate on the total amount of heat (above some reference ambient temperature, about 15°C) under the continental US (CONUS) to a depth of about 10 km. Various assumptions are then appended with respect to recoverability at the surface and use as direct heat or electricity. USGS Circular 790 showed about 500,000 quads recoverable from convective sources and about the same amount available near recent volcanos. The DOE Geothermal Research Program used those numbers for many years as, "500,000 quads of HDR and 500,000 quads of magma energy."

In rough terms, 10 quads of reasonable quality geothermal heat would support about 1000 MW of electricity production for 30 years. So 500,000 quads, if technologically accessible, would support 50,000,000 MW of electricity production for 30 years. That level of capacity and potential energy output is on the order of 60 times the currently installed electricity capacity in the U.S. today. Unfortunately, most of that "hot dry rock" heat lies at depths that lie at the far limits of technological accessibility today. It would certainly would be very uneconomic at the deepest reservoirs, and most of the shallowest also.

There are essentially no estimates of the potential of EGS. Sass and Walters, 1999, estimated the accessible heat at the margins of some of the more promising hydrothermal KGRAs. That heat would support perhaps 1,000 to 2,000 MWe of electricity production for 30 years (Entingh, unpublished calculations, 1999).

1.4 Status of Economic Assessments

a. Hydrothermal

Economic assessments for hydrothermal electricity are by and large broken. There are two main problems. (1) One is that technology cost effectiveness in all of the available materials is pegged at 1985-vintage technology. While PERI believes that rather large improvements in cost-effectiveness have occurred in the past 15 years, it is very difficult to prove that to the satisfaction of all. (2) The second is that the amounts of the resource in the working database were estimated in about 1991, and include much "resource" that later exploration results suggest is not there.

This situation came about as follows. All of the current U.S. economic supply curves for geothermal (hydrothermal) electricity are derived from the work Entingh, Petty, and Livesay did on the IMGEO hydrothermal cost of power model, for DOE, in 1987. The costs in the model are calibrated to technology that existed in 1985.

In 1992, Entingh provided the generic design for EIA's Geothermal Electricity Submodule (GES) in 1992. When he did that, he assumed that the technology would be adjusted to roughly 1991 levels of cost effectiveness. He recommended that the cost basis in the GES be IMGEO results, since those were proving to be reasonable in studies conducted for industry and the California Energy Commission.

When Petty and Livesay extended that to more reservoirs in 1992, for Sandia (on OGT funds) and EIA, the technology vintage was not adjusted. In the revisions that EIA made to the GES in 2000, the technology vintage was not adjusted, even though Entingh provided copious evidence that it should be.
This has yet to play out, in 2001. EIA stated in an October 2000 staff meeting that it will accept formal statements of technology goals for renewables from the EERE/DOE research Offices for the EIA "Renewables Excursion" runs.

b. Hot Dry Rock

The key assessment here is that of Tester and Herzog, MIT, 1990. The authors reviewed a great deal of information about drilling and power plant costs from the hydrothermal domain. They posited that electricity from HDR would be drawn from a band that was at most 2 km thick at sites with relatively high geothermal gradients.

They concluded that the following amounts of MWe for 20 years (not 30 years) were likely to be available in the continental U.S. Their estimated cost of power would have to be multiplied by about 1.4 to adjust the values to year-2000 dollars.

Less than or equal to:	MWe, for 20 years:
3.6 cents/kWh	2,900,000
3.9 cents/kWh	8,200,000
5.7 cents/kWh	23,000,000
7.7 cents/kWh	33,000,000
15.7 cents/kWh	41,609,000

This is about 50 times the currently installed electric generating capacity in the U.S. (800,000 MWe).

There were two controversial assumptions in this study. One is that eventually technology will be invented that will drill deep wells that increase in cost only linearly with depth. The other is that the analysis assumes flow rates between wells that are not likely to be achieved, given the results of the field work conducted at Fenton Hill, Rosemanowes, Soultz, Hijiori, and Ogachi.

Using rational flow rates, the Rosemanowes team, the Japanese, and PERI have estimated that the best near term cost for HDR would be on the order of 10 to 14 cents per kWh, estimated in about 1995. (Inflate by a factor of about 1.2 to get year-2000 costs.) The Soultz team projects costs on the order of 7 or 8 cents per kWh, in 1998 dollars. (Inflate by about 6 percent to get to 2000 costs.) The main difference is simply that the Soultz reservoir is larger and more permeable than any of the others.

1.5 Next Steps

1.5.1 Hydrothermal (HT)

New approaches to estimating of undiscovered (non-identified) hydrothermal resources are needed. This is because the current estimates of undiscovered resources, from USGS and from Petty et al, are based on seemingly vague estimation factors.

This has now become a key area of need, given that most of the 1978 KGRAs have been explored to some degree, and new methods are needed for detecting and evaluating hidden resources. "Hidden" or "blind" here means that there are no recent surface shows of hydrothermal activity like hot springs, fumaroles, or geysers.

The few such hidden reservoirs that are known, e.g., the Salton Sea field, were discovered through wells drilled during petroleum or mineral exploration. It is not clear that there is, or is not, a much "hidden" hydrothermal resource still out there. The surface of the continental U.S. has been pretty well pin-cushioned by literally millions of gas and oil wells. Very few of those, except in the deep Gulf Coast and California geopressured zones, have come up with lots of hot water or steam.

It would make sense to develop a consensus of the more well-known geothermal geologists about this.

1.5.2 Enhanced Geothermal Systems (EGS)

PERI has been informed that designs for assessments for EGS will have to await DOE's reviews of the concept reports that originate from the 2000 EGS concept solicitation. The deadline for submission of those reports is February 1, 2000.

It is likely that any discussion of how to identify and to assess EGS resources will be intertwined with discussion of how to do that for "hidden" and "undiscovered" hydrothermal resources also.

Two main approaches would seem to be important:

a. Survey the better U.S. geothermal geologists to ascertain if any of them believe there are areas that are especially promising for EGS work. Pin-point down to areas of not greater than 100 square km, perhaps, so that "Western Basin and Range" is too wide-scale an answer.

b. One reviewer of this draft suggested that an analysis of the colocation of high heat flow and the coordinates of mineral and oil/gas exploration wells in the West could provide leads to what firms' records might be pursued for hints. But this is in part what Dave Blackwell and his colleagues have been doing with heat flow records.

1.5.3 Hot Dry Rock (HDR)

The working problem here is estimating recovery factors for a number of different regimes. Geological considerations, e.g., is the reservoir in compression, extension, or neither, were largely ignored in the HDR estimates prepared by Los Alamos and MIT. Some (e.g., the original LANL HDR theorists) believe that practical HDR can work only in a compressional regime -- fluid would do nothing but leak away in an extensional area.

Others (e.g., the staff of the EU Soultz project), believe just the opposite. Only in extensional regimes will hydrofracturing produce enough fracture to allow economic production.

It is inevitable that any work that seeks to define EGS resources will have to grapple with the various definitions and outlooks on hot dry rock concepts, experimental results, and economic analyses. Resource estimates for HDR have been expansive, and entail much resource that, while probably in the earth, could never be produced commercially for either economic or institutional reasons. Nevertheless, the very-high thermal gradient portion of the HDR resource base (e.g., that estimated for Roosevelt Hot Springs, Utah) will have to considered part of the mid-term and long-term EGS resource base.

1.6 Summary of Needs for EGS Assessment

The emerging reasons that DOE needs to define and fund a comprehensive new geothermal resource assessment, concentrating on EGS-capable and new possible hydrothermal reservoirs, are:

a. The last definitive assessment is more than twenty years old, and clearly outdated by both results of exploration and emergence of new exploration approaches and technologies.

b. Many of the most knowledgeable geologist are retiring and taking precious information and insights with them.

c. The records, such as they are, of most of the main industry-based U.S. geothermal exploration efforts of the 1960s through 1990s have either been deposited in a few open libraries (GRC, INEEL Geothermal Group, LANL Hot Dry Rock Group). Other critical collections have been transferred from firm to firm during the recent mergers and acquisitions in the industry. (Salton Sea properties to CalEnergy, Coso and Oxbow units to Caithness, most of The Geysers to Calpine, etc. FPL holds all of East Mesa. Ogden Energy holds all of Heber.)

d. The USGS open file collection on geothermal resources may or may not be still available. If it is, it perhaps should be moved to an agency and organization that retains interest in the materials, perhaps to INEEL.

e. Estimates of EGS resource amounts are needed to stage strategic R&D planning. Government policy makers (both Federal and state) are no longer sure of the attractiveness of the U.S. geothermal option. They need current information to refine policy. Some sense of what bang (economic new reservoirs) can be got for what bucks (both R&D, direct incentives, and industry investment.)

f. DOE has spent significant amounts on resource assessments for solar and wind. It has spent very little to do the same for geothermal.

2.0 INTRODUCTION

2.1 Purpose and Scope

This report describes the history and issues about assessing useful geothermal resources of the United States.

The report concentrates on relatively high-temperature resources that are likely to be suitable for the production of electricity. Electricity is clearly the product of geothermal energy that has the highest economic value, and high environmental value also because it can replace the burning of coal and nuclear fuels.

Direct uses of geothermal energy are also of value in lots of places, but have not been as important in the U.S. as electricity production. Direct heat estimates will be addressed later. Traditionally, different groups of experts have assessed the electric capable resources and those of lesser quality.

While this report was funded through the "Enhanced Geothermal Systems" part of the Department of Energy geothermal research budget, it seems clear improved assessments are needed for hydrothermal resources also. Also, some discussion of "Hot Dry Rock" resources is in order, since the HDR concept led to the current EGS thinking.

2.2 Organization of this Report

Section:	Material:
1.0:	The general summary of this report. Some matters there are not described elsewhere.
2.0:	General background information and definitions.
3.0:	Discusses aspects of methodology for geothermal resource assessments.
4.0:	Describes assessments that have concentrated on physical characteristics of resources.
5.0:	Describes assessments that have added economic considerations to those of Section 4.0.
6.0:	Describes some general aspects of undiscovered geothermal resources.
7.0:	Compares results of some of the main assessments.

2.3 Types of Geothermal Resources to be Reviewed

Defining ways to assess "Enhanced Geothermal Systems" resource potential is an essential focus of this report. It is clear that doing that requires bridging what have been traditionally discussed as "hydrothermal" or "hot dry rock" assessments.

Improved assessments are needed for hydrothermal resources also. Since 1991 or so, when the most recent assessment was done, it has become clear that some of the originally-most-promising U.S. hydrothermal prospects are not likely to produce electricity, and perhaps not direct heat. These include Newberry Volcano and Vale, both in Oregon. The Baca Ranch part of the Valles Caldera, New Mexico, is shortly to become incorporated into the Bandellier National Monument and off limits to geothermal development. The future of much of Glass Mountain/Medicine Lake is now clouded by Federal findings and controversy about Native American rights.

Recent statements by U.S. geothermal industry managers indicate that industry now believes that there is relatively little hydrothermal resource that can be developed economically, say at 3 cents/kWh, the typical average wholesale price for electricity in California during most of 1999. A liberal Federal incentive of 1.5 to 1.7 cents per kWh produced during the first 10 years of the life of new projects might bring 1,500 to 2,000 MW of new geothermal capacity on line in the U.S.

While there are very large estimates floating around for the U.S. "Hot Dry Rock" geothermal resource, economic technology for producing that heat is simply unknown, and now deemed by many to be likely only in the distant future.

2.4 A Few Definitions

A few of the terms used are defined here.

Assessment: A process of estimating amounts of energy in the ground and amounts that are likely to be producible using current, or near-future, technology. To some extent, technology should be specified so that if advances in technology occur, the estimates made in the assessment can be adjusted in logical ways.

Chemical Constituents: Certain chemicals in the geothermal fluid need to be dealt with by technological means. So these often increase the price power, by as much as one cent per kWh. These usually cannot be known until the KGRA is drill and flow tested. But some moderate cost for amelioration of brine chemistry should always by assumed, unless the reservoir temperature is not much higher than 100 degrees C.

DOE: U.S. Department of Energy. It is the author's understanding that the Federal law(s) that establish DOE's role with respect to assessing geothermal energy lie in interpreting the economic quality or value of the resources that the USGS assesses on a physical basis.

Enhanced Geothermal Systems: Systems with sub-commercial properties where either the permeability, fluid contents, or both need to be "enhanced" through engineered means. Some folks like to include the effluent pipelines to The Geysers as "enhancements." Others don't because injection was being done and studied long before DOE coined the term "EGS" in 1998.

Geothermal: Energy and other matters related to natural heat contained in the earth. The observed elevated temperatures of "geothermal" resources arise from a combination of three main sources: radiative heating of rock, conduction of heat from the Earth's very high temperature core, and solar and atmospheric heating of the upper 10s of meters of the surface.

Hydrothermal: Geothermal reservoirs or systems that contain significant amounts of water, either as steam, liquid, or both.

Megawatts: A measure of a geothermal energy system's ability to produce power. Direct heat systems are rated in megawatts-thermal, MWt. Electricity generating systems are rated in terms of megawatts-electric, MWe. Most geothermal electricity systems are about 10 percent efficient in converting heat to electricity. So on an order-of-magnitude basis, one MWe uses ten MWt of geothermal heating capability.

National Laboratories: Large laboratories that support missions of the U.S. Department of Energy. Those that have conducted or supported geothermal research related to exploration and might be mentioned in this report are: INEEL: Idaho National Energy and Environmental Laboratory; LANL: Los Alamos NL; LBNL: Lawrence Berkeley NL; LLNL: Lawrence Livermore NL; NREL: National Renewable Energy Laboratory; SNL: Sandia NL.

Recoverability Factor: Fraction of heat in place in the earth that can be brought to the surface and either converted to electricity or used in a direct-heat-use application. Primary considerations are: (a) The amount of heat that can be brought to the surface, (b) The efficiency or effectiveness of use of the heat at the surface, and (c) The degree to which injection of either endogenous or exogenous fluids can improve the rate and longevity of heat extraction.

Reservoir Volume: An effective volume of the reservoir, measured by whatever means are available. The standard "early" assessment method uses heat flow measurements (thermal gradient wells) to estimate the X,Y area of the reservoir, and an assumption or result of drilling to estimate the thickness.

Supply Curve: This economics term denotes estimates of what amount of useful energy is available as a function of increasing cost to produce or deliver it. Supply curves (either smooth curves or step functions) are primary policy tools for comparing the economic attractiveness of various energy supply options.

Standard Geothermal Assessment Method: This is the approach used by the U.S. Geological Survey and in many industrial estimates of the capacity of a geothermal reservoir. It basically consists of estimating the volume of the reservoir from the surface area of the heat anomaly and some estimate of thickness. The temperature of the reservoir is estimated, from direct measurement or via geochemical thermometry. Permeabilities in the reservoir are estimated from early flow test results or by analogy to reservoirs of similar lithography. The permeable volume is assumed to be full of liquid unless there are indications of dryness, such a superheat. Factors are assumed for how much of the fluid can be produced (generally on the order of 25 percent.) Theoretical power plant thermodynamic performance is then applied to estimate the electricity that can be drawn from that fluid over, typically, a 30 year period.

USGS: United States Geological Survey. It is the Survey's responsibility to assess the geology and mineral/energy resources of the United States.

2.5 Uses of Geothermal Resource Assessment

There are at least three main uses.

1. Inform industry and other interest parties of reasonable estimates of the amounts and likely locations of known and prospective geothermal resources. This provides a basis for private-sector decisions to enter the geothermal energy business at all, and for where to look for useful resources.

   Note that this function explicitly includes a geographical component. It must be done with location information that is accurate enough to encourage industry to continue to look for the next good land position to be developed.

2. Inform government agencies (Federal, State, local) of the same kinds of information. This can inform strategic decisions, such as whether to continue to invest in creating and stimulating a geothermal industry -- e.g., through research or financial incentives. And it informs certain agencies, e.g., Department of Interior, about what kinds of tactical operations might be required to support such activities as exploration and leasing.

   Location information here is required only to the Congressional District level.

3. It helps the experts who are performing the assessment(s) to clarify their procedures and data, and in turn, provide the other two kinds of users with a more accurate interpretation of what the resulting estimates mean.

   The process of conducting this assessment brings a spotlight to bear on what has been accomplished in the domain of detecting and understanding reservoirs, in the period since the last major assessment was conducted.

Use 2, "Inform government agencies," has reached a fairly refined epitome in the uses to which the U.S. Energy Information Administration (an independent agency housed within DOE) puts some of the available physical and economic information about geothermal energy resources and production in the U.S. EIA has constructed a complex model of the U.S. national energy economy, the National Energy Modeling System (NEMS). NEMS competes a large number of energy supply and energy conservation technologies (and fuels) to meet the estimated demands for energy in the 2001 - 2020 period.

NEMS contains a Geothermal Electricity Submodule (GES). The GES system cost and capacity estimates are based on the Petty/Livesay resource capacity estimates (1993) and the Entingh/Livesay/Petty economic modeling embodied in the IMGEO geothermal cost of electricity model (1987 - 1990). This is the single U.S. national modeling "proving ground" wherein estimates of geothermal energy availability and cost are compared to other sources of electricity in a numerically modeled economic competition.

3.0 APPROACHES TO ASSESSMENT

3.1 General Approach

The general approach makes estimates of the heat in the ground at depths that can be approached by drilling, and then estimates of the fraction of the heat that can be recovered. This is done for various defined geographical regions. The estimated amounts of energy are then summed across regions. The assessment has to keep separate accounts for resources of high, moderate, and relatively low temperature because these are of decreasing thermodynamic and thus economic value. That is, more electricity can be made, per British Thermal Unit (Btu) of heat exiting from a wellhead of a high-temperature site, compared to a moderate temperature site. In thermodynamic terms, it is said that there is more Available Work per Btu in the higher temperature geothermal fluid.

The accuracy of the approach depends mightily upon the amount of geological and geophysical investigation of the various geothermal "prospects" and the degree to which the existing data are known to the assessors.

3.1.1 Case with Moderate Data

Let's consider first a prospect for which a moderate amount of data are in hand. These might consist of fluid temperatures measured by geothermometry (analysis of chemicals in brine) from a few geothermal hot springs. Rock temperatures have been estimated through a few geothermal gradient wells of moderate depth. The geothermal gradient wells have been spread out over a few square miles of the surface, and thus have indicated where on the surface the center of the hot zone is, and given some indication of the areal extent of the reservoir. One or two core holes have indicated there is fluid at depth and that it enters the wells through a zone of measurable thickness (vertical extent). The coreholes indicate that the heat capacity of the rock is not unusual, may provide a rough estimate of the porosity of the reservoir rock, and indicate the degree of difficulty in drilling into the reservoir.

These numbers can be combined to estimate the size of the heated volume, the typical temperature of that volume, the depth of the needed wells, and whether the rock is easy or hard to drill.

Theoretical (heat transfer and thermodynamic) considerations, and experience with similar reservoirs allows the calculation of a recoverability factor. The recoverability factor is an estimate of what fraction of the heat in the ground can be brought to the surface and converted to electricity (or other uses).

This process is approximated by a conceptual equation:

E.useful = Vol.rock X Porosity X F.fluid X (T.s - T.e) X (Eff(T.r,T.a),

where:

E.useful =	useful energy, in megawatt-years
Vol.rock =	geothermal reservoir rock volume
Porosity =	fraction of volume filled by fluid
F.fluid =	fraction of fluid that is recoverable
T.s =	reservoir temperature at start of utilization
T.e =	reservoir temperature at end of deployment
Eff =	efficiency of energy conversion, a function of T.r and T.a
T.r =	average reservoir temperature during use,

essentially = (T.s + T.e) / 2.

The factor E.fluid is based on a number of factors, including the geometry of the reservoir and the degree to which produced fluid is replenished through injection. For most work its value is on the order of 0.3 to 0.5. With injection and recirculation of fluid, the value can be higher than 1.

3.1.2 Case With Extensive Data

If many wells have been drilled over the areal extent of the reservoir, and the reservoir has been actively produced for some period of time, then much more is known about the characteristics of the rock, the degree of communication among the wells, and rate of flow of fluid early and later during the history of production from the wells. This lends itself to analytical modeling of the properties and behavior of the reservoir, and can lead to very sophisticated and relatively accurate predictions of reservoir behavior.

This degree of detail is available for only a few reservoirs: The Geysers, part of the Salton Sea, Coso, Heber, East Mesa, and Roosevelt Hot Springs.

3.1.3 Cases With Very Little Data

In cases with very little data, most of the estimates are made by analogy to regions that are geologically similar. This leads to the not very useful result that there might be 10 MWe (30 years) recoverable from a site where the only data is the geothermometry from a hot spring.

USGS Circ. 790 itself does not reveal much about ancillary evidence (e.g., rhyolite domes) that suggest much recently-emplaced heat might be available in such an area.

3.1.4 Mixed Cases

An interesting case in point here is the Salton Sea field in Imperial County, southern California.
There a number of quite different estimates for this field, ranging from about 1,000 MWe for 30 years to as much as 8,500 MWe for 30 years. The lower estimates come from relatively detailed analysis of part of the field that has been produced from about 1980. Much detail is known there about underground conditions. There is lots of heat, lots of fluid, and lots of well-connected pore space for the fluid to move about in.

The hot portion of the field is believe to extend to the west of the currently produced area, under the surface of the Salton Sea itself. To mine that heat would require well pads in the Sea, or direction drilling under it from the shore line. So that would be somewhat more expensive to access. The characteristics of the under-sea part of the resource are not well measured, and the estimates about its properties are based on geological analysis.

3.2 General Factors and Issues

3.2.1 Effective Permeability

The assessment formula used by the USGS team contained no term for permeability, the degree to which fluid is free to move through a mass of rock. While it is fair to say that no easy way to estimate permeability was available to the authors of USGS Circ. 790, it is also fair to say that their estimates probably ended up being too optimistic because that was not considered.

Many of the KGRAs have turned out to have relatively low permeability. Westmorland, CA, Fish Lake, NV, Newberry, OR, and Vale, OR are leading examples. There may be others. At these sites the effective permeability is so low that either the tested parts of the prospect contain little or no water, or the fluid that is there flows too slowly to allow commercially economic production.

Something needs to be done in future assessments to take this into account. One way to do that would be to discount the estimate for every KGRA to account for a likelihood of low permeability. A better way would likely be to show one or more values of "Total Potential" that have been adjusted for the historical experience in encountering various degrees of effective permeability.

3.2.2 Availability of Water

Water availability issues are very important. They have been largely ignored in U.S. geothermal resource assessments because, "that's not geological science."

Producibility of economic geothermal electricity means that the following factors have to be colocated: high temperature, rock that is both porous and permeable, water, rock-water-interactions that are not too problematic. Generally in the western U.S., high temperature heat and water are not colocated. This means that much of what appears to be tempting geothermal resources, based on high temperature and recency of intrusion, simply have no economic working fluid either in the resource or nearby.

This fact is perhaps the greatest disappointment of the last thirty years of geothermal exploration in the western U.S. "Dry as a bone." However, limited municipal or industrial waste water might be available at some key sites.

Another possibility is using sea water at sites that are near oceans or saline lakes. Al Truesdell has indicated [at EGS Workshop 3, Berkeley, CA, August 1999] that sea water is not useful because ugly chemicals tend to precipitate from it. But there's a paper in GRC Transactions, September 2000, using sea water to stimulate. And on the other hand, there are not many known heat sources within a few miles of the Pacific Ocean.

3.2.3 Need to Capture the Results of the Past Three Decades

There is a great need to interview the geologists who have or are about retire from work on geothermal. Some U.S. geothermal exploration geologists think there's quite a bit of useful resource still out there. Others think there's not. Many important geothermal geologists have been recently laid off or are retiring.

In general, it's time to get a roundtable going, since exploration has not been intense during the past 15 years, but many of those who are retiring know a lot. Their main insights need to be captured.

Similarly, the records, such as they are, of most of the main industry-based U.S. geothermal exploration efforts of the 1960s through 1990s are now at risk of disappearing. So
Some have been deposited in a few open libraries (GRC, INEEL Geothermal Group, LANL Hot Dry Rock Group). Other critical collections have been transferred from firm to firm during the recent mergers and acquisitions in the industry. (Salton Sea properties to CalEnergy, Coso and Oxbow units to Caithness, most of The Geysers to Calpine, etc. FPL holds all of East Mesa. Ogden Energy holds all of Heber.)

As much as possible of these needs to be collected by DOE, and made accessible in an ongoing open collection.

3.2.4 Need to put Site Statistics in a Accessible Record

Part of the main statistics for KRGAs are shown in Circular 790. The Bonneville study and the Ebasco study also show some of the underlying numbers. The Petty 1992 study shows very little information about specific KGRAs (although much of the site-defining data from Petty et al. were gotten from Petty and incorporated into a special multi-site costing feature of IMGEO Version 4.0, 1992.

Richness in reporting the underlying estimates, and their sources, is to be treasured. Especially so as folks update the work five or ten years later. General notes of why each site is believed to possess the reported characteristics would also be very valuable. It would be useful if all of this could end up on a Web site, preferably either at INEEL or NREL.

3.3 Special Approaches to Assessing EGS Resources

The spectrum of EGS resources is going to bridge the U.S. concepts of "commercial hydrothermal" and "Fenton-Hill-like hot dry rock".

"Commercial hydrothermal" has heat, generous effective porosity and permeability, and usually copious fluid. Injection wells can be configured relative to production wells to allow disposal of fluid and pressure maintenance without rapid thermal breakthrough. Costs are low enough, and production rates high enough for developers to make a profit.

We define "Fenton-Hill-like hot dry rock" to entail a body of very hot deep impermeable rock situated in a compressive stress regime. The Fenton Hill concept emphasized the need to minimize the amount of water that would escape from the main pathways between injection well and production wells. This occurred, perchance, because of the aridity in the location where LANL staff began to work on HDR. The net result was the development of a very expensive, quite small volume of fractured rock, through which water flowed only poorly.

Other concepts for hot dry rock now being pursued, notably at Hijiori, Japan, and Soultz, France, are based in rock that is much more porous and permeable than the Fenton Hill rock. The new idea is to try to recover some large fraction of injected cold water as very hot water or steam. Flow rates are a great deal higher than at Fenton Hill, but not near those for commercial hydrothermal.

So the "EGS" resources being sought, in a coming assessment, are those that are more like the Hijiori and Soultz reservoirs than like the Fenton Hill conditions.

Some of the types of resources that will have to be enumerated are:

1. Margins of hydrothermal reservoirs.

   John Sass, Ann Robertson-Tait, and Mark Walters have theory and practice on this front underway.

2. Free standing areas that are known to have both heat and permeability.

   E.g., Clear Lake, east of The Geysers, is of this type. There is much heat, and much emission of carbon dioxide. LANL was interested in Clear Lake as a potential HDR site. This lies in a place where the power could be used, and where there is at least some water that could be used for experimental injection ... at least.

3. Extensional regimes in the Basin and Range.

Here John Sass and possibly other geothermal geologists still with the USGS will be able to provide major inputs. What are the ten most promising fields? What are the cheapest experiments that could be done to assess a few of them for production potential? Where is the water?

4. How should the EGS classification grade into classical (Fenton Hill-like) HDR?

The author believes there is no simple answer to this question. But it needs to be addressed, or all that an "EGS resource assessment" can ever do is claim most of the heat in the top 10 km (about 33,000,000 Quads), just as Circular 790 and eventually LANL did.

There has to be some cut point that hints at practicability of commercial production. That probably should be that the reservoir rock has some intrinsic permeability, as well as heat.

4.0 EXISTING PHYSICAL ASSESSMENTS

4.1 USGS Circular 726

While this most commonly thought of as merely the predecessor to United States Geological Survey (USGS) Circular 790, Circular 726 does contain useful information on a few KGRAs that does not appear in Circular 790.

4.2 USGS Circular 790

"Assessment of Geothermal Resources of the United States - 1978" is the "definitive" geothermal high-temperature resource assessment for the U.S. It has guided much U.S. Government energy policy until very recently.

MITRE Corporation compendia of KGRA characteristics provide another retrievable source of some of the information in the USGS open files. These reports were called "the giant green doorstoppers." But they do contain a fair amount of detail about KGRAs that is not easily accessible elsewhere. Entingh has copies of some of them. It is possible that other volumes were sent to Dr. Joel Renner in the 2000 transfer of much of the DOE HQ Geothermal Library from PERI (Princeton Energy Resources International, Rockville, MD) to INEEL.

4.3 USGS Circular 892

Assessment of lower temperature resources. This is the study that Marshall Reed led at the USGS. It is listed here only for completeness.

4.4 Assessment by New Mexico State University, Las Cruces

This is mainly an economic assessment, as described elsewhere. It was done in about 1980. This is of interest here, however, because it captured a fair amount of detail about KGRAs in New Mexico, Arizona, Nevada, and Colorado. It is the author's recollection that many sites were listed here that didn't make it into Circular 790 or other later assessments.

4.5 The Pacific Northwest Survey of Bloomquist et al.

Funded by Bonneville Power Administration. Had unique and useful ways to rate and rank data and prospects. Initial estimates were way too high, because a couple of very large but probably very dry areas, e.g., Island Park, ID, were included. See more about this under Economic Assessments, below.

4.6 The Petty/Livesay 1992 Study for Sandia

This has become the defining study for most of the estimates that are now used in the U.S., because it became the basis for the resource estimates in the EIA's NEMS Geothermal Electricity Submodule. More detail is presented in the next Section, Economics. The estimates included undiscovered resources.

4.7 Petty's GIS 1993 Survey for NREL

The Petty et al. 1992 estimates were revised to help NREL build a Geographical Information System for all forms of renewable energy in the U.S. To do that, Petty et al. more or less stripped the undiscovered resources from the 1992 assessment since there were no GIS coordinates associated with them. Locations and characteristics of lesser hot springs were added to the data base, and the total resource estimated is not too much different.

4.8 The EBASCO Study

This considered California only. It was done in 1991 by "Ebasco Services, Inc., staff," who are not identified. It summarized a number of previous studies, and showed the work. It did not include cost estimates. More details are presented below in Section 4.16.

4.9 Wright's Estimate of Exploration Potential

In 1991 Mike Wright, University of Utah Research Institute (more recently called the Energy and Geophysics Institute) published an estimate of the exploration potential for new hydrothermal resources for electrical power generation in the 48 contiguous United States. His estimates were as follows, as MWe for 30 years:

Imperial Valley -	750 MW
The Geysers megadistrict -	500 MW
The Cascades -	750 MW
Basin and Range -	2,000 MW
Rio Grande Rift -	500 MW
Snake River Plain -	100 MW
Northern Rocky Mtns. -	100 MW
Misc. other areas -	100 MW
Total	4,800 MW

So this estimate weighs in with a total of only 4,800 MW, and likely, not all of that identified.

4.10 SMU Ongoing Heat Flow Mapping Research

Dr. David Blackwell of Southern Methodist University has spent many years collecting and analyzing heat flow data from all regions of the U.S., including the East. Significantly revised heat flow maps for the West have been available since about 1990, and need to be reckoned with in new geothermal resource assessments.

4.11 John Sass's Work on the Basin and Range Province

Dr. John Sass of the USGS, Flagstaff, AZ, office, has devoted much of his career to understanding heat sources in the Basin and Range.

4.12 Summary of Work in Cascades Range

A report in roughly 1990, by Blackwell, Muffler, and others, summarized a decade of increasingly disappointing survey and exploratory work, especially in Oregon. It concluded that it is unlikely that there are large volumes of hot fluid-filled permeability associated with the Cascades Range volcanoes, at least in Oregon and Washington. Published in GRC Transactions, roughly 1990.

4.13 The GeoHeat Center Colocation Study

In 1998 and 1999 the GeoHeat Center at the Oregon Institute of Technology concluded a long assessment of the colocation of moderate and lower temperature geothermal resources in the West with cities and towns. The main purpose of this was to accelerate use of geothermal heat in direct applications such as space heating and aquaculture. But there are some indications in the results of a few sites that might be useful for electricity production.

4.14 The Gawell/Reed/Wright 1990 Assessment

In early 1999 the Geothermal Energy Association published results of a survey of experts (by Karl Gawell, Marshall Reed, and Mike Wright) about U.S. and world-wide geothermal energy potential. They survey asked for low and high estimates of potential available using "todays technology" or "enhanced technology" currently under development, including permeability enhancement and drilling improvements.

Economics were not considered, so it is not clear whether "economic or nearly so" was an operating criterion in the minds of most of the responders. Units of response were in megawatts (MWe), with life of operation not specified -- but again, reasonable to assume operating for 30 years, as in most such assessments.

Results for the U.S. were:

Current technology, Low:	3,780 MWe
Current technology, High:	6,520 MWe
Enhanced technology, Low:	10,660 MWe
Enhanced technology, High:	18,880 MWe

It is reasonable to assume that the Enhanced technology - High estimate forms somewhat of an upper bound of what these experts believe is feasible to develop in the U.S. in the foreseeable future. But it is not clear whether or not these estimates include undiscovered resources or not.
The author believes that these results should be viewed as outputs from a process that was designed to produce somewhat optimistic estimates of how much geothermal electricity-capable resources are available.

4.15 PERI's 2000 Review of Resource Estimates

As part of a process to revise resource values in the EIA National Energy Modeling System (NEMS) Entingh developed a preliminary update of the Petty et al. 1992 basis for the geothermal site in that model. He interviewed Marshall Reed of the Department of Energy, and two other reputable experts who do not want to be identified, about current estimates of the useful potential at the sites that Petty et al. had worked up in 1992.

This included two main processes: (a) deleting from the working database records for sites that Petty et al. had identified as "environmentally" burdened, but had been retained in EIA's working data base anyway, and (b) revising -- almost always downward -- estimates of potential at sites where exploration in the past decade has indicated that the potential is very low, or much lower than estimated in 1992. Sites discounted because of exploration results included Newberry Volcano, OR, Medicine Lake, CA, Fish Lake, NV.

The results were as follows, in units of MWe for 30 years. Identified: 5,520 MWe; Undiscovered: 10,460

MWe; and Total: 15,980 MWe. These numbers are much lower than those from most previous surveys.

Interestingly, the 15,980 total here is not much different from the Gawell et al. estimate for Enhanced technology - High of 18,880 MWe. This suggests that the U.S. geothermal resource-expert community is beginning to converge on a working estimate in the high teens of MWe, rather than 40,000 MWe or more of ten or so years ago.

4.16 Early Estimates of EGS Potential

John Sass, USGS, has led the charge in estimating the portion of U.S. EGS potential that would be most easily developable: that lying near the margins of operating and well-characterized hydrothermal electric systems. He first broached this concept at the EGS-defining mini-workshop at the 1998 DOE Geothermal Program Review, Berkeley, CA. Ann Robertson-Tait and Mark Walters have worked closely with him since then to elaborate the site descriptions and preliminary estimates of potential.

The first quantitative estimates of such potential are in a paper by Sass and Walters, GRC Transactions, 1999. When the physical estimates of heat at the margins of a number of such systems are converted to MWe potential (Entingh, in draft), the amounts are only on the order of about 2,000 MWe available.

Robertson-Tait elaborated on some of this work in the GRC Transactions, 2000.

4.16 General Trends

A comparison of the USGS Circular 790, the Ebasco Study, and the Petty et al. 1992 results is informative. That is shown in Table 4-1 and Appendix A.

Table 4-1. GEOTHERMAL RESOURCE CAPACITY ESTIMATES FOR CALIFORNIA SITES FROM PETTY ET AL., EBASCO, AND USGS CIRCULAR 790

(Estimates of capacity are MWe for 30 years.)

Site Identifier, from Petty et al. study	Petty et al. 20Yr	Petty et al. 40Yr	EBASCO CALC'D	EBASCO EST'D	USGS Circular 790
1. SURPRISE VALLEY	250	500	502	502	1,490
2. LASSEN	116	116	-	-	116
3. CLEAR LAKE	500	900	-	-	900
4. COSO	650	650	431	431	650
5. LONG VAL., LOW-T (d)	250	500	294	294	500
6. LONG VAL., HIGH-T	500	1,600	-	-	1,600
7. RANDSBURG	50	84	10	0	84
8. SALTON SEA	2,000	3,400	1,242	1,242	3,400
9. WESTMORLAND	150	300	135	135	1,710
10. GEYSERS	2,000	2,000	-	-	1,610
11. BRAWLEY (a)	350	640	797	797	640
12. EAST MESA	360	360	254	254	360
13. HEBER	350	650	144	144	650
14. MEDICINE LAKE	500	2,000	2,616	750	
15. KELLY HS	300	760	-	-	
16. WENDELL-AMADEE	250	650	13	13	
17. WILBUR HS (c)	250	1,400	13	0	
18. BUCKEYE HS	250	725	-	-	
19. GLAMIS (b)	275	680	41	0	
20. SESPE HS	125	330	11	0	
(e) BODIE	-	-	46	0	
(e) SALINE VALLEY	-	-	4	0	
(f) Other					130
	9,476	18,245	6,553	4,562	13,840

NOTES:
(a) EBASCO totals for Brawley included Brawley, East Brawley, and South Brawley.
(b) EBASCO values for Dunes is set here.
(c) Calistoga included under Wilbur HS.
(d) Moderate-temperature resources.
(e) Sites not identifiable in Petty et al. report.
(f) Not identifiable in Petty et al. or EBASCO reports.

Comments:

For the California sites covered by Petty et al. that seem not to be included in the EBASCO tabulation, Petty et al. estimated an 4,160 additional MWx30 years at the 20-year exploration horizon, and 8,151 MWx30 years at the 40-year exploration horizon. If those 4,160 MWe for the Petty et al. 20-year horizon were to be added to the EBASCO estimated and calculated values, then the total EBASCO estimates would be raised to about 10,700 and 8,700, respectively. These two numbers nicely bracket the Petty et al. total of 9,500 MWx30 years for the 20-year exploration horizon.

The U.S.G.S. Circular 790 geothermal capacity estimate for California (published in 1979) was 13,840 MWex30 years. The EBASCO estimated value is 4,562, about 33 percent of the USGS Circular 790 estimate. Taken alone, this would indicate a striking shrinkage of the perceived amount of electric-quality hydrothermal energy available.

However, the Petty et al. group, using approximately the same approach but with more direct interviewing of anonymous industry sources, places the roughly equivalent estimate at 9,476 MWex30 years, about 68 percent of the USGS Circular 790 estimate. When the respondents were asked to envision a longer horizon for exploration and development, their responses led to an estimate of 18,145 MWex30 years, about 30 percent greater than that of U.S.G.S. Circular 790.

5.0 ECONOMIC ASSESSMENTS

5.1 General Background

a. Economic Supply Curves

Generally the idea is to construct an "economic supply curve" or "supply curve." A supply curve is a function that shows how much resource could likely be developed at a given price. When, in its standard form, the supply amount is on the horizontal (x) axis and the cost is on the vertical (y) axis, the curve ascends smoothly or in steps to the right.

For example, in terms of MWe for 30 years (the standard measure of capacity for hydrothermal systems) there might be 1,000 MWe available if the cost were 3.0 cents per kWh, 1,500 MWe available at 4.0 cents, 2,200 MWe available at 5.0 cents, 3,000 MWe at 6.0 cents, and so on.

The value of the supply curve is that it allows rapid analysis of how much geothermal electric capacity can compete in a market where the market wholesale price is known. For example, if the above estimates were for CA and NV sites that could serve CA (including transmission costs) and the CA price were 4.0 cents, then about 1,500 MWe of geothermal would be available. If the price rose to 5.0 cents, then an additional 700 MWe would be available.

b. Specification of Cost of Energy

Note that the "cost" of energy (electricity) specified includes all economic costs to produce electricity, including capital costs, operating and maintenance cost, and a reasonable profit. Expressed costs are ordinarily presented as: (a) first year costs (FYC), (b) levelized in current dollars (LCOE), or (c) levelized in constant (i.e., "real") dollars (RLCOE).

LCOE is a flat amount over the life of the project. The year-1 RLCOE is always less than LCOE, but RLCOE increases each year by the annual rate of inflation. In numerical terms, FYC is less than LCOE but greater than RLCOE. For example, for the same project LCOE might be 7 cents/kWh, FYC might be 5.5 cents/kWh, and RLCOE might be 4.5 cents/kWh. All reflect exactly the same costs and economic assumptions, and thus can be transformed amongst each other in a one to one fashion, if certain of the underlying costs and economic factors are known.

5.2 The MITRE Work for DOE HQ

MITRE Corporation (Washington Division, McLean, Virginia) did significant resource and technology assessments for the renewable energy programs of the Energy Research and Development Administration and then the Department of Energy, starting in about 1974. Work included photovoltaics, solar thermal, wind, geothermal, and small hydropower.

MITRE's GELCOM geothermal cost of power model was based on estimates of power plant costs developed by industry consultant John Schilling, in about 1976. Site characteristics for about 25 promising sites -- some of them relatively expensive -- were drawn by MITRE staff from the USGS publications and other meager sources. Special attention was paid to estimating well costs based on stratigraphy at geothermal sites. These results formed the basis of much of the Department of Energy's strategic planning for geothermal energy research and development in the late 1970's and early 1980's.

Later work (the IMGEO development, 1986 and following) proved that these estimates were really quite close to what industry actually experienced when it constructed the first liquid-dominated systems in the U.S. in 1980 - 1985 or so. GELCOM was in FORTRAN.

5.3 Battelle PNL Work

Clem Bloomster developed the GEOCOST model. It was used for site screening studies, in a number of major reports. GEOCOST was written in FORTRAN. Cost estimates for flash systems were similar to MITRE's GELCOM estimates, but estimates of cost of binary systems were quite a bit higher.

5.4 Assessment by New Mexico State University, Las Cruces

This was based on MITRE's GELCOM model, Circular 790, and information known to workers at NMSU. There were many sites listed here in NM, AZ, NV, and CO that didn't make it into Circular 790 or the MITRE work for DOE HQ. Entingh has copies of the two reports.

5.5 Analyses of the Heber Binary Demonstration Plant

Extensive analyses were made of these costs, since they were in the public domain. It is now clear that the Heber Demonstration plant was probably quite a bit less cost effective than the least expensive smaller binary geothermal plants being developed at the same time. E.g., Diablo Canyon, at Mammoth Lakes, CA.

Note that later analyses have shown that binary plants built out of many small one-MW units are quite a bit more expensive than plants built out of units sized at about eight to ten MW. [Val Tianco, California Energy Commission Review, December 1997].

5.6 The Technecon Studies

Starting in about 1978, DOE's Geothermal Technology Division (GTD) funded Technecon Corporation of Philadelphia to do a series of studies on geothermal electric system costs and possible markets for geothermal electricity in the West. The analyses were buttressed by estimates of power plant costs garnered from applications for Geothermal Loan Guarantees [by Tom Lawford, INEL]. The work included analysis of different preferences for risk and economic exposure by different types of developers (small and large).

Most of the programs were written in APL, a language that is very terse and very powerful in matrix manipulations. Almost no one can read these now.

The predictions of market penetration, completed in about 1982, were fairly aggressive. At that time, geothermal electricity was competing against electricity from coal -- the latter generated some distance from California markets. In about 1980, coal cost perhaps 4 cents per kWh, and some liquid-dominated geothermal looked like it would cost not much more than that. So things looked somewhat rosy.

5.7 The Pacific Northwest Survey

Bonneville Power Administration (BPA), U.S. Dept. of Energy, paid for a pretty comprehensive analysis of geothermal potential in Idaho, Montana, Oregon, and Washington. The work was led by Gordon Bloomquist, Washington State Energy Office, with a number of knowledgeable collaborators. Much work was done to assess the sources and quality of the available data.

The initial study came out with very high numbers. This was due to the inclusion of very high estimates of potential for a couple sites. Most folks familiar with the estimates suggest a lot of HDR resource was mistakenly listed as hydrothermal, because the reservoirs studied are today believed to be much less permeable than was estimated in the early 1990s. One of those sites was Island Park, Idaho. That is now known to be not as hot as estimated.

This study is a case where the data, process, and results are very well documented. PERI has the three-volume report. Entingh has the site data bases, and reduced them to DOS data files during National Energy Strategy analysis work in 1990.

5.8 The IMGEO Model

DOE Headquarters began supporting geothermal economics analysis work in 1996. Development of the IMGEO "Geothermal Electricity Cost of Power Model" began late in 1996. The work was done by Dan Entingh, Billy Joe Livesay, and Susan Petty, under the supervision of Dr. Dick Traeger of Sandia National Laboratories. The bulk of the work was completed in early 1997. Extensive revision of the power plant performance and costing codes was done in 1988.

This was different from all previous U.S. geothermal public domain site-screening models because the well and power plant cost estimation algorithms were based in large part on industry experience in the 1980 - 1986 period, rather than earlier feasibility studies or proposals.

The early versions of IMGEO analyzed 8 synthetic representative reservoirs, one each high temperature (double flash plant) and low temperature (binary plant) for four regions: Imperial Valley, Basin and Range, Cascades, and Young Volcanics (basically Coso and Hawaii). Versions after 1990 (4.0 and later) included a detailed data base of sites worked up during the 1992 Petty/Livesay study.

5.9 The Petty/Livesay 1992 Study for Sandia

With the advent of the analytical requirements for the National Energy Strategy development of 1989 - 1990, it was important to update the estimates of geothermal resource potential, because much had been learned in the rapid development of about 1,000 MW of plant at liquid-dominated sites during the 1990's. Petty et al. pursued what they basically construed as an update of Circular 790, with copious input from industry sources. The costing was done using IMGEO 3.05.

5.10 Petty's GIS 1993 Survey for NREL

In the early 1990's NREL began building up a Geographical Information System (GIS) data base or locations and characteristics of renewable energy resources, including geothermal. Here, all sites had to have an identified location. Dr. Allan Jelacic of DOE recently found the electronic version of the data prepared by Susan Petty and Bill Livesay for this purpose, and relayed a copy of it to Entingh.

A cursory comparison of the Petty 1993 data to the Petty 1992 data suggests that "unidentified" resources were stripped from the 1992 data set. Those sites were replaced, in essence, by the names and locations of a number of hot springs that show at least moderate temperature, but for which it is not generally clear if they ever would be hot enough and large enough to support power generation. As in the Petty et al. 1992 study, the costing was done using IMGEO 3.05.

Some of the results are included in the summary table below.

5.11 The Geothermal Electricity Submodule (GES) in NEMS

The GES was based on IMGEO version 4.00.

IMGEO 4.00 differed from 3.05 and other 3.nn versions in that 4.00 had: (a) the capability and database to analyze all of the 40 odd specific sites postulated by Petty et al., 1993, and (b) extensive adjustments to inflate the 1985 costs of IMGEO 3.05 to 1990 values. The base case results from this version basically produces estimates for 1995 geothermal technology, priced at 1990 inflation levels.

This gave IMGEO the capability of producing a reasonable U.S. hydrothermal economic supply curve, a curve that had last been available from the Technecon studies of about 1982 or so. That capability was used for various DOE Geothermal Programmatic policy studies (Entingh) in 1992 and 1993.

IMGEO 4.00 then also became the basis for the GES submodule in EIA's National Energy Modeling System (NEMS) electricity market (supply) module (EMM). The work was contracted to Meridian Corp., Alexandria, Virginia. Dan Entingh developed IMGEO 4.00 and wrote the General Design for the GES. Bill O'Neill wrote the Fortran code for the GES, and helped integrate it into the EMM over a period of about two years. Lynn McLarty wrote (Quick Basic) a preprocessor that supplied the IMGEO 4.00 data file to the GES.

The module appeared to work fairly well until about 1996 or 1997, when EIA staff changed the market shares algorithm within the EMM. The signals sent between EMM and GES became confused in meaning in a way such that the GES was inhibited from building economic capacity in about three years out of four. While EIA knew there was a problem, correction was not high on its list of NEMS priorities.

5.12 Revisions to GES in NEMS for AEO 2001

In late 1999, EIA began revising the GES submodule, to create what we here will call GES-2. EIA staff (Tom Petersik and Dave Schoeberlein) did the rebuild directly. The results were intended for use in EIA's *Annual Energy Outlook* (AEO) 2001 report, to be released in December.

A number of complicating features in GES-1 (primarily about geothermal industry investment behavior) were struck out, because features of that type were not included for any other supply technology represented in NEMS. (For example, NEMS will build 1 MW of a coal plant in any simulation year for the same cost per kilowatt capacity as the nominal 600 MW plant that the costs were derived for.)

While the geothermal sites database used in GES-2 remains based on the Petty et al. 1993 results, in this rebuild Petersik added a number of "economist's" assumptions about how costs of geothermal must climb with increased deployment at each KRGA. The assumptions made were "by analogy" to wind farm installations, and remain a matter of discussion between EIA's Office of Integrated Analysis and Forecasting and the DOE Office of Wind and Geothermal and Technologies.

Petersik has reported to the author that all seems to run well. As of October 10, the results (for EIS's report *Annual Energy Outlook 2001*) had not been released to the public.

6.0 UNDISCOVERED HYDROTHERMAL RESOURCES

The amount of "identified" geothermal resources shown in USGS Circular 790 was deemed to be capable of supporting about 23,000 MW of geothermal capacity for 30 years.

The currently installed electricity capacity of all types in the U.S. now (in 2000) stands at about 800,000 MW. So if all of the geothermal capacity identified in C-790 were economic and installed today, it would account for only about 3 percent of the need. Further, since the earliest economic modeling-based assessments (MITRE, Battelle PNL), it was clear that the near-term economic portion of the 25,000 MW was only about 5,000 to 8,000 MW. That would be equivalent to about 1 percent of the Nation's need in 2000.

Thus, since that time, it has been continually important to ask if there are other types of geothermal resources in the U.S. that could be significant from a national policy perspective.
At the time Circular 790 was done, those resources were: undiscovered hydrothermal and hot dry rock conduction-based and igneous resources. Estimates of the undiscovered resources remain of interest and importance.

The authors of USGS Circular 790 included a useful degree of detail of where they expected undiscovered hydrothermal resources to lie. Their Table 8 is included here as our Table 6-1.

Part of the Circular 790 explanatory text is quoted here. That will be useful to frame current discussions of "undiscovered" resources.

> "In the preparation of the estimates summarized in Table 8, the undiscovered component is usually estimated to be 1, 2, 5, 10, or 20 times the identified accessible resource base for each geologic province considered. In provinces where substantial information is available on the hydrothermal convection systems, the estimate is based primarily on the size of the area that appears favorable for the occurrence of systems similar to the identified systems. Where little information is available on the hydrothermal convection systems, the estimate of the undiscovered component is based on thermal models inferred from geologic, geophysical, and hydrological data. However, because the geologic settings of hydrothermal convection systems are so diverse, subjectivity necessarily plays an important role in making our estimates.
>
> *Pacific Border* -- Most of the geothermal systems in the Pacific Border Province are in The Geysers-Clear Lake area of the Coast Ranges. This area appears to be unique, and no similar systems are likely to be found in the remainder of the province. Although considerable exploration has been carried out in The Geysers-Clear Lake area, the total accessible resource base has not been completely defined, and the undiscovered component is estimated to equal the identified component.

Table 6-1. USGS C-790 Listing of Undiscovered Hydrothermal Resources

Table 8. Summary of the identified and undiscovered accessible resource base for geologic *provinces of the Western United States* (Province boundaries are shown in figure 12. Identified component includes energy in National Parks.)

Province	Accessible resource base (X 10^18 J) Identified	Undiscovered
Pacific Border		
The Geysers-Clear Lake area	150	150
Other	3	15
Cascades Mountains	57	1,140
Sierra Nevada Mountains	5	5
Columbia Plateau	0	0
Oregon Plateaus	80	400
Snake River Plain		
Western Central and Southwest	470	940
Camas Prairie and northern margin	21	100
Eastern	21	1,520
Yellowstone-Island Park	1,240	170
Basin and Range		
Northwestern	280	1,400
Sierra Nevada front	120	40
Wasatch Front and northeastern margin	67	170
Other	12	60
Salton Trough	240	480
Rio Grande Rift		
Valles Caldera area	87	87
Other	6	60
Colorado Plateaus	1	50
Rocky Mountains		
Idaho batholith	14	70
Boulder batholith	11	55
Middle Rocky Mountains and Wyoming Basin	2	10
Southern Rocky Mountains	5	25
Alaska		
Alaska Peninsula and Aleutian Islands	10	580
Central Alaska	11	220
Southeast Alaska	10	100
Other	0	100
Hawaii	9	45
TOTAL	2,900	8,000

In the Pacific Border Province outside of The Geysers-Clear Lake area, a few relatively small geothermal systems have been identified. In the Coast Ranges south of San Francisco Bay, the heat flow is about average for the Western United States; elsewhere in the province it is below average. The undiscovered accessible resource base outside of The Geysers-Clear Lake area is not likely to be large and is estimated to be five times the identified for this same area.

Cascade Mountains -- Although no large hydrothermal convection systems have been identified in the Cascade Mountains, the abundance of young volcanic rocks and the isolated occurrences of hot water along the range suggest that a large resource may exist. Much more work must be done before the identified systems can be evaluated and the undiscovered accessible resource base estimated. The Cascade Mountains probably lie over a subduction zone, and magma moving into or through the upper crust has transported large amounts of heat into the upper crust under the range, as is indicated by the numerous volcanoes. Precipitation is high over much of the area, and the resulting abundance of shallow cold water is likely to be masking underlying convection systems. Primarily because of the favorable geologic setting, we estimate the undiscovered accessible resource base in the Cascade Mountains to be twenty times the identified and recognize that it may be even greater.

Sierra Nevada -- The identified accessible resource base (5.6 x 1018 J) in the Sierra Nevada is not large. The Sierra Nevada is a region of unusually low heat flow, and there is no reason to expect a large geothermal resource there. Hydrothermal reservoirs in the batholithic terrane are probably of limited extent and confined to narrow conduits within fault zones. The undiscovered component is estimated to be equal to the identified accessible resource base.

Columbia Plateau -- The Columbia Plateau Province is underlain primarily by the Miocene Columbia River Basalt Group. No identified geothermal systems with reservoir temperatures > 90°C occur here, and there is no evidence indicating that a large geothermal resource will be discovered."

The USGS discussion continues for the other provinces, in some detail.

Today, we can use that table (Table 6-1 here) to refine our own estimates of what undiscovered hydrothermal resource might exist. For example, U.S. geothermists are now pretty confident that the Cascades province (1,140 X 10^18 joules, about 1,000 Quads) in Table 6-1 is very hot, but essentially impermeable and therefore dry at useful depths. Similarly, Basin and Range estimates are today also much lower than they were 20 years ago. Considerable work needs to be done to revise this table, but its numbers are a useful starting point.

7.0 COMPARISONS OF RESULTS

Table 7-1 compares the estimates made in some of the more important studies.

Table 7-1. Comparison of U.S. Geothermal Hydrothermal Assessments, Nationwide

			MWe for 30 years
Assessment Report	Identified	Undiscovered	Total
USGS Circular 726, 1975	26,700	126,700	153,500
USGS Circular 790, 1978	23,000	100,000 [a]	123,300
Bonneville 1985 [b]	318,000	--	318,000
Wright, 1991	--	4,800	4,800
Petty et al., 1992	27,400	22,600	50,000
Petty et al., 1993	--	--	49,300
Wright et al., 2000 [c]	6,520	12,360	18,880
PERI, 2000	5,520	10,460	15,980

Notes:
[a] Range of 72,000 to 127 MWe.
[b] Included Idaho, Montana, Oregon, Washington only. Two years later was reduced greatly.
[c] Here the high and low estimates are for current technology (6,520) and enhanced technology (total 18,880).

Identified Resources

The values estimated for identified resources have become quite a bit smaller over a period of about 20 years. They have changed from about 25,000 MWe (for 30 years) to about 6,000 MWe. The Ebasco values, for California only, are more or less consistent with the lower value.

The value of 318,000 from the Bonneville 1985 study essentially were retracted about two years later in Pacific Northwest power planning reports. The high values were caused by estimates of very large amounts of heat in two areas, which today are no longer viewed as useful hydrothermal areas.

The decline in amount of identified resources is almost predictable, in hindsight. Since the USGS team could not consider permeability in most of the sites they assessed, it is only natural that many of those sites would be found to be too impermeably to host hydrothermal systems.

Undiscovered Resources

Working estimates of undiscovered resources now have become controversial. PERI has interviewed a number of geologists and reservoir engineers who have broad familiarity with the U.S. geothermal scene for the past 20 years. Some of them believe that there are essentially no large undiscovered resources, after about 20 years of search for them by a few major firms (e.g., Unocal, Magma Power, Phillips, Chevron, CalEnergy.) Others believe that there may be a few quite large reservoirs out there, hidden, yet to be discovered.

This "gentlemen's disagreement" now needs to be brought out of the closet, aired out, and settled by some sort of rational process. Much discussion among the best technical experts in the U.S. is needed to achieve this.

8.0 REFERENCES

[An incomplete list as of November 20, 2000.]

__. *Annual Energy Outlook 2001.* Energy Information Administration, U.S. Dept. of Energy. In press, November 2000.

__. Blackwell, D.D., Steele, J.L., Carter, L.S., "Heat flow patterns of the United States: a key component of geothermal resource evaluation," Geothermal Resources Council Transactions, Vol. 16, 1992, pp. 119-124.

__. Blackwell, D.D., Steele, J.L., Wisian, K., "Results of geothermal resource evaluation for the eastern United States," Geothermal Resources Council Transactions, Vol. 18, 1994, 161-164.

__. Bloomquist, Gordon, *Principal Investigator*, "Evaluation of Ranking of Geothermal Resources for Electrical Generation or Electrical Offset in Idaho, Montana, Oregon, and Washington," prepared for Bonneville Power Administration, U.S. Department of Energy, Portland, OR, by Washington State Energy Office, Idaho Dept. of Water Resources, Montana Dept. of Natural Resources & Conservation, Oregon Dept. of Energy, and Oregon Dept. of Geology and Mineral Industries, June, 1985.

__. Bloomster, Clem and Linda Fassbender, "GEOCOST model," Battelle PNL. Circa 1978.

__. EBASCO, Geothermal Resources in California Study, 1991

__. EIA, Geothermal Electricity Submodule (GES) in NEMS. Energy Information Administration, U.S. Dept.1993 and following.

__. Entingh, D., S. Petty, B.J. Livesay, *IMGEO Geothermal Hydrothermal Cost of Power Model, Version 3.05.* Contractor product for Sandia National Laboratories and Geothermal Technology Division, U.S. Department of Energy. 1988.

__. Entingh, D., and S. Petty. "IMGEO Geothermal Cost of Power Model, Version 4.00," NOVA Analytics, Falls Church, Virginia, and Susan Petty and Associates, San Diego, California. 1992.

__. Entingh, D. PERI Review of U.S. Hydrothermal Resource Estimates, 2000.

__. Gawell, Reed, and Wright, 1999 Geothermal Resources Estimates

__. GeoHeat Center, OIT, Geothermal Resources Colocation Study, 1999 and 2000.

__. GeothermEx Sites and Systems Report, 1999.

__. Guffanti, M., Muffler, L.J.P., Mariner, R.H., Sherrod, D.R., Smith, J.G., Blackwell, D., Weaver, C.S., "Geothermal segmentation of the Cascade Range in the United States of America," Geothermal Resources Council Transactions, Volume 14 - Part II, 1990, pp. 1431-1435.

__. Hydrothermal Resources of the Southwest U.S., Assessment by New Mexico State University, Las Cruces, circa 1980.

__. Leigh, J., et al., GELCOM Geothermal Cost of Power Model, MITRE. 1976-1978.

__. MITRE Corporation compendia of KGRA characteristics. In three or four large volumes. MITRE Corp., McLean, Virginia, 1976 - 1978.

__. Muffler, P, and Guffanti, M., "Are there significant hydrothermal resources in the U.S. part of the Cascade Range?", Stanford Geothermal Program Proceedings, Vol. 20, January 1995, pp. 9-16.

__. Petersik, T., et al., "Revisions to GES in NEMS for AEO 2001," documentation being prepared. Energy Information Administration, U.S. Dept. of Energy, November 2000.

__. Petty, S., et al., "~A study of the cost of geothermal power in 20 and 40 years," 1992 Study for Sandia NL.

__. Petty, S., and B. Livesay, GIS Geothermal Survey for NREL, 1993

__. Reed, Marshall J., *Editor*, "Assessment of Low-Temperature Geothermal Resources of the United States - 1982," USGS Circular 892, 1982.

__. Robertson-Tait, Ann, EGS Sites Evaluation Report, at GRC 2000.

__. Sass, J. Work on the Basin and Range Province

__. Sass 1998. EGS sites. At DOE Geothermal Program Review.

__. Sass John, and Ann Robertson-Tait, "Potential U.S. Sites for Development of Enhanced Geothermal Systems," Fourth European HDR Meeting, Strasbourg, France, 1998.

__. Sass, J. and Mark Walters. GRC 1999.

__. San Diego Gas and Electric. Analyses of Economics of the Heber Binary Demonstration Plant. Various authors.

__. Technecon Studies, 1988 - 1990.

__. USGS Circular 726

__. USGS Circular 790. "Assessment of Geothermal Resources of the United States - 1978"

__. Wright, P.M., "Exploration Potential for New Hydrothermal Resources for Electrical Power Generation in the 48 Contiguous United States," GRC Transactions, Volume 15, pp. 217-228, 1991.

APPENDIX A. COMPARISON OF CIRCULAR 790, PETTY ET AL. 1992, and EBASCO ESTIMATES

COMPARISON OF THREE ASSESSMENTS OF CALIFORNIA'S GEOTHERMAL HYDROTHERMAL RESOURCES: U.S.G.S CIRCULAR 790, EBASCO STUDY, AND SANDIA STUDY

1/21/93

Daniel J. Entingh

NOVA Analytics
3025 Pine Spring Road,
Falls Church, Virginia

This report is a brief comparison of the geothermal hydrothermal resource assessments recently completed by EBASCO [1] for the California Energy Commission, and by Petty, Livesay, Long, and Geyer [2] for Sandia National Laboratories. The reevaluation of the data and assumptions contained in the 1978 U.S.G.S. Circular 790 [3] is timely and necessary, especially since industry activities in hydrothermal development during the 1990's have generated much new information.

The Geothermal Division (GD) of the U.S. Department of Energy (DOE), in concert with the Energy Information Administration (EIA) of DOE, initiated the Petty et al. assessment of hydrothermal resources in 1990, as inputs to the supporting analyses for the DOE 1991 National Energy Strategy. The results from the Petty et al. study, were available in draft in late 1990 and were revised in a draft of June 1991. EIA used those results in its 1991 report on U.S. geothermal energy resources [4].

The approach and results of Petty et al. study differ from those of EBASCO in a few major ways. The Petty et al. study:

1. Spent more effort in direct interviews of geothermal development firms and consultants.

2. Included estimates of costs to develop the prospects.

3. Placed greater emphasis on longer-term potentials.

4. Included estimates of potential of non-KGRA resources, and included estimates of developed and recoverable resource potential at The Geysers KGRA.

5. Included estimates of additional resources that might be discovered if exploration were intensified.

The Ebasco assessment:

1. Concentrated on legally defined Known Geothermal Resource Areas

2. Did not consider The Geysers KGRA.

3. Are documented in more detail as to specific sources.

Data from the three assessments are shown in Table 1. Table 2 lists other sites that are included by reference in the Petty et al. estimates.

For the California sites covered by Petty et al. that seem not to be included in the EBASCO tabulation, Petty et al. estimated an 4,160 additional MWx30 years at the 20-year exploration horizon, and 8,151 MWx30 years at the 40-year exploration horizon. If those 4,160 MWe for the Petty et al. 20-year horizon were to be added to the EBASCO estimated and calculated values, then the total EBASCO estimates would be raised to about 10,700 and 8,700, respectively. These two numbers nicely bracket the Petty et al. total of 9,500 MWx30 years for the 20-year exploration horizon.

The U.S.G.S. Circular 790 geothermal capacity estimate for California (published in 1979) was 13,840 MWx30 years. The EBASCO estimated value is 4,562, about 33 percent of the USGS Circular 790 estimate. Taken alone, this would indicate a striking shrinkage of the perceived amount of electric-quality hydrothermal energy available.

However, the Petty et al. group, using approximately the same approach but with more direct interviewing of anonymous industry sources, places the roughly equivalent estimate at 9,476 MWx30 years, about 68 percent of the USGS Circular 790 estimate. When the respondents were asked to envision a longer horizon for exploration and development, their responses led to an estimate of 18,145 MWex30 years, about 30 percent greater than that of U.S.G.S. Circular 790.

REFERENCES:

[1] "Assessment of the Electrical Generating Capacities of Liquid Dominated Geothermal Fields in California," Ebasco Services, November 25, 1991.

[2] Petty, S., B.J. Livesay, W.P. Long, and J. Geyer, "Supply of Geothermal Power from Hydrothermal Sources: A Study of the Cost of Power Over Time," Sandia National Laboratories Contractor Report, Albuquerque, NM, Draft, June, 1991.

[3] Muffler, L.J.P., Ed,, "Assessment of Geothermal Resources of the United States - 1978," Circular 790, U.S. Geological Survey, Washington, D.C., 1978.

[4] "Geothermal Energy in the Western United States and Hawaii: Resources and Projected Electricity Generation Supplies," Energy Information Administration, Report DOE/EIA-0544, Washington, D.C., September 1991.

TABLE 1

GEOTHERMAL RESOURCE CAPACITY ESTIMATES FOR CALIFORNIA SITES

FROM PETTY ET AL., EBASCO, AND U.S.G.S. CIRCULAR 790

(Estimates of capacity are MWe for 30 years.)

Site Identifier, from Petty *et al.* study	Petty *et al.* 20Yr	Petty *et al.* 40Yr	EBASCO CALC'D	EBASCO EST'D	USGS Circular 790
1. SURPRISE VALLEY	250	500	502	502	1,490
2. LASSEN	116	116	-	-	116
3. CLEAR LAKE	500	900	-	-	900
4. COSO	650	650	431	431	650
5. LONG VAL., LOW-T (d)	250	500	294	294	500
6. LONG VAL., HIGH-T	500	1,600	-	-	1,600
7. RANDSBURG	50	84	10	0	84
8. SALTON SEA	2,000	3,400	1,242	1,242	3,400
9. WESTMORLAND	150	300	135	135	1,710
10. GEYSERS	2,000	2,000	-	-	1,610
11. BRAWLEY (a)	350	640	797	797	640
12. EAST MESA	360	360	254	254	360
13. HEBER	350	650	144	144	650
14. MEDICINE LAKE	500	2,000	2,616	750	
15. KELLY HS	300	760	-	-	
16. WENDELL-AMADEE	250	650	13	13	
17. WILBUR HS (c)	250	1,400	13	0	
18. BUCKEYE HS	250	725	-	-	
19. GLAMIS (b)	275	680	41	0	
20. SESPE HS	125	330	11	0	
(e) BODIE	-	-	46	0	
(e) SALINE VALLEY	-	-	4	0	
(f) Other					130
	9,476	18,245	6,553	4,562	13,840

NOTES:
(a) EBASCO totals for Brawley included Brawley, East Brawley, and South Brawley.
(b) EBASCO values for Dunes is set here.
(c) Calistoga included under Wilbur HS.
(d) Moderate-temperature resources.
(e) Sites not identifiable in Petty et al. report.
(f) Not identifiable in Petty *et al*. or EBASCO reports.

TABLE 2

SITE AGGREGATION LIST FOR PETTY ET AL. STUDY

Site Name, in Petty et al.	Notes on areas included or defined
1. SURPRISE VALLEY	FORT BIDWELL
2. LASSEN (a)	MORGAN SPRINGS, GROWLER SPRINGS
3. CLEAR LAKE	SULPHUR BANK
4. COSO	COSO CAL ENERGY AND LADWP
5. LONG VALLEY-LOW TEMPERATURE	CASA DIABLO, SHADY REST AREA
6. LONG VALLEY-HIGH TEMPERATURE	OTHER LONG VALLEY AREAS
7. RANDSBURG	OTHER OWENS VALLEY RESOURCES
8. SALTON SEA	NILAND
9. WESTMORLAND	CALIPATRIA
10. GEYSERS	GEYSERS STEAM FIELD ONLY
11. BRAWLEY	
12. EAST MESA	
13. HEBER	MEXICO BORDER REGION
14. MEDICINE LAKE	ALIAS: GLASS MOUNTAIN
15. KELLY HS	WEST VALLEY RESERVOIR
16. WENDELL-AMADEE	GROVERS HS, HONEY LAKE
17. WILBUR HS	CALISTOGA HS, CHALK MT., SKAGGS HS
18. BUCKEYE HS	TRAVERTINE HS, GROVERS HS, FALES HS
19. GLAMIS	DUNES, 29 PALMS, PILGER
20. SESPE HS	ARROWHEAD HS

(a) These areas are outside of the National Park.