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ASSESSMENT OF ENERGY RESERVES AND COSTS OF GEOTHERMAL RESOURCES IN HAWAII

for

THE STATE OF HAWAII

DEPARTMENT OF BUSINESS, ECONOMIC DEVELOPMENT AND TOURISM

Honolulu, Hawaii

by

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Richmond, California

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EXECUTIVE SUMMARY

On behalf of the Department of Business, Economic Development and Tourism (DBEDT), GeothermEx has assessed the capacity for electrical generation of seven geothermal resource areas in Hawaii (five on the Island of Hawaii and two on the Island of Maui). We have also estimated a realistic range of costs for future geothermal power plants in Hawaii, based on published sources and industry experience, including estimates of capital cost (dollars per installed kilowatt) and operations and maintenance (O&M) costs (cents per kilowatt-hour). Moreover, we have reviewed the probability of occurrence of geothermal resources throughout the state of Hawaii, and we have found no change in the probability values since the statewide assessment five years ago (GeothermEx, 2000). The probabilities of occurrence are summarized in Table 1.1, and the potential resource areas indicated in Figure 1.1.

The seven geothermal resource areas with significant potential for electrical generation are:

- the East Rift Zone of Kilauea volcano (KERZ);
- the Kilauea Southwest Rift Zone
- the Mauna Loa Southwest Rift Zone;
- the Mauna Loa Northeast Rift Zone;
- Hualalai;
- the Haleakala Southwest Rift Zone; and
- the Haleakala East Rift Zone.

In assessing the MW capacity of these areas, we have used a probabilistic technique (Monte Carlo simulation) to account for uncertainties of key resource parameters. This results in a probability distribution curve for each area, which allows one to estimate the likelihood that recoverable energy reserves of a given area will exceed a specified level. For the purposes of

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this report, we have considered the 10th percentile MW value to be a minimum; there is a 90% probability that geothermal energy reserves will exceed this level for the area being evaluated. Because of the uncertainty in reservoir characteristics, the most likely values of MW capacity for the various areas are not known with precision. For each area, this study assumes the mean value of the MW capacities from Monte Carlo simulation to be the most likely.

Table 1.2 summarizes the reserve estimates for each of the geothermal resource areas considered. Separate estimates were made for the upper and lower portions of the KERZ and of the Kilauea Southwest Rift Zone, because the upper portions of these rift zones are within either national park land or state forest reserves. The Lower KERZ (from the western boundary of the Kamaili Geothermal Subzone to Cape Kumukahi on the east coast) has a minimum MW capacity of 181 MW and a most likely MW capacity of 438 MW. The five geothermal resource areas on the Island of Hawaii have a combined minimum MW capacity of 488 MW and a combined most likely MW capacity of 1,396 MW. For the two geothermal resource areas on Maui, the combined minimum MW capacity is 38 MW, and the combined most likely MW capacity is 139 MW.

It is important to note that these estimates of reserves reflect the amount of recoverable heat energy anticipated to be present at drillable depths, without implying that this energy can necessarily be exploited commercially. For commercial exploitation to be feasible, conditions must be adequate for productive wells to be drilled and operated over the lifetime of a power generation project. In addition, significant portions of the identified resource areas may be unavailable for geothermal development, for a variety of reasons. Therefore, the geothermal energy reserves available for development are a subset of the estimates presented above.

GeothermEx has also used Monte Carlo simulation to estimate the levelized cost of power from a hypothetical, new, 30-MW, geothermal power plant on the Island of Hawaii. For the purposes of this simulation, we have assumed unit capital costs in the range of $2,500 to $5,000 per installed kilowatt (with a most likely value of $3,500 per installed kilowatt) and O&M costs in the range

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of 4 to 6 cents per kilowatt-hour. From these parameters and several others, we estimate a mean levelized power cost of 7.84 cents per kilowatt-hour, with a standard deviation of 0.70 cents per kilowatt-hour. With a cumulative probability of 90%, levelized cost is expected to be higher than 7.0 ¢/kWh but lower than 8.7¢/kWh.

The current study has made certain assumptions about market demand and transmission constraints for the purpose of forecasting the growth of electrical generation capacity from geothermal resources on the islands of Hawaii and Maui:

- The maximum generating capacity of the Lower KERZ has been assumed not to exceed 30% of the projected maximum peak load for the Island of Hawaii (Figure 1.10).

- The potential contributions of the upper portions of the KERZ and of the Kilauea Southwest Rift Zone are not included in the forecast due to their location within Hawaii Volcanoes National Park or state natural area reserves.

- The Lower Kilauea Southwest Rift Zone and the Mauna Loa Northeast Rift Zone are also not included in the forecast, because they are subject to the same constraint on east-to-west transmission as the Lower KERZ, which is assumed to have priority.

- On the Island of Maui, it has been assumed that only one of the two areas with electrical generation potential will be developed within the next 20 years.

- The geothermal areas outside the Lower KERZ that are included in the forecast (i.e., Hualalai and the Mauna Loa Southwest and Haleakala Southwest Rift Zones) are assumed to require at least three years for permitting, drilling, plant construction, and connection to transmission. For the purposes of this study, electrical generation in these three areas is assumed to start in successive years: 2008 for Hualalai, 2009 for the Mauna Loa Southwest Rift Zone, and 2010 for the Haleakala Southwest Rift Zone (Figure 1.10).

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- The sizes of developments projected to be achieved within 20 years outside the Lower KERZ are estimated to be 25 MW at Hualalai, 60 MW at the Mauna Loa Southwest Rift Zone, and 35 MW at the Haleakala Southwest Rift Zone.

Based on these assumptions, this study has delineated two scenarios for the development of geothermal electrical generation capacity through 2025: a likely scenario and an upside scenario. These scenarios are summarized in Table 1.3 and are plotted in Figure 1.11 (for the Island of Hawaii) and Figure 1.12 (for the islands of Hawaii and Maui combined).

- The likely scenario consists of a base case for the Lower KERZ alone. This scenario reaches a geothermal generation capacity of 82 MW by 2025.

- The upside scenario consists of the sum of an upside case for the Lower KERZ and the three development projections for areas outside the Lower KERZ (Hualalai and the Mauna Loa Southwest and Haleakala Southwest Rift Zones). By 2025, this scenario reaches a geothermal generation capacity of 180 MW for the Island of Hawaii, and 205 MW for the islands of Hawaii and Maui combined.

Alternate scenarios of MW contributions from the seven resource areas considered in this study are certainly possible. However, the upside scenario presented here is considered a practical “upper limit” in terms of projected total MW for planning purposes.

The daily load swings on the Island of Hawaii present an opportunity to more fully utilize capacity for generation and transmission during off-peak hours. HELCO has a contractual right to curtail the output of the PGV facility during off-peak hours. Assuming generation losses in the range of 5% to 10% due to off-peak curtailment, then current energy losses at PGV would be in the range of 36 to 72 MWh each day. For the likely scenario of geothermal energy development described above, energy losses due to off-peak curtailments of facilities in the Lower KERZ as of 2025 would be approximately 100 to 200 MWh per day. For the upside

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scenario, energy losses on the Island of Hawaii as of 2025 would be over 200 to 400 MWh per day.

The production of hydrogen is one potential use of electrical generating capacity from geothermal sources during off-peak hours. The estimates of energy losses due to off-peak curtailments of geothermal facilities can be used in conjunction with several recent studies to facilitate more quantitative analysis of the potential for hydrogen production on the Island of Hawaii.

There are several challenges to the use of geothermal energy for district heating in Hawaii:

- As a result of Hawaii's mild climate, energy requirements for space heating are not high, and potential savings to pay out the investment in a district heating system are low.
- Most of the geothermal resource areas in Hawaii are located in areas of low population density, so the pipeline network to bring hot water to potential users would be relatively large and expensive.
- Installing district heating in areas with existing structures would require customized retrofits to individual units, which would be more expensive than if plans for district heating had been incorporated into the original construction.
- New wells to confirm a water supply of adequate temperature and flow rate for district heating represent a significant up-front cost. Moreover, there is no guarantee that such wells will actually achieve the desired temperature or flow rate.

On the positive side, if the use of geothermal energy for power generation is expanded in Hawaii, opportunities may arise in which wells drilled in exploring for high-temperature resources may eventually be used for district heating projects. District heating in such situations will have a

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better chance of being economic if it is incorporated into the planning phase of a new development area, including both residential and commercial structures.

Geothermal waters with temperatures too low for electrical generation can potentially be applied in a variety of direct uses, including:

- dehydration for fruits and other agricultural products
- lumber drying
- cold storage and ice-making
- aquaculture
- greenhouse bottom heating
- soil sterilization.

Sources of geothermal water at Puna could include (1) residual heat from the PGV plant, (2) existing shallow wells (less than 1,000 feet) with temperatures as high as 95°C (203°F), and (3) new well drilling. PGV has reportedly offered the heat of the discharge water from its Puna plant at no charge. PGV currently injects its discharge water at temperatures at or above 300°F, but they are considering the addition of a bottoming cycle that could lower the temperature of the discharge water to the range of 150°F to 250°F. A possible location for direct use applications of this water is the four-acre Noii O Puna research site adjacent to PGV's lease.

If direct use projects prove to be economically viable at Puna, they could potentially generate interest in similar projects at other geothermal resource areas, especially if these areas are being explored anyway for purposes of electric power generation.

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1. ASSESSMENT OF RESOURCE CAPACITY

1.1 Introduction

Assessments of the geothermal resource potential of the State of Hawaii have been prepared periodically under the direction of the Department of Land and Natural Resources (DLNR). These have included statewide assessments made in September 1984 (DLNR, 1984) and December 1992 (DLNR, 1992), with the most recent assessment having been prepared by GeothermEx at the request of the Department of Business, Economic Development and Tourism (DBEDT) in June 2000 (GeothermEx, 2000).

In the 2000 assessment, the probability of finding geothermal resources was assessed on a county-by-county basis, identifying specific areas where resources may exist and estimating the probability of their occurrence, taking into account evidence from geological, geophysical and geochemical investigations, and from exploratory drilling where it has taken place. The results of the assessment are summarized in Table 1.1, with the respective potential resource areas indicated in Figure 1.1.

As Table 1.1 indicates, most of the geothermal areas in the State of Hawaii have a low probability of occurrence (20% or less) of high-temperature resources (>125°C or >257°F), suitable for electric power generation using technology that is commercially available at present. Higher estimated probabilities are restricted to just 7 areas, all located on the islands of Maui and Hawaii. These areas are:

- the East Rift Zone of Kilauea volcano (KERZ);
- the Kilauea Southwest Rift Zone (contiguous with the Kilauea summit area and the KERZ);
- the Mauna Loa Southwest Rift Zone;

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- the Mauna Loa Northeast Rift Zone;
- Hualalai (upper west rift near the summit);
- the Haleakala Southwest Rift Zone; and
- the Haleakala East Rift Zone.

In addition to their greater probability of resource occurrence, these areas are the only ones for which sufficient technical data exist to make reasonable estimates of the specific location and potential extent of the resource areas. Therefore, they represent the areas for which it is reasonable and feasible to make quantitative estimates of the potential for geothermal power generation.

In the 2000 assessment, the evaluation of resource potential was limited to estimates of the probability of occurrence of a geothermal resource. In earlier reports for DBEDT (GeothermEx, 1992 and 1994), GeothermEx had included a more quantitative estimate of the geothermal energy reserves of the KERZ only. These earlier estimates for the KERZ were based on a probabilistic volumetric method modified from the approach introduced by the United States Geological Survey (USGS). This approach takes into account the uncertainties in determination of key resource parameters, and uses a Monte Carlo simulation technique to calculate the probability distribution of potentially recoverable energy reserves. The probability distribution allows determination of the likelihood that energy reserves exceed any specified level.

In the present assessment, a quantitative estimate of resource potential is made for each of the 7 areas listed above, using a probabilistic method essentially the same as the one used in the earlier KERZ assessments, but with some additional modifications. This method has been used by GeothermEx in similar assessments of geothermal resources on a regional scale in other studies (e.g., GeothermEx, 2004), as well as in assessments of a large number of individual geothermal fields.

Section 1.2 discusses the approach to the resource assessment, the criteria applied, and the background of the probabilistic reserves calculation methodology. Section 1.3 presents the results of the assessment, describing the estimate of reserves for each of the identified resource areas.

1.2. Assessment Criteria and Methodology

1.2.1 Criteria for Resource Areas

This assessment is been based on the same types of data that were considered in earlier statewide assessments, including, principally, ground-water temperatures, volcanological studies (including age dates of volcanic deposits and the interpretation of the evolution of magmatic systems), geochemistry, resistivity surveys, infrared surveys, seismic data, magnetics, gravity, self-potential anomalies, and the results of exploratory drilling. The relationship of each of these types of data to the potential presence of a geothermal resource has been discussed in the 1984 assessment and in a State publication entitled “Geothermal Resource Subzone Designations in Hawaii” (Department of Planning and Economic Development, 1986). That discussion is not repeated here. In addition, for the Kilauea East Rift Zone (KERZ), this assessment has taken into account the production performance of the Puna Geothermal Venture (PGV) power plant that has been producing electricity since 1993 (GeothermEx, 1994; Novak, 1995).

Since the 2000 resource assessment was completed, there has been little new data applicable to the identification and characterization of geothermal resources in Hawaii. The exception to this comes from the continued operation of the Puna Geothermal Venture (PGV) project within the KERZ, where several new deep wells have been drilled, in addition to the continued operation of the well field and power plant, which has generated data related to the nature and behavior of the geothermal reservoir that serves that project. However, the additional project data have not led to a fundamentally changed picture of the geothermal energy reserves within the PGV lease area, and therefore do not provide any basis for altering the estimates of resource potential in similar

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but undeveloped areas. Therefore, the overall estimate of the probability of resource occurrence, as reflected in Table 1.1, is unchanged from the 2000 assessment.

As established in the earlier statewide assessments, potential high-temperature resource areas (suitable for either electrical generation or direct use) are defined as areas that satisfy (or are expected to satisfy) the following criteria:

- temperature: > 125°C (> 257°F)
- depth to resource: < 3 kilometers (< 9,843 feet)
- ground elevation: < 2,133 meters (7,000 feet)

Potential areas of low-temperature resources (suitable primarily for direct use) are defined as those that meet the same criteria as above, except that the estimated or expected temperature range is 65–125°C (122–257°F).

The cut-off of 125°C between high- and low-temperature resources was based on an estimate of the lower temperature limit at which binary geothermal plants could generate electricity. This is still a reasonable estimate, and the cut-off of 125°C has been retained in the present assessment. The depth limit of 3 kilometers (approximately 10,000 feet) and the elevation limit of 7,000 feet were based on "limits of current drilling technology." The elevation limit appears to have been related to the depth that a well would need to achieve in order to reach basal ground water (roughly at sea level). Although deeper wells have been drilled in geothermal fields elsewhere in the world, the depth and elevation limits are still reasonable for Hawaii; deeper wells would be prohibitively expensive under current economic conditions.

1.2.2 Theoretical Basis of the Estimation Method

To estimate geothermal energy reserves of the areas of Hawaii with significant potential for electrical power generation, we have used a method of reserve estimation introduced by the

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United States Geological Survey (USGS) in Circular 790 (USGS, 1979), modified to account for uncertainties in some input parameters by using a probabilistic approach (Monte Carlo simulation).

This technique to estimate reserves is based on a volumetric calculation of the heat-in-place for each area of interest, with reasonable assumptions made about:

- the percentage of that heat that can be expected to be recovered at the surface; and
- the efficiency of converting that heat to electrical energy.

As explained below, the heat-in-place calculation takes into account only a volume of rock and water that is reasonably likely to contain adequate permeability and temperature for the generation of electricity using contemporary technology. Hot rock that is deeper than likely to be economically drillable in a commercial project is not included.

The term "reserves" as used herein is analogous to the "geothermal reserve(s)" of Circular 790 (p.4), and different from the overall "geothermal resource," which includes all heat underground. In Circular 790, the concept of "resource" is further subdivided into "inaccessible" (very deep) and "accessible" (likely to be drillable in the 'foreseeable' future). "Accessible" resource is further subdivided into "residual" (too deep for present economics) and "useful" (perhaps drillable at currently acceptable cost). Finally, "useful" is subdivided into "sub-economic" (probably too deep, especially if the resource temperature is not very high, or displaying inadequate permeability), and "economic" (considered likely to be viable).

In Circular 790 (p.4), the term "geothermal reserve" is defined as "that part of the geothermal resource that is identified and also can be extracted legally at a cost competitive with other commercial energy sources at present." It must be emphasized that an estimate of reserves using the volumetric method does not imply any guarantee that a given level of power generation can be achieved. Before a given level of generation can be realized, wells capable of extracting the

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heat from the rock by commercial production of geothermal fluid must be drilled and tested. This is the only way to unequivocally establish the presence of commercially viable reserves and to demonstrate the desired generating capacity of each locally defined resource.

In the reserve-estimation method used herein, the maximum sustainable generation (power plant) capacity (E) is given by:

$$E = V\, C_v(T-T_o)\cdot R/F/L \qquad (1.1)$$

where V = volume of the reservoir,

C_v = volumetric specific heat of the reservoir,

T = average temperature of the reservoir,

T_o = rejection temperature (equivalent to the average annual ambient temperature),

R = overall recovery efficiency (the fraction of thermal energy in-place in the reservoir that is converted to electrical energy at the power plant),

F = power plant capacity factor (the fraction of time the plant produces power on an annual basis), and

L = power plant life.

The parameter R can be determined as follows:

$$R = \frac{W \cdot r \cdot e}{C_f \cdot (T - T_o)} \qquad (1.2)$$

where r = recovery factor (the fraction of thermal energy in-place that is recoverable as thermal energy at the surface),

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C_f = specific heat of reservoir fluid,

W = maximum available thermodynamic work from the produced fluid, and

e = utilization factor to account for mechanical and other losses that occur in a real power cycle.

The parameter C_v in (1.1) is given by:

$$C_v = \rho_r C_r (1-\varphi) + \rho_f C_f \varphi \tag{1.3}$$

where ρ_r = density of rock matrix,

C_r = specific heat of rock matrix,

ρ_f = density of reservoir fluid, and

φ = reservoir porosity.

The parameter W in (1.2) is derived from the First and Second Laws of Thermodynamics as follows:

$$dW = dq\,(1-T_o / T) \tag{1.4}$$

and

$$dq = C_f\, dT \tag{1.5}$$

where q represents thermal energy and T represents absolute temperature.

The Monte Carlo method proceeds by repeatedly performing the above calculations to generate a large number of reserve estimates for each area. Each time the calculation is done, uncertain parameters are assigned random values within their respective ranges. The results of the

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multiple reserve estimates are then compiled to determine the mean, median, and 10th percentile values. (The 10th percentile value has a cumulative probability of more than 90%; i.e., 90% of estimates will be equal to or greater than this value). The simulation also calculates the standard deviation of the mean value.

1.2.3 Selection of Resource Parameters

With the exception of parts of the KERZ, there is insufficient information from deep drilling in the potential resource areas to make direct and accurate estimates of the critical parameters for resource estimation (area, thickness, average temperature, average rock porosity, and recovery factor). However, the direct information from the PGV project regarding the occurrence and nature of the geothermal system in this part of the KERZ can be used in combination with geologic data, volcanological studies and other sources of information to make reasonable estimates for the ranges of these parameters in other areas.

The present assessment assumes that the as-yet-undeveloped geothermal resources in Hawaii occur in essentially the same setting and with similar characteristics to the resource that supplies the PGV project. That is, geothermal reservoirs are anticipated to be present within volcanic rift zones. This is a reasonable inference, because, apart from the summit areas, repeated and persistent intrusion (as well as extrusion) of magma occurs almost uniquely within the rift zones, particularly during the principal shield-building stage of activity. This model of geothermal resource occurrence may be slightly less valid for the older volcanoes that are no longer in the main shield-building stage, but the available data nonetheless appear to be generally consistent with the model.

With this assumption in mind, the parameters for the reserves estimates have been selected as follows:

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Reservoir Area

Data from deep drilling in the KERZ indicate that high temperatures at drillable depths occur within a fairly narrow reservoir zone roughly centered on the rift axis. Although there is bound to be some variability in the width of the reservoir zone within a given rift, the data suggest that the width of the reservoir zone is likely to fall within a range of 0.5 to 1.0 mile. This range has been used as the basis for estimating the area of the reservoir zone in each of the resource areas. The lower limit of reservoir area is calculated as the expected length of the reservoir along the rift, multiplied by the minimum width (0.5 mile). The upper limit is calculated by multiplying the same length by the maximum width (1.0 mile). The reservoir area distribution is assumed to have equal probability between these limits (i.e., a rectangular distribution). The length along the rift estimated for each area is based on the resource areas identified in the 2000 assessment (Figure 1.1), following the same assumptions, criteria and technical data.

The reservoir zones in the KERZ and the Kilauea Southwest Rift Zone are partly contained within Hawaii Volcanoes National Park (Figure 1.2). In addition, a significant portion of the KERZ reservoir zone is within a tract known as Wao Kele o Puna (Figure 1.3). The Office of Hawaiian Affairs (OHA) has announced a plan under which the Trust for Public Land will purchase Wao Kele o Puna in 2006 and transfer the property to the OHA (OHA, 2005). The land between Wao Kele o Puna and the national park is part of a state natural area reserve. Therefore, the chances that the upper portions of the KERZ or of the Kilauea Southwest Rift Zone will ever be open to geothermal development seem rather remote. In recognition of this reality, the reservoir zones of these two rifts have been subdivided into upper and lower portions for purposes of geothermal reserve estimation. The dividing line between the upper and lower portions of the KERZ is assumed to be the western boundary of the Kamaili Subzone (Figure 1.3). For the Kilauea Southwest Rift Zone, the dividing line between upper and lower portions of the rift is assumed to be the boundary of Hawaii Volcanoes National Park (Figure 1.2).

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Thickness

Data from the developed portion of the KERZ indicate that the top of the geothermal reservoir occurs at an elevation of about -3,000 feet with respect to mean sea level (msl). Assuming (conservatively) a maximum drilling depth of 10,000 feet, the drillable reservoir thickness is roughly

$$d = 10,000 - h + z$$

where d is the reservoir thickness, h is the ground-surface elevation, and z is the elevation of the top of the reservoir (-3,000 feet msl in this case). The top of the reservoir is assumed to have the same average elevation in the undeveloped portion of the KERZ and in the Kilauea Southwest Rift Zone, since both these rift zones are of similar age and occur in relatively low-lying areas. For the other resource areas (which have higher average surface elevations), the top of the reservoir is assumed to range from –3,000 msl to as high as sea level ($z = 0$). In these areas, the thickness is assumed to vary with equal probability within the range defined by the variation in the top of the reservoir.

Average Temperature

Drilling data from the KERZ indicate an average temperature that is quite high for geothermal fields (approaching, and in some locations exceeding, the critical point of water). The high temperatures are probably a result of frequent intrusion of magma along the rift zone, providing a nearly continuous, shallow, high-temperature heat source. A range of average temperature of about 580° to 650°F has been estimated for the entire KERZ and for the Kilauea Southwest Rift Zone. This range has been used as the basis for a rectangular probability distribution of average reservoir temperature in these areas.

With decreasing frequency and intensity of shallow magmatic activity, average rock temperatures can be expected to be lower. The history of magmatic activity in the Hawaiian

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volcanoes is well understood from numerous detailed investigations; however, the quantitative relationship of subsurface temperatures to the intensity of activity has not been defined by direct data, so it is necessary to make approximate estimates that reflect the known relative differences between the volcanic environments.

Both Kilauea and Mauna Loa are within the stage of intense, tholeiitic shield-building volcanism that has been determined to account for 95 to 98% of the volume of the edifices of the Hawaiian volcanoes (Clague and Dalrymple, 1987). Kilauea has been somewhat more active than Mauna Loa over at least the last several thousand years (Holcomb, 1987; Lockwood and Lipman, 1987), though in the active rifts of both volcanoes there is frequent enough injection of magma to create the potential for high temperatures comparable to those found in the KERZ. Therefore, the same upper limit (650°F) has been assumed for the average reservoir temperature in the two Mauna Loa rift zones, while the lower limit of average temperature for these zones has been assumed to be 400°F.

The other volcanoes that host areas for which estimates have been made (Haleakala and Hualalai) are in the post-shield stages of volcanic activity, during which magmatic activity and eruptions are much less frequent and intense, accounting for not more than about 2% of the total volume of the volcanoes. Although zones of high temperature are possible, the less intense activity is likely to result in significantly lower resource temperatures. The minimum average reservoir temperature for the resource areas in these older volcanoes has been assumed to coincide with the limit used to define “high-temperature” resources (125°C, or 257°F). The upper limit has been assumed to be 500°F. As for the other areas, the probability distribution is assumed to be rectangular.

Average Rock Porosity

A range of 3% to 7% average rock porosity, with equal probability, has been assumed for all areas. This range is typical of geothermal fields in similar environments. The calculation of energy reserves is, in any case, not very sensitive to changes in this parameter.

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Recovery Factor

This assessment has assumed a rectangular probability distribution of recovery factors ranging from 1% to 10% for all resource areas except the lower KERZ. This is a conservative range for this parameter, but it is appropriate given the uncertainties associated with resources in which no development or exploratory drilling has taken place. Within the lower KERZ, which contains the PGV project and several exploratory wells, a conservative range of 2.5% to 15% has been used.

Fixed Parameters

The following fixed parameters have been used for the estimate of recoverable energy reserves in all of the areas evaluated:

- Volumetric heat capacity of rock: 34.0 BTU/ft^3°F (a typical average value for rocks of the type that occur in this geologic setting)
- Rejection temperature: 65°F (18.3°C). This parameter would, in practice, be somewhat variable from area to area, depending on the average ambient temperature where plant facilities would be built.
- Utilization factor: 45%. This value reflects the typical efficiency of modern geothermal power plants.
- Power plant capacity factor: 95%, which is within the typical range for operating geothermal facilities.
- Power plant life: 30 years, which is a typical lifetime used for planning purposes.

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1.3 Capacity Estimates

The probability distribution of recoverable geothermal energy reserves was estimated for each of the identified resource areas (including separate estimations for upper and lower portions of the KERZ and the Kilauea Southwest Rift Zone), using the methodology and parameters discussed above. The results of the estimates are summarized in Table 1.2. Tabulations and plots of results for each area are included in Appendix A. The plots show probability distributions of reserves in megawatts (MW) for a plant lifetime of 30 years, and they are presented in two formats: (1) histograms of the probability of occurrence of different MW values, and (2) cumulative probability functions.

The MW value corresponding to 90% probability on the y-axis of the cumulative probability plot is the 10th percentile value (i.e., there is a 90% probability that the geothermal energy reserves exceed this level for the area being evaluated). For the purposes of this assessment, the 10th percentile value is considered to be the minimum estimate of MW capacity. Because of the uncertainty in the reservoir characteristics (reflected in the use of rectangular probability distributions in the input parameters for Monte Carlo simulation), the histograms of potential MW values for the various Hawaiian geothermal areas show broad crests, indicating that their most likely MW values are not known with precision. The MW value with the highest probability of occurrence (the highest bar in a histogram plot) is customarily considered the most likely value. However, in this case, successive iterations of Monte Carlo simulation for a given area can yield different “most likely” values, within the range defined by the broad crest of the histogram plot. For the purposes of this assessment, the mean value for each area is considered to be the area’s most likely estimate of MW capacity.

Table 1.2 shows that geothermal energy reserves on the Island of Hawaii have a 10th percentile value of 488 MW and a mean value of 1,396 MW. For the Island of Maui, these values are 38 MW and 139 MW, respectively. Energy reserve estimates for specific areas are discussed below.

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Kilauea East Rift Zone (KERZ)

The KERZ extends approximately 32 miles from the summit of Kilauea Volcano to the sea (Figure 1.3). The large potential resource area and demonstrated high temperatures within the rift zone give it a high level of estimated reserves. The calculated reserves within the entire KERZ have a 10th percentile value of approximately 291 MW and a mean value of approximately 778 MW. For the lower KERZ (excluding areas within the national park and existing or planned forest reserves), these values are 181 MW and 438 MW, respectively.

Kilauea Southwest Rift Zone

The southwest rift of Kilauea is approximately 21 miles long. The 10th percentile value of recoverable energy reserves is estimated to be 133 MW, with a mean value of 393 MW. The corresponding values for the lower portion of the rift (excluding areas within the national park) are 64 MW and 193 MW, respectively.

Mauna Loa Southwest Rift Zone

The portion of the southwest rift of Mauna Loa that is identified as a potential geothermal resource area (applying the elevation cut-off criterion) is 11.5 miles long. The average elevation along this part of the rift is about 4,600 feet, resulting in an estimated range of average reservoir thickness from 2,400 feet to 5,400 feet. The calculated 10th percentile value of reserves is 35 MW, and the mean value is 125 MW.

Mauna Loa Northeast Rift Zone

The area within the northeast rift of Mauna Loa identified as a potential resource area lies along about 8.5 miles of the upper part of the rift. The average elevation in this zone is about 5,400 feet, resulting in an estimated range of average reservoir thickness of 1,600 feet to 4,600 feet. The calculated 10th percentile value of reserves is 22 MW, and the mean value is 75 MW.

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Hualalai

The identified geothermal resource area on Hualalai lies along a relatively short (5 mile) section of the northwestern rift zone of the volcano, at an average elevation of about 5,200 feet. The range of average reservoir thickness is estimated at 1,800 to 4,800 feet. As discussed in Section 1.2, the assumed temperature range for geothermal resources that may exist on this post-shield-stage volcano is 257° to 500°F, lower than for the resource areas on Mauna Loa and Kilauea. The calculated 10th percentile value of reserves is 7 MW, and the mean value is 25 MW.

Haleakala Southwest Rift Zone

The identified resource area on Haleakala's southwest rift extends over approximately 9 miles. The average elevation in this zone is about 3,500 feet (half-way between sea level and the maximum elevation cut-off of 7,000 feet). This results in an estimated range of reservoir thickness 3,500 to 6,500 feet. The calculated 10th percentile value of reserves is 20 MW, and the mean value is 69 MW.

Haleakala East Rift Zone

The identified resource area on Haleakala's east rift is similar to that on the southwest rift, extending over a distance of about 9 miles. The calculated 10th percentile value of reserves is 18 MW, and the mean value is 70 MW.

Summary

The estimated reserves of heat energy recoverable from the 7 identified resource areas vary over a broad range, with estimated mean values of capacity (for a 30-year period of exploitation) ranging from less than 25 MW (on Hualalai) to more than 775 MW (in the KERZ). This range reflects the variability in size of the different resource areas, expected reservoir temperatures and thicknesses, and anticipated distributions of recovery factors. For the islands of Hawaii and

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Maui combined, the total of the 10th-percentile values (reflecting a 90% confidence level) is 525 MW, and the sum of the mean values of estimated reserves for the 7 areas is 1,535 MW.

It is important to note that these estimates of reserves reflect the amount of recoverable heat energy anticipated to be present at drillable depths, without implying that this energy can necessarily be exploited commercially. For commercial exploitation to be feasible, conditions must be adequate for productive wells to be drilled and operated over the lifetime of a power generation project. In addition, as noted above, significant portions of the identified resource areas may be unavailable for geothermal development, for a variety of reasons. Therefore, the geothermal energy reserves available for development are a subset of the estimates presented.

1.4 Predictions of Electricity Generation

Electricity generation from geothermal resources is a function not only of recoverable energy reserves but also of market demand and transmission constraints. Therefore, predictions of electricity generation need to take into account projections of market growth and the potential impact of geothermal power on the transmission system. The following observations about the demand for electricity and the nature of the transmission system on the Island of Hawaii are based on information from the Hawaii Electric Light Company (HELCO, 2004; 2005). These observations set the framework for the predictions of geothermal electrical generation in this study:

- The load profile of electrical demand on the Island of Hawaii shows a daily swing between a peak in the evening and a low in the early morning hours. For example, Figure 1.6 shows the weekday load profile for the Island of Hawaii on 30 December 2003. This was the date of the highest peak load for that year. The ratio of the evening peak to the early morning low is typically about 2:1. Weekend load profiles are similar in magnitude and shape (see Figure 1.7).

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- On an annual basis, evening peak loads on the Island of Hawaii are typically highest in December and lowest in June. Figure 1.8 compares the annual cycle of evening peaks for 2002 and 2003, and it shows that the peaks in 2003 were about 5 MW above the peaks in 2002 for comparable times of year. As of December 2005, the maximum peak load is expected to be approximately 200 MW.

- A recent projection (HELCO, 2005) of maximum peak loads for the Island of Hawaii shows growth of about 4 MW per year for a “base peak” case and about 6.5 MW per year for a “high peak” case (Figure 1.9). The base peak and high peak forecasts reach about 273 MW and 328 MW, respectively, by 2025. It should be noted that these are provisional forecasts as of mid-year 2005 for purposes of developing an Integrated Resource Plan (IRP) for HELCO. The forecasts could be different when the IRP is finalized.

- The area with the greatest electrical demand (and the highest rate of load growth) is on the western side of the Island of Hawaii, in the vicinity of Kailua-Kona (Figure 1.2). The only geothermal power generation to date has been at the Puna Geothermal Venture (PGV) project in the Lower KERZ, on the eastern side of the island. Any major increase in generation on the eastern side of the island to meet peak load demands on the western side would require significant system-wide upgrades in transmission.

- The PGV project currently has a plant capacity of 30 MW (net), and it supplies about 20% of the electricity generated on the Island of Hawaii. PGV is considering increasing its capacity by 8 to 10 MW in the near term, and it has permits from the County of Hawaii to allow expansion to 60 MW.

- The largest power plant currently operating on the Island of Hawaii is a 60-MW naptha-burning plant operated by an independent power producer named Hamakua Energy Partners (HEP). The capacity of this plant amounts to roughly 30% of the present

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maximum peak load. There is currently enough spare capacity connected to the grid to allow the system to accommodate a shut-down of this plant and still meet peak load requirements.

Given the foregoing information, the current study has made certain assumptions for the purpose of predicting the growth of electrical generation capacity from geothermal resources on the islands of Hawaii and Maui:

- The maximum generating capacity of the Lower KERZ has been assumed not to exceed 30% of the maximum peak load for the Island of Hawaii, based on the example of the HEP plant. This constraint is driven by the consideration that an island grid system cannot afford to have too much of its generating capacity concentrated at one location, especially a location that has experienced volcanic eruptions within the past several decades (as recently as 1955 at the PGV site). The growth in plant capacity in the Lower KERZ has been assumed to occur in increments of 8 to 10 MW every 3 years, up to the 30% limit (Figure 1.10).

- The potential contributions of the upper portions of the KERZ and of the Kilauea Southwest Rift Zone are not included in the forecast due to their location within Hawaii Volcanoes National Park or state natural area reserves.

- The Lower Kilauea Southwest Rift Zone and the Mauna Loa Northeast Rift Zone are also not included in the forecast, because they are subject to the same constraint on east-to-west transmission as the Lower KERZ, which is assumed to have priority.

- On the Island of Maui (Figure 1.4), it has been assumed that only one of the two areas with electrical generation potential will be developed within the next 20 years, due to potential challenges on environmental and cultural grounds, as well as likely transmission constraints. For forecasting purposes, the Haleakala Southwest Rift Zone is assumed to be the area developed, based on its closer proximity to load centers in central and western

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Maui, as well as the fact that it already contains a designated geothermal subzone (Figure 1.5). However, since the east and southwest rift zones of Haleakala are of roughly equal size, the choice of one versus the other is not consequential for forecasting purposes. The actual area developed would depend on the results of future exploratory drilling.

- The geothermal areas outside the Lower KERZ that are included in the forecast (i.e., Hualalai and the Mauna Loa Southwest and Haleakala Southwest Rift Zones) are assumed to require at least three years for permitting, drilling, plant construction, and connection to transmission. For the purposes of this study, electrical generation in these three areas is assumed to start in successive years: 2008 for Hualalai, 2009 for the Mauna Loa Southwest Rift Zone, and 2010 for the Haleakala Southwest Rift Zone. The actual timing would depend on the success of any project proponents in obtaining appropriate permits and in confirming the presence of commercial geothermal resources through drilling. These three areas are assumed to be developed in increments of 5 to 10 MW every 3 years (Figure 1.10).

- The sizes of developments projected to be achieved within 20 years outside the Lower KERZ are estimated to be 25 MW at Hualalai, 60 MW at the Mauna Loa Southwest Rift Zone, and 35 MW at the Haleakala Southwest Rift Zone. The resource at Hualalai is assumed to be the most fully utilized because of its proximity to the Kailua-Kona load center, and its projected MW value is estimated to be equal to its mean reserve value. The projected MW values for the Mauna Loa Southwest and Haleakala Southwest Rift Zones are intermediate between their respective 10^{th} percentile and the mean reserve values. None of these three projects is considered likely to approach the constraint of 30% of the maximum peak load for their respective islands within 20 years.

Based on these assumptions, this study has delineated two scenarios for the development of geothermal electrical generation capacity through 2025: a likely scenario and an upside scenario.

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These scenarios are summarized in Table 1.3 and are plotted in Figure 1.11 (for the Island of Hawaii) and Figure 1.12 (for the islands of Hawaii and Maui combined).

- The likely scenario consists of a base case for the Lower KERZ alone, limited to 30% of the base peak forecast for the Island of Hawaii. This scenario reaches a geothermal generation capacity of 82 MW by 2025.

- The upside scenario consists of the sum of an upside case for the Lower KERZ and the three development projections for areas outside the Lower KERZ (Hualalai and the Mauna Loa Southwest and Haleakala Southwest Rift Zones). By 2025, this scenario reaches a geothermal generation capacity of 180 MW for the Island of Hawaii, and 205 MW for the islands of Hawaii and Maui combined.

Alternate scenarios of MW contributions from the seven resource areas in Table 1.2 are certainly possible. However, based on the assumptions listed above, the upside scenario presented here is considered a practical “upper limit” in terms of projected total MW for planning purposes.

1.5 Potential for Hydrogen Generation

The daily load swings on the Island of Hawaii (Figures 1.6 and 1.7) present an opportunity to more fully utilize capacity for generation and transmission during off-peak hours. Geothermal resources are best utilized to supply base-load demand, i.e., to run at steady output during all hours of the day and all seasons of the year. In various geothermal fields around the world, plant operators are sometimes required to curtail power output at night in order to accommodate daily load swings. In Hawaii, HELCO has a contractual right to curtail the output of the PGV facility by approximately 8 MW during 10 off-peak hours in every 24-hour cycle (PGV, 2005). Such a curtailment would amount to a loss of about 11% of the potential energy generated each day, or 80 megawatt-hours (MWh) out of a possible total of 720 MWh. In practice, the curtailment in PGV’s daily generation may be less, depending on the mix of other power plants operating during off-peak hours. If one assumes a range of 5% to 10% curtailment in terms of energy

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generated, then current energy losses at PGV would be in the range of 36 to 72 MWh each day. For the likely scenario of geothermal energy development described above, energy losses due to curtailments of facilities in the Lower KERZ as of 2025 would be approximately 100 to 200 MWh per day. For the upside scenario, energy losses on the Island of Hawaii as of 2025 would be over 200 to 400 MWh per day.

The production of hydrogen is one potential use of electrical generating capacity from geothermal sources during off-peak hours. The possibility of producing hydrogen as transportation fuel from renewable sources on the Island of Hawaii has been described in recent studies by the Hawaii Natural Energy Institute (HNEI) and SENTECH, Inc. (HNEI and SENTECH, 2001; HNEI, 2004). The estimates of energy losses due to off-peak curtailments of geothermal facilities can be used in conjunction with these studies to facilitate more quantitative analysis of the potential for hydrogen production on the Island of Hawaii.

1.6 Potential for Direct Use

1.6.1 District Heating

There are several challenges to the use of geothermal energy for district heating in Hawaii:

- As a result of Hawaii's mild climate, energy requirements for space heating are not high, and potential savings to pay out the investment in a district heating system are low.

- Most of the geothermal resource areas in Hawaii are located in areas of low population density, so the pipeline network to bring hot water to potential users would be relatively large and expensive.

- Installing district heating in areas with existing structures would require customized retrofits to individual units, which would be more expensive than if plans for district heating had been incorporated into the original construction.

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- New wells to confirm a water supply of adequate temperature and flow rate for district heating represent a significant up-front cost. For example, the cost for drilling, casing, and testing water wells with depths of up to 1,000 feet and diameters of 16 to 20 inches has recently been estimated at $600 to $700 per foot for the Puna area (Gill, 2005). Moreover, there is no guarantee that such wells will actually achieve the desired temperature or flow rate.

On the positive side, if the use of geothermal energy for power generation is expanded in Hawaii, opportunities may arise in which wells drilled in exploring for high-temperature resources may eventually be used for district heating projects. District heating in such situations will have a better chance of being economic if it is incorporated into the planning phase of a new development area, including both residential and commercial structures. A district heating project could potentially use residual heat in water discharged from a geothermal power plant, prior to this water being injected back into the reservoir. This would likely entail using heat exchangers to transfer the residual heat to water from another source (such as municipal wells), in order to bring the heat to the district heating project. Such a project would need to be far enough away from the plant to minimize issues relating to plant operations (such as atmospheric emissions, noise and lights), yet close enough to minimize heat losses. Distances up to several miles should be possible if the source temperature is high enough and if the pipeline between the plant and the district heating project is adequately insulated. A feasibility study would need to be conducted based on site-specific conditions to establish the practical range of source temperatures and transport distances, and to confirm that such a district heating project would make economic sense.

1.6.2 Other Direct Use

Geothermal waters with temperatures too low for electrical generation can potentially be applied in a variety of direct uses. Such possibilities in the Puna area are currently being investigated by the Hawaii County Geothermal Direct Use Working Group, comprising a number of interested

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parties (including local residents, businesses, land-owners, PGV, agricultural specialists, government representatives, and geothermal experts), with funding from the GeoPowering the West Program of the U. S. Department of Energy (Gill, 2004). Potential uses include dehydration for fruits and other agricultural products, lumber drying, cold storage and ice-making, aquaculture, greenhouse bottom heating, and soil sterilization. Sources of geothermal water at Puna could include (1) residual heat from the PGV plant, (2) existing shallow wells (less than 1,000 feet) with temperatures as high as 95°C (203°F), and (3) new well drilling (Gill, 2005).

PGV has reportedly offered the heat of the discharge water from its Puna plant at no charge (Gill, 2005). PGV currently injects its discharge water at temperatures at or above 300°F, but they are considering the addition of a bottoming cycle that could lower the temperature of the discharge water to the range of 150°F to 250°F (PGV, 2005). A possible location for direct use applications of this water is the four-acre Noii O Puna research site adjacent to PGV's lease. PGV's offer of the heat of the discharge water for direct use is subject to several constraints (Gill, 2005):

- The discharge water would need to be returned to the PGV lease for injection.
- The use of the discharge water should have no negative impact on PGV's power-generation activities.
- A third party would need to invest in the necessary infrastructure (heat exchangers, pipes, circulation pumps, etc.) for the direct use operation.

If direct use projects prove to be economically viable at Puna, they could potentially generate interest in similar projects at other geothermal resource areas, especially if these areas are being explored anyway for purposes of electric power generation.

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2. COSTS OF GEOTHERMAL ENERGY PRODUCTION IN HAWAII

2.1 Introduction

For this analysis, GeothermEx has estimated the levelized cost of geothermal power in Hawaii with KERZ as the prototype area. While we are familiar with the well and reservoir performance as well as capital costs (exploration, drilling, power plant and other surface facilities) and operations costs in the KERZ area, most of the information is proprietary; and as such, can not be released. Therefore, we have estimated, from published sources and anecdotal information, the various cost and resource parameters required for this analysis within realistic ranges.

2.2 Factors that Affect Levelized Cost of Geothermal Power

These factors can be grouped into four categories: (a) economy of scale, (b) well productivity characteristics, (c) development and operational options, and (d) macro-economic climate. In general, economy of scale allows both unit capital cost (in dollars per kW installed) and unit O&M cost (in ¢/kWh) to decline with increasing installed capacity. We have assumed a base case plant capacity of 30 MW. For this analysis we have used the methodology of Sanyal (2005), but have adapted a probabilistic approach to account for significant uncertainties in some cost and resource variables. Based on GeothermEx's experience, we believe the representative unit O&M cost in Hawaii would range approximately from 4¢/kWh to 6¢/kWh for a 30 MW plant.

Well productivity characteristics affect geothermal power cost in mainly two ways: (1) if well productivity is higher, fewer wells are needed to supply a plant, thus reducing power cost; and (2) a higher rate of decline in well productivity with time calls for more make-up well drilling, and therefore, leads to higher power cost.

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For the purposes of this analysis, an average initial productivity of 5 to 30 MW per well was assumed; this is a typical range for the KERZ. We have assumed the probability to be equal (i.e., a rectangular probability distribution) over this range.

Geothermal wells generally undergo "harmonic" decline in well productivity with time (Sanyal, *et al*, 1989):

$$W = \frac{W_i}{1 + D_i t}, \qquad (2.1)$$

where W_i is initial productivity, D_i is initial annual decline rate in productivity and W is productivity in year t. Make-up wells are drilled to maintain steam supply to the plant in the face of this productivity decline. The harmonic decline trend implies a decline rate that slows down with time, the annual decline rate (D) in productivity in year t being given by (Sanyal, et al, 1989):

$$D = \frac{D_i}{1 + D_i t} \qquad (2.2)$$

For the 30-MW base case, we have estimated a D_i value of 1% to 5% with equal probability; this is reasonable based on the performance of such systems worldwide.

The unit capital cost for a 30 MW project was estimated at $2,500/kW to $5,000/kW with $3,500/kW as most likely, based on GeothermEx's experience in projects recently developed (or currently under development) in the United States, plus our experience in Hawaii. While the unit capital cost includes initial drilling cost, the unit O&M cost does not include make-up well drilling cost. In order to estimate the make-up well drilling cost as a function of time, it is necessary to estimate first the initial number of wells required for a given plant capacity. This estimate was based on the initial productivity per well plus the customary need for at least one stand-by well and a minimum of 10% reserve production capacity at all times. With the above

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assumptions it can be shown that the installed plant capacity can be maintained without any make-up well drilling for up to t_c years following plant start-up, as given by:

$$t_c = \frac{1}{D_i}\left[\frac{W_i N_{wi}}{(1+r/100)P} - 1\right], \tag{2.3}$$

where D_i is initial annual harmonic decline rate, W_i is initial productivity per well (MW), N_{wi} is initial number of wells (including at least one stand-by well), P is plant capacity (MW), and r is minimum production capacity reserve required (%).

2.3. Calculation of Levelized Power Cost

Figure 2.1 shows the schematic generation and make-up well drilling histories of a typical power project. Generation can be maintained without make-up well drilling up to year t_c, as given by Eq. 2.3. Then generation is maintained by make-up well drilling up to year t_d in response to decline in well productivity according to Eq. 2.1. After year t_d, no make-up wells are drilled, and generation is allowed to decline as per Eqs. 2.1 and 2.2. Sanyal (2005) argues that t_d should ideally be about 20 years.

Given the generation and make-up well drilling histories represented in Figure 2.1, levelized cost of geothermal power $(\bar{c})$ in ¢/kWh is given by (Sanyal, 2005):

$$\bar{c} = \frac{100D(t_d)}{G\{D(t_d)t_d + \ln[1 + D(t_d)(n - t_d)]\}}$$

$$\cdot \left\{\frac{iC(1+i)^n}{(1+i)^n - 1}\right\}\left\{\frac{(1+I)^n - 1}{I(1+I)^{n-1}}\right\} + c_{ov} + \left(\frac{t_d}{n}\right)c_{ofi}$$

$$+ \frac{c_{ofi}}{n}\left\{(n - t_d) + \frac{D(t_d)}{2}(n - t_d)^2\right\} + \frac{100C_{wi}N_{wi}D(t_d)D(t_c)(t_d - t_c)}{G\{D(t_d)t_d + \ln[1 + D(t_d)(n - t_d)]\}}, \tag{2.4}$$

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where $D(t)$ is annual productivity decline rate in year t; G is initial annual generation (kWh); N is power plant life (assumed to be 30 years); C is total capital cost, that is, unit capital cost ($/kW) multiplied by P (kW); c_o is unit annual O&M cost (¢/kWh); i is annual interest rate (assumed to be 8% in base case); I is annual inflation rate (assumed to be 3% in base case); c_{ofi} is fixed portion of the annual O&M cost at plant start-up divided by initial annual generation (¢/kWh); c_{ov} is variable portion of the annual O&M cost divided by annual generation (¢/kWh); N_{wi} is number of initial production wells; and C_{wi} is drilling cost per initial production well (assumed to be $4 to 9 million with equal probability).

Capital costs include exploration cost, power plant cost, gathering and injection system cost and cost of capital. Annual O&M cost includes personnel, general and administrative costs, insurance, supplies and consumables, engineering and laboratory services, wellfield maintenance, generator and turbine maintenance, and other equipment and maintenance costs.

The variable portion of the annual O&M cost represents costs that vary with the level of generation, such as costs of supplies and consumables, which remain proportional to generation; this cost divided by the annual generation gives c_{ov}. The fixed portion of the annual O&M cost represents costs that are independent of the generation level; these include costs of personnel, administration, insurance, wellfield maintenance, generator and turbine maintenance, other equipment maintenance, which may not decline in response to any decline in generation. This fixed annual cost divided by annual generation gives c_{of}. For the purposes of this analysis, 20% of the annual O&M cost was assumed to vary with generation at plant start-up; however, results are found to be relatively insensitive to the fraction of O&M cost that is variable. As generation declines, c_{ov} remains constant, but the fixed portion of annual O&M costs (c_{of}) increases from its initial value of c_{ofi}.

A typical plant capacity factor of 95% was assumed in estimating annual generation. In Eq. 2.4, the total capital cost (C) is assumed to be amortized over the plant life of n years at an interest rate i (annual compounding). The calculated power costs in future years are discounted for

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inflation to arrive at a levelized power cost in present dollars $(\bar{c})$, as given by Eq. 2.4. The levelized power cost $(\bar{c})$ was estimated probabilistically using the Monte Carlo sampling technique. As stated before, the following variables were treated as uncertain:

Variable	**Probability Density Function**
Unit Capital Cost	Triangular ($2,500 to $5,000 per kW with $3,500 per kW most likely
Unit Operations Cost	4 to 6 ¢ per kWh with equal probability
Initial Well Productivity	5 to 30 MW with equal probability
Initial Annual Well Productivity Decline Rate	1% to 5% with equal probability
Initial Drilling Cost per Well	$4 million to $9 million with equal probability

The remaining variables were assigned fixed values as discussed above. Table 2.1 lists the values of all uncertain as well as fixed parameters.

For the 30-MW base case we have estimated the probability distribution of levelized power cost as shown in Figure 2.2 and the cumulative probability distribution as shown in Figure 2.3. From these two figures, we estimate a mean levelized power cost of 7.84 cents per kW-hour with a standard deviation of 0.70 cents per kilowatt-hour. With a cumulative probability of 90%, levelized cost is expected to be higher than 7.0 ¢/kWh but lower than 8.7¢/kWh.

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TABLES

Table 1.1 Probabilities of Finding Geothermal Resources in Hawaii[1]

County	Island	Resource Area	Probability of High-Temperature Resource (> 125°C)	Probablility of Low-temperature Resource (65–125°C)
Kauai	Kauai	Lihue	<5%	<15%
Honolulu	Oahu	Koolau	<5%	<10%
		Waianae	<5%	<15%
Maui	Molokai	West Molokai	<10%	<45%
	Lanai	Palawai	<15%	<50%
	Maui	Honolua	<5%	<5%
		Lahaina	<5%	<15%
		Olowalu	<15%	<50%
		Haleakala NW Rift Zone	<5%	<10%
		Haleakala East Rift Zone	25% or less	35% or less
		Haleakala SW Rift Zone	25% or less	35% or less
Hawaii	Hawaii	Kohala	<5%	<10%
		Kawaihae	<10%	<45%
		Mauna Kea East Rift Zone	<10%	<30%
		Mauna Kea NW Rift Zone	<20%	<50%
		Mauna Loa NE Rift Zone	35% or less	60% or less
		Mauna Loa SW Rift Zone	<35%	60% or less
		Hualalai	<35%	70% or less
		Kilauea SW Rift Zone	>90%	>90%
		Kilauea East Rift Zone	>95%	>95%

Note 1: Probabilities as reported in 2000 Statewide Geothermal Resource Assessment (GeothermEx, 2000)

Table 1.2: Summary of Reserves Estimates For Hawaiian Geothermal Areas

	Megawatt Capacity	
Resource Area	10th Percentile	Mean
Kilauea East Rift Zone		
Lower	181	438
Upper	110	339
Total	291	778
Kilauea Southwest Rift Zone		
Lower	64	193
Upper	68	201
Total	133	393
Mauna Loa Southwest Rift Zone	35	125
Mauna Loa Northeast Rift Zone	22	75
Hualalai	7	25
Haleakala Southwest Rift Zone	20	69
Haleakala East Rift Zone	18	70
Totals:		
Island of Hawaii	488	1,396
Island of Maui	38	139
Islands of Hawaii and Maui	525	1,535

Table 1.3: Forecast of Electrical Generation Capacity from Hawaiian Geothermal Resources

	Likely Scenario	Upside Scenario					
Year	Base Case For Lower KERZ (Net MW)	Upside Case For Lower KERZ (Net MW)	Hualalai (Net MW)	Mauna Loa SW Rift Zone (Net MW)	Upside Total for Island of Hawaii (Net MW)	Haleakala SW Rift Zone (Maui) (Net MW)	Upside Total for Islands of Hawaii and Maui (Net MW)
2005	30	30			30		30
2006	38	40			40		40
2007	38	40			40		40
2008	38	40	0		40		40
2009	46	50	5	0	55		55
2010	46	50	5	10	65	0	65
2011	46	50	5	10	65	5	70
2012	54	60	10	10	80	5	85
2013	54	60	10	20	90	5	95
2014	54	60	10	20	90	10	100
2015	62	70	15	20	105	10	115
2016	62	70	15	30	115	10	125
2017	62	70	15	30	115	15	130
2018	70	80	20	30	130	15	145
2019	70	80	20	40	140	15	155
2020	70	80	20	40	140	20	160
2021	70	90	25	40	155	20	175
2022	78	90	25	50	165	20	185
2023	78	90	25	50	165	25	190
2024	78	95	25	50	170	25	195
2025	82	95	25	60	180	25	205

Table 2.1: Parameter Values in Levelized Power Cost Analysis for Hawaiian Geothermal Power

Fixed Parameters

Plant capacity	30 MW (net)
Plant capacity factor	95%
Project life	30 years
Period of make-up well drilling following plant start-up	20 years
Fraction of annual O&M cost that varies with generation	20%
Annual interest rate	8%
Annual inflation rate	3%

Uncertain Parameters

Unit capital cost	\$2,500 to \$5,000 with \$3,500 most likely
Unit O&M cost	4 to 6 ¢/kWh
Initial well productivity	5 to 30 MW (net)
Initial annual well productivity decline	1% to 5%
Initial drilling cost per well	\$4 million to \$9 million

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FIGURES

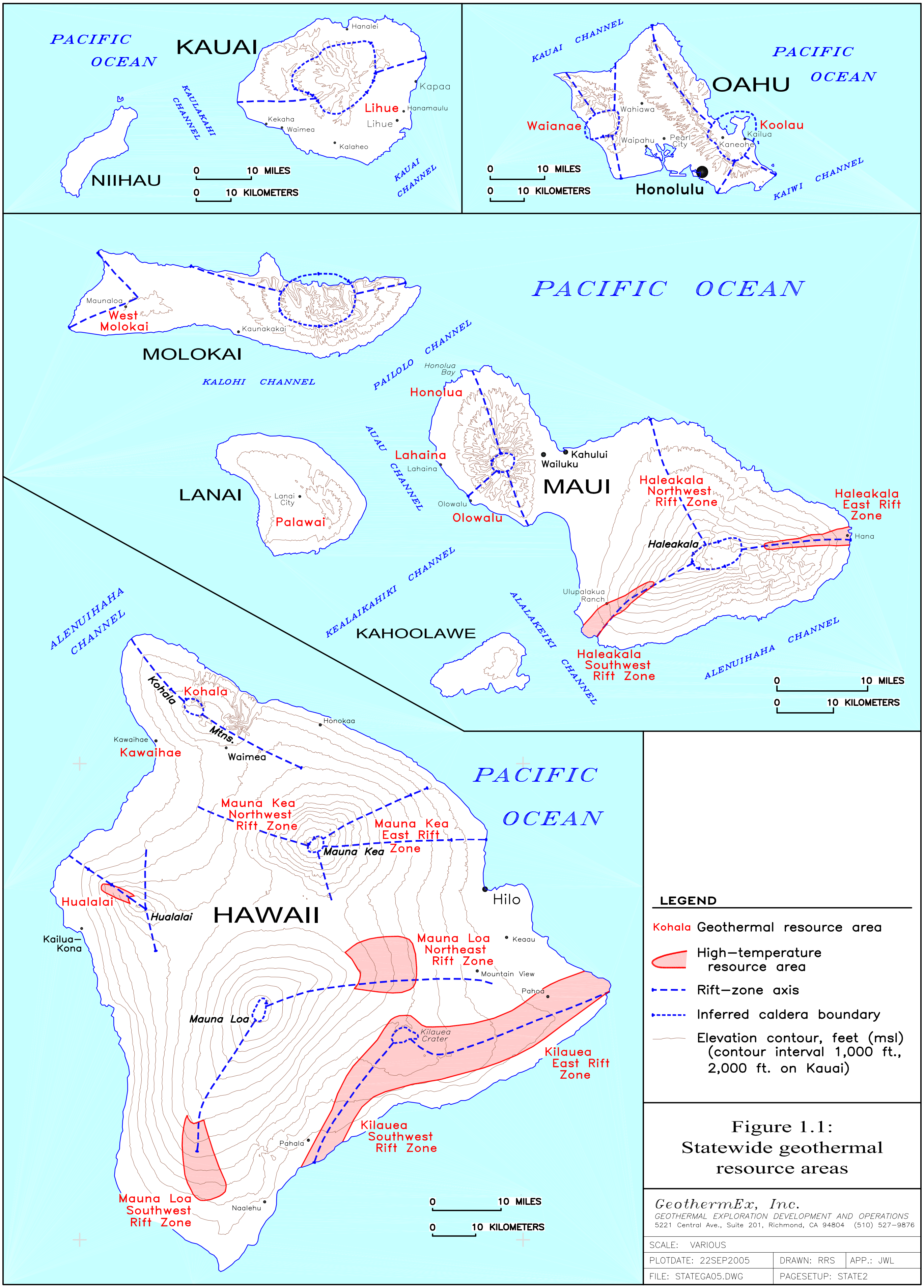

Figure 1.1:
Statewide geothermal resource areas

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SCALE: VARIOUS		
PLOTDATE: 22SEP2005	DRAWN: RRS	APP.: JWL
FILE: STATEGA05.DWG	PAGESETUP: STATE2	

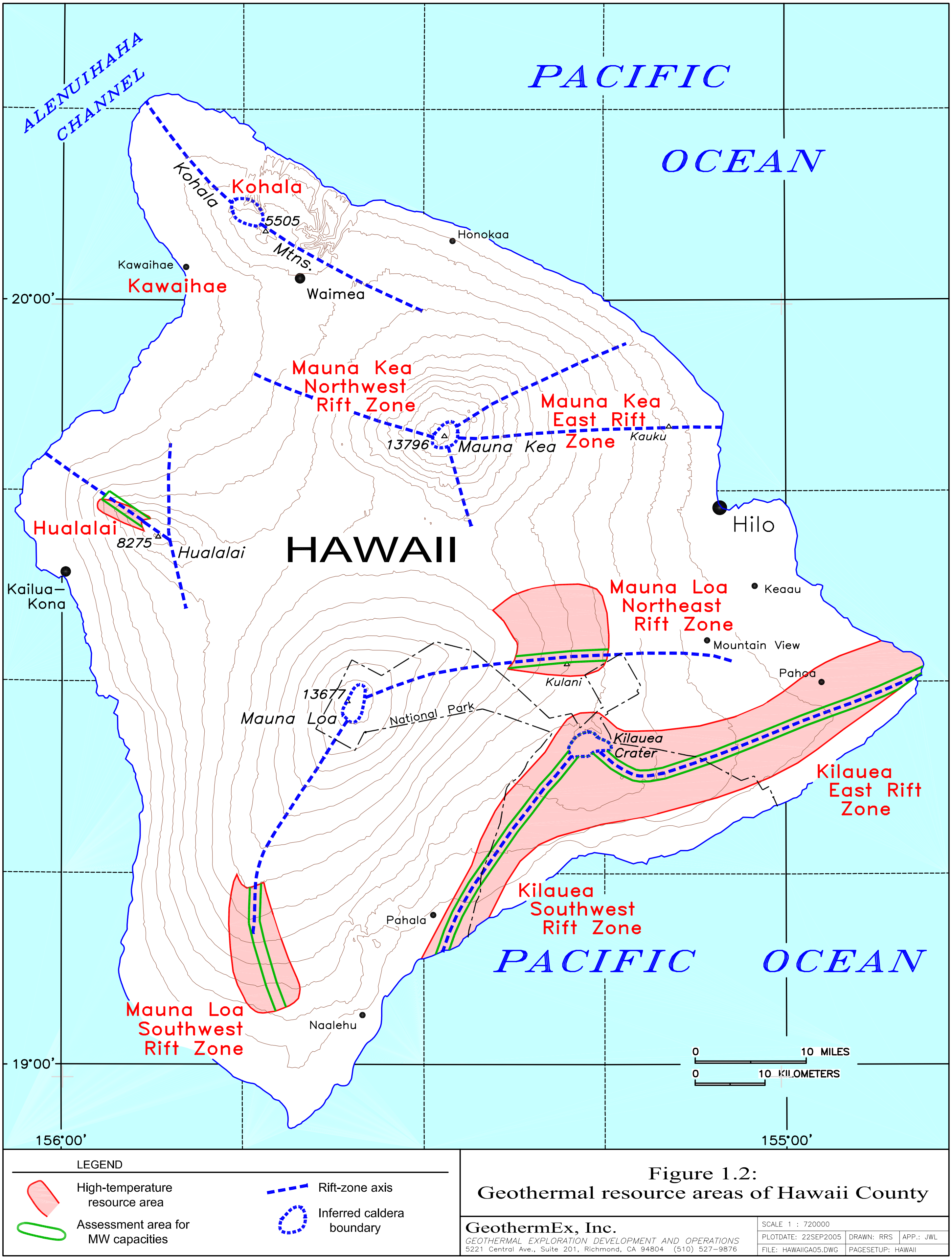
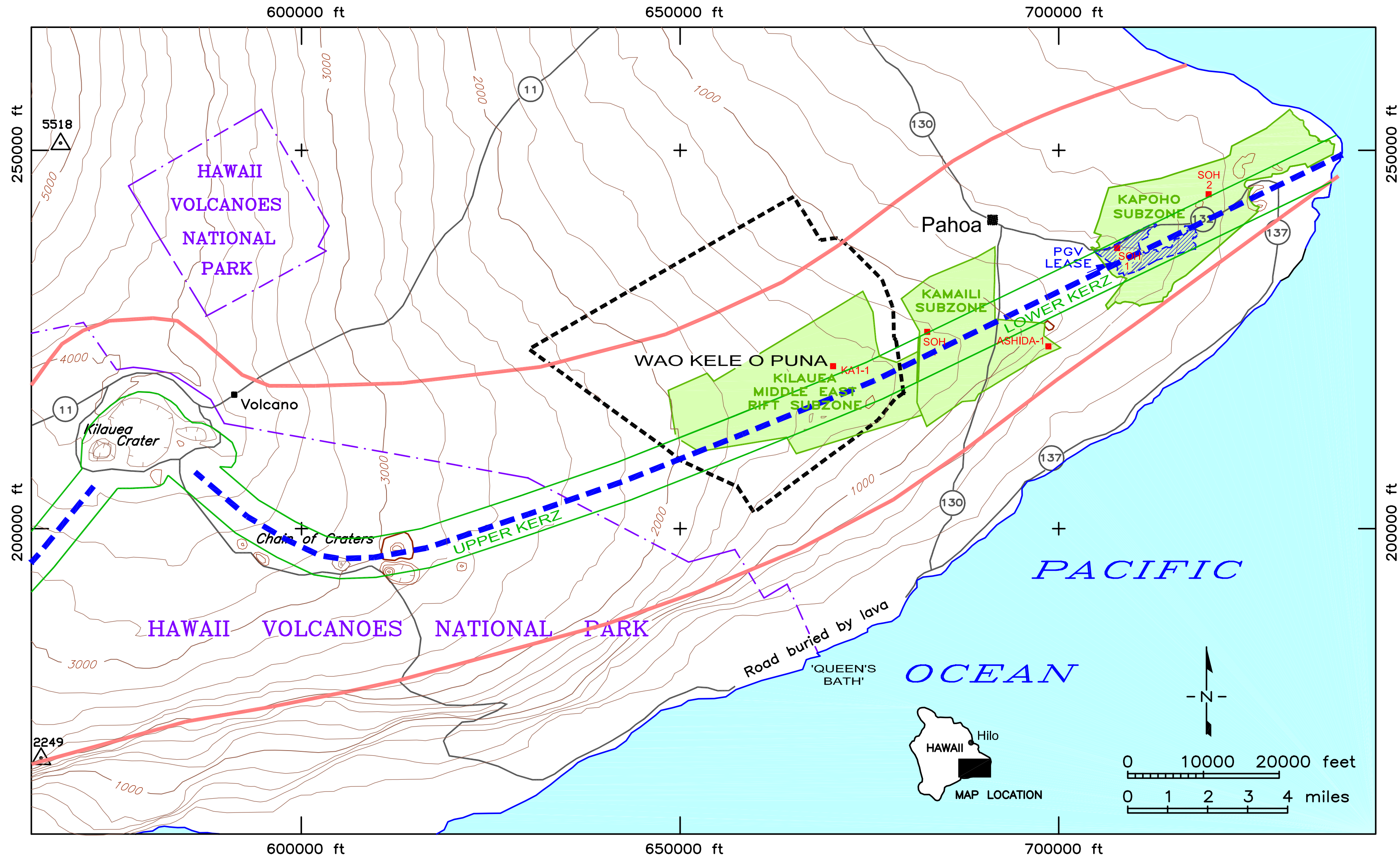


Figure 1.2:
Geothermal resource areas of Hawaii County



LEGEND

	High-temperature resource area		Main road
	Geothermal resource subzone		
	Well location		
	Rift axis		
— 1000 —	Elevation contour, feet (interval 200ft)		
	Assessment area for MW capacities		

Figure 1.3: Kilauea East Rift Zone

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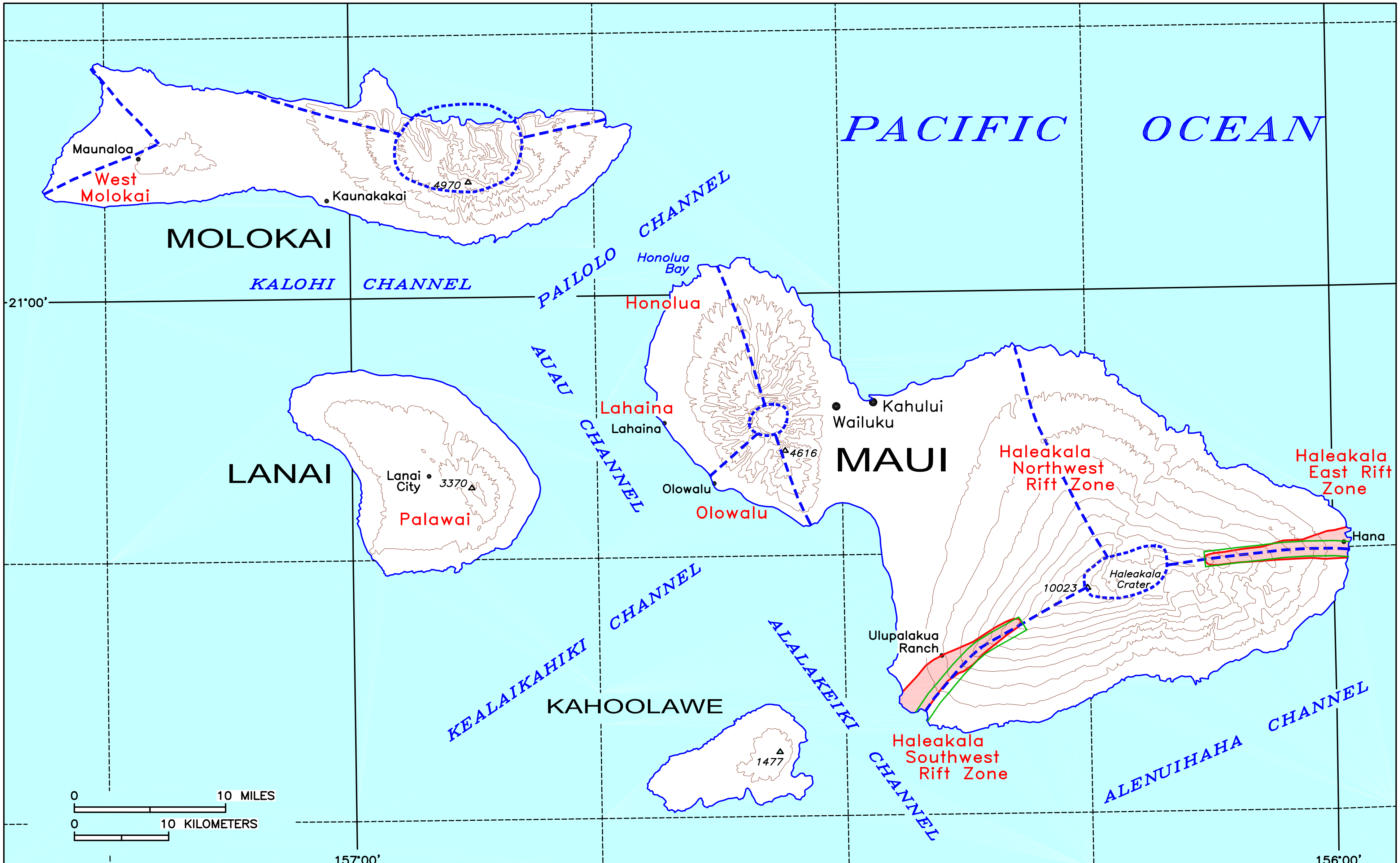
FILE: HAWAIIKERZGA05.DWG
PLOTDATE: 30SEP2005
PLOTSETUP: WAO
DRAWN: RRS
APP.: JWL



LEGEND

- Elevation contour, feet (msl) (contour interval 1,000 ft.)
- Palawai — Geothermal resource area
- High-temperature resource area
- Assessment area for MW capacities
- Rift-zone axis
- Inferred caldera boundary

Figure 1.4:
Geothermal resource areas of Maui County

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SCALE 1 : 580000		
PLOTDATE: 23SEP2005	DRAWN: RRS	APP.: JWL
FILE: MAUIGA05.DWG	PAGESETUP: MAUI	

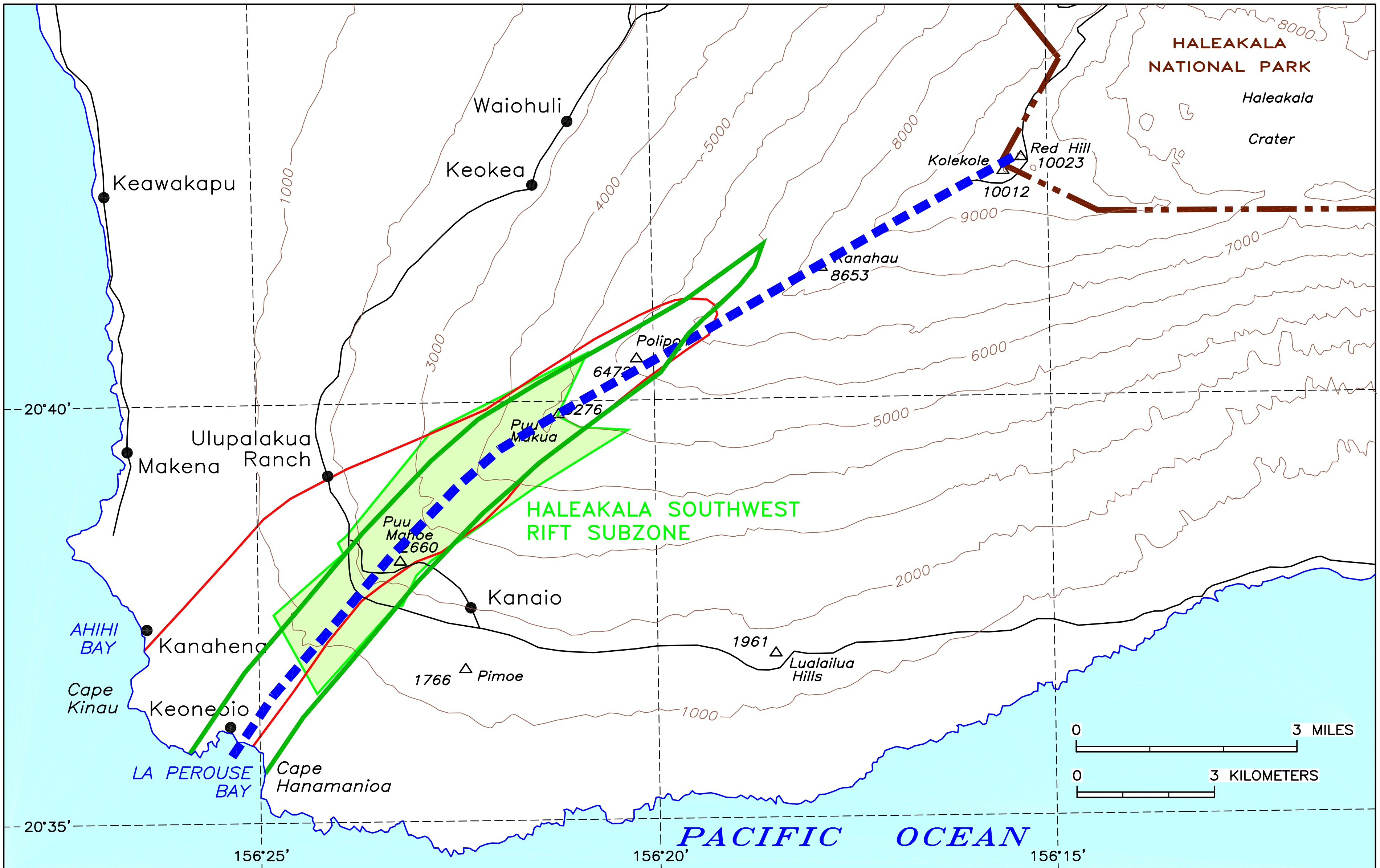

Figure 1.5: Haleakala Southwest Rift Zone

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SCALE 1 : 120000		
PLOTDATE: 23SEP2005	DRAWN: RRS	APP.: JWL
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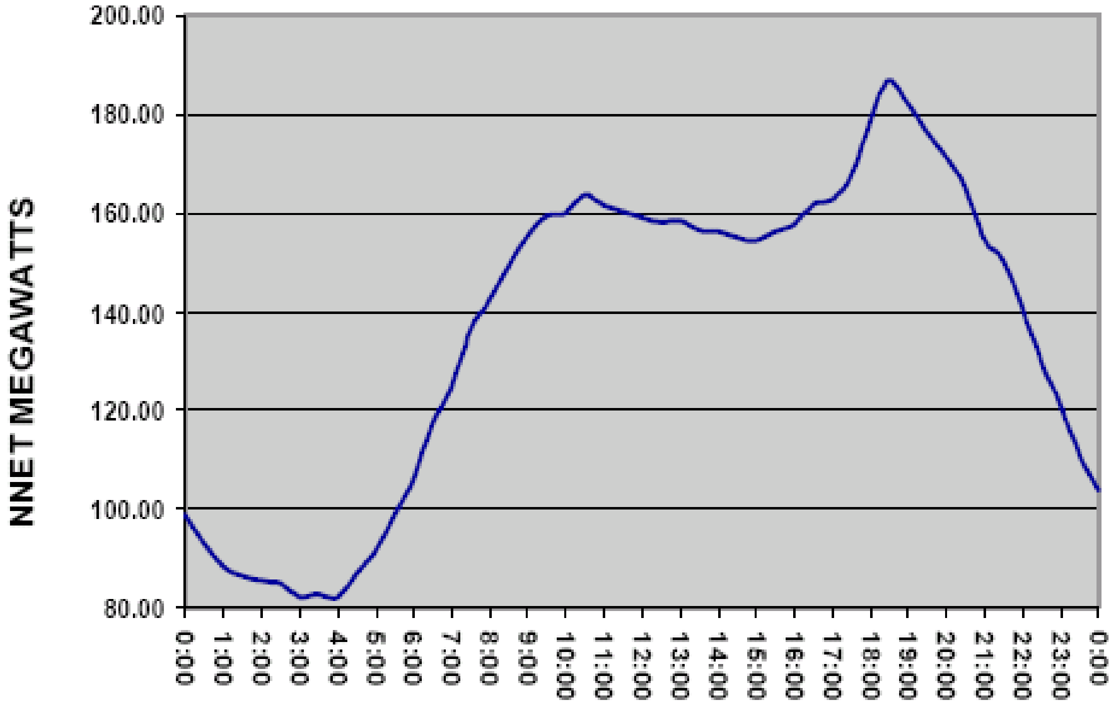


Figure 1.6: Weekday load profile for the Island of Hawaii, 30 December 2003
Source: HELCO, 2004

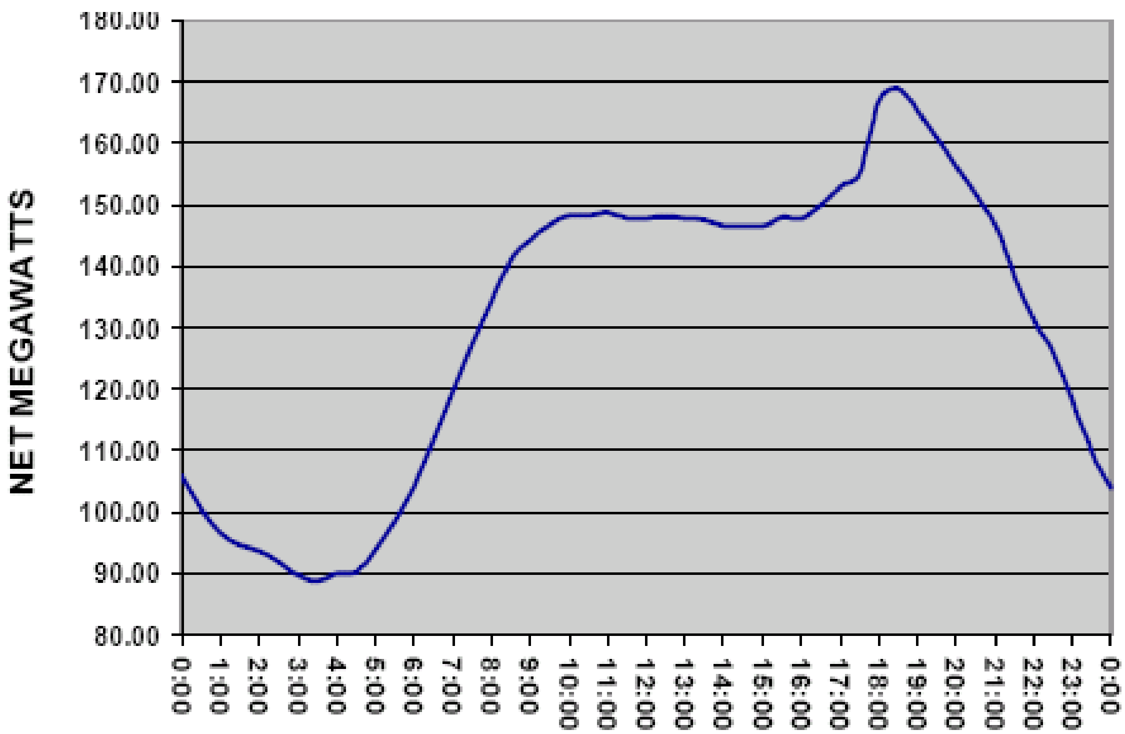


Figure 1.7: Weekend load profile for the Island of Hawaii, 6 December 2003
Source: HELCO, 2004

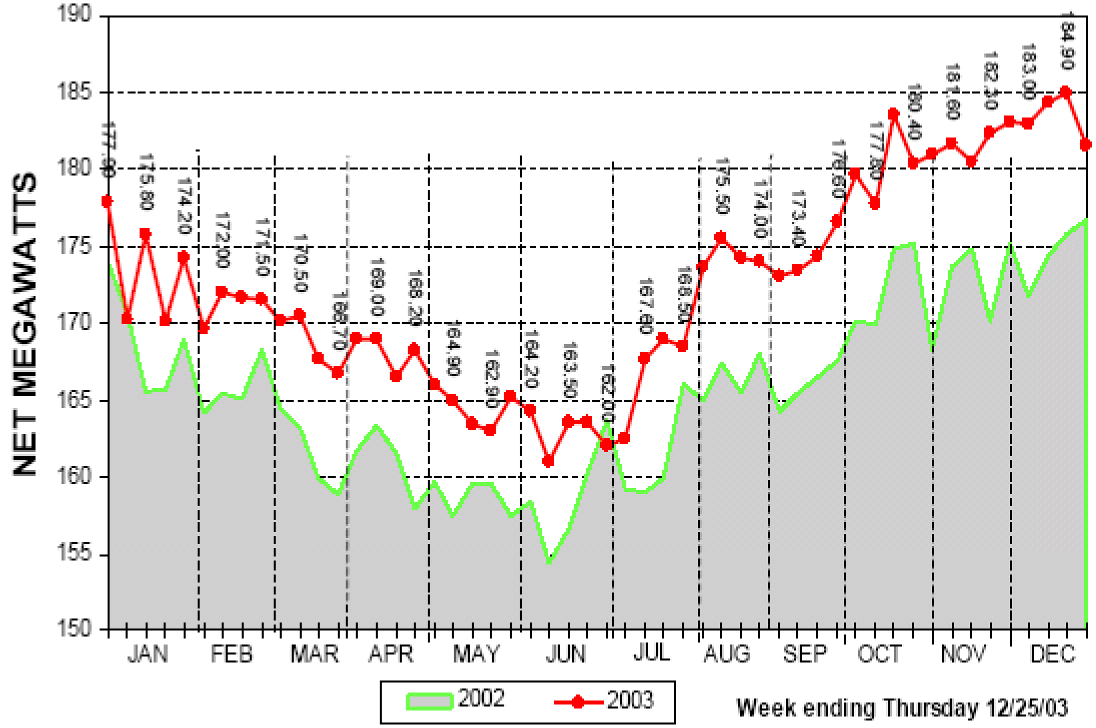


Figure 1.8: Annual cycle of evening peaks for Island of Hawaii, 2003 vs. 2002
Source: HELCO, 2004

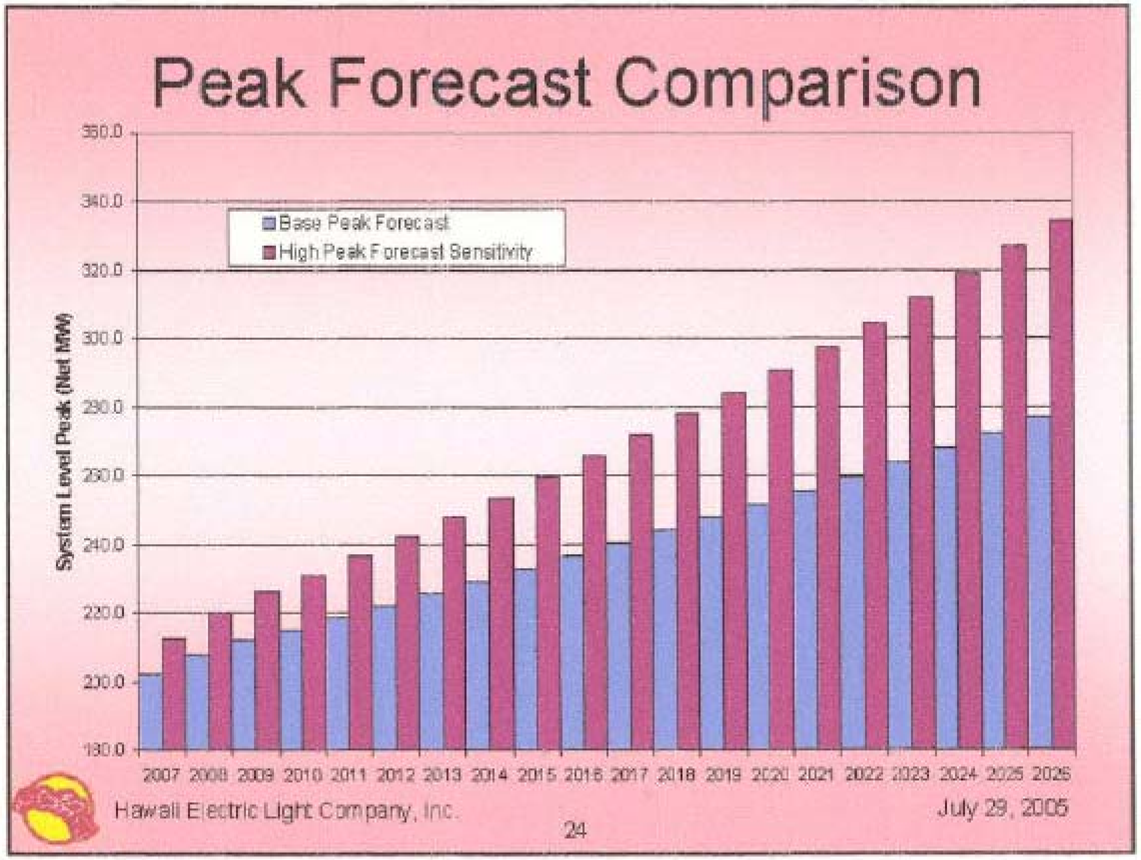


Figure 1.9: Forecasts of maximum peak load on Island of Hawaii
Source: HELCO, 2005
Note: These are provisional forecasts as of mid-year 2005 for purposes of developing an Integrated Resource Plan (IRP) for HELCO. The forecasts could be different when the IRP is finalized.

Figure 1.10: Forecast of Electrical Generation Capacity from Individual Geothermal Resource Areas

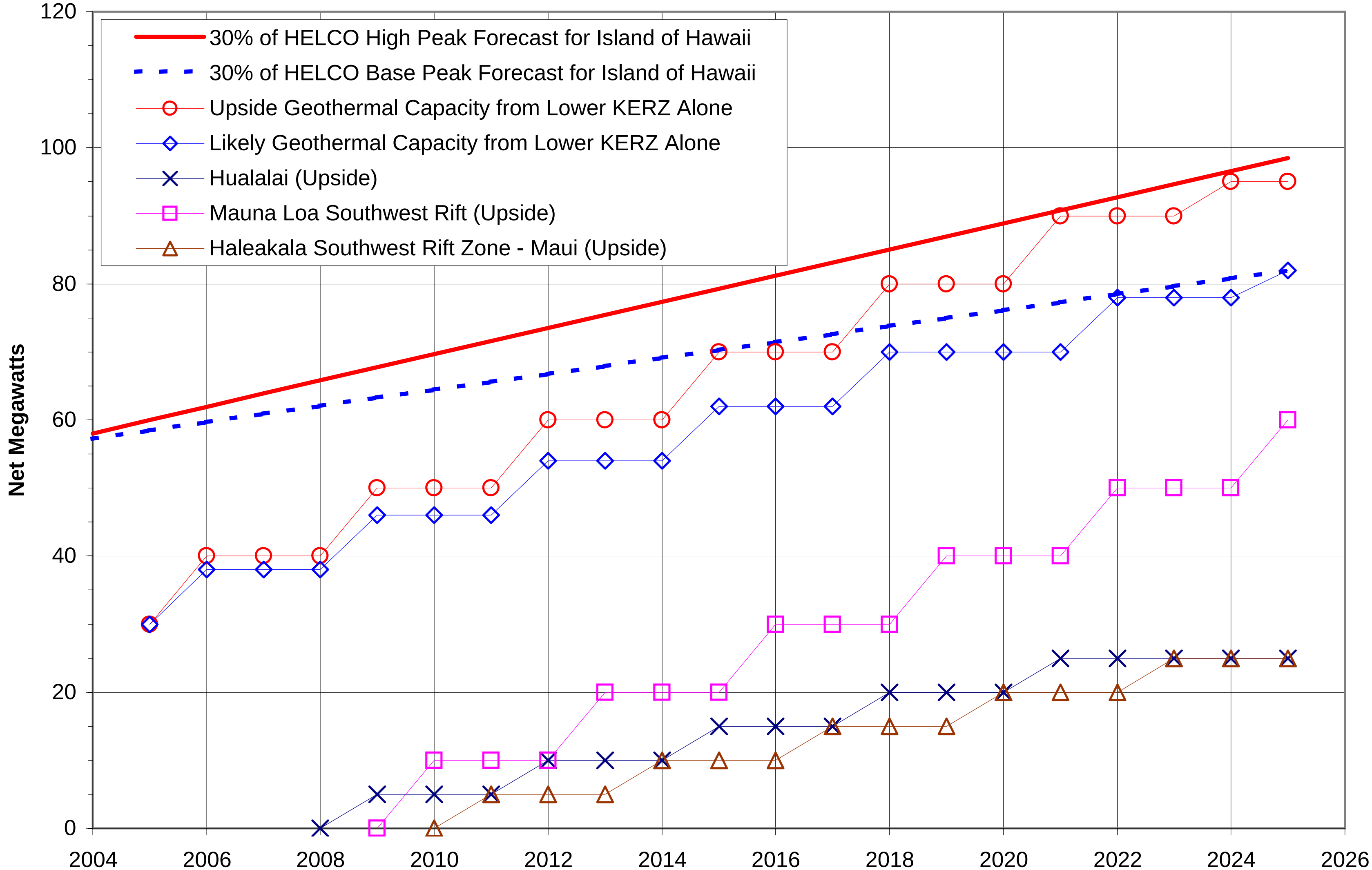


Figure 1.11: Forecast of Electrical Generation Capacity from Geothermal Resources on the Island of Hawaii

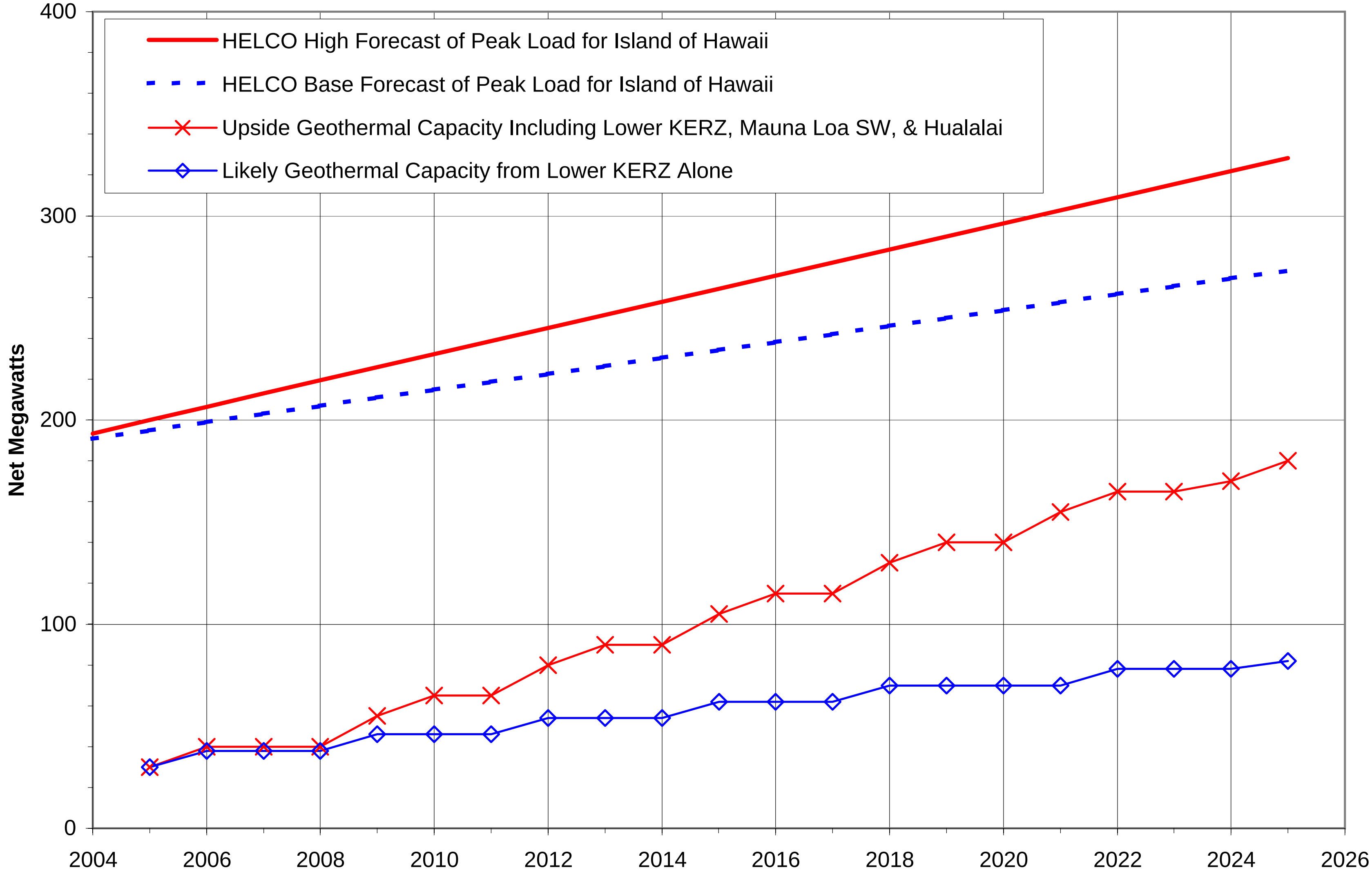
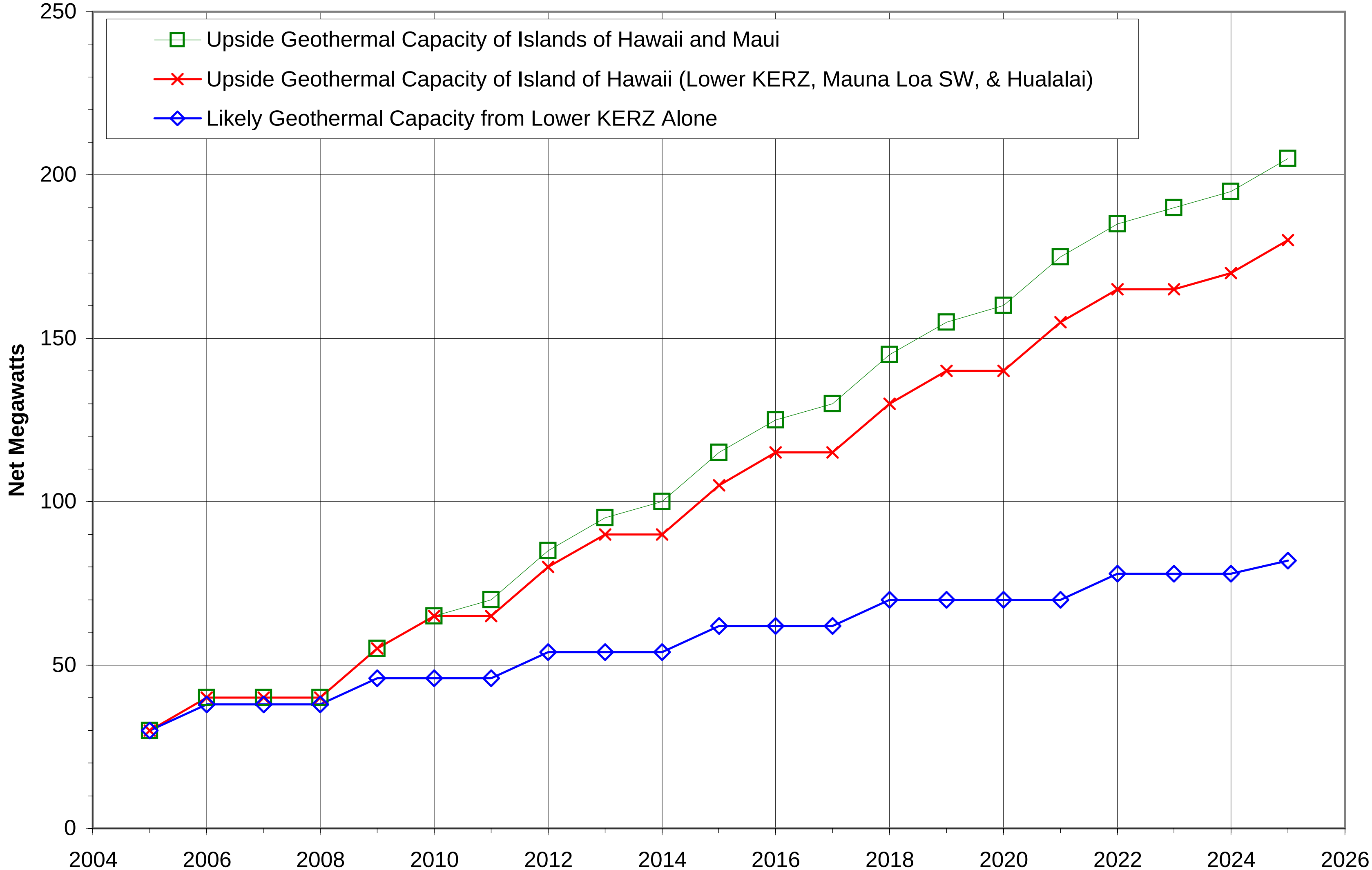


Figure 1.12: Forecast of Electrical Generation Capacity from Geothermal Resources on the Islands of Hawaii and Maui



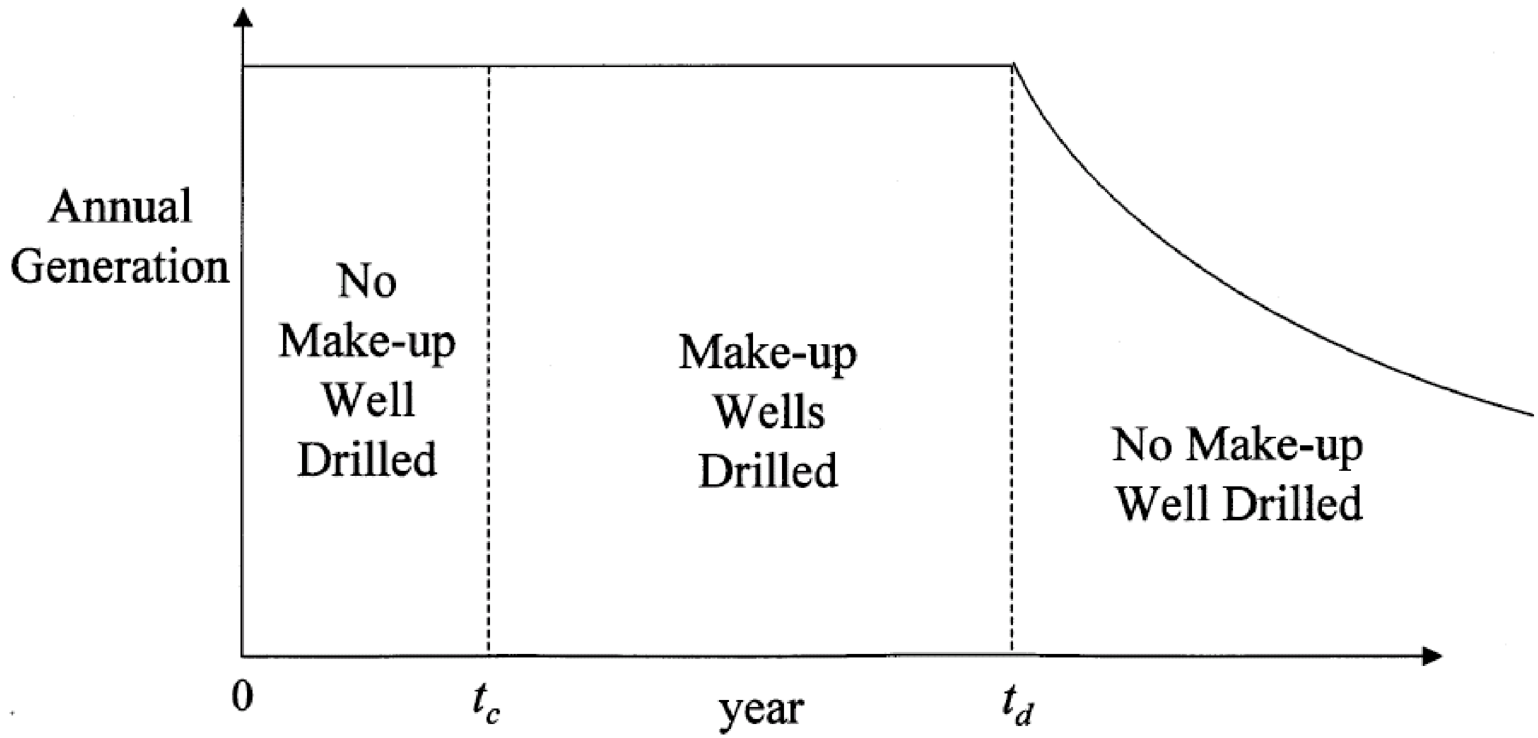


Figure 2.1: Schematic Generation and Make-up Well Drilling History of a Project
Source: Sanyal, 2005

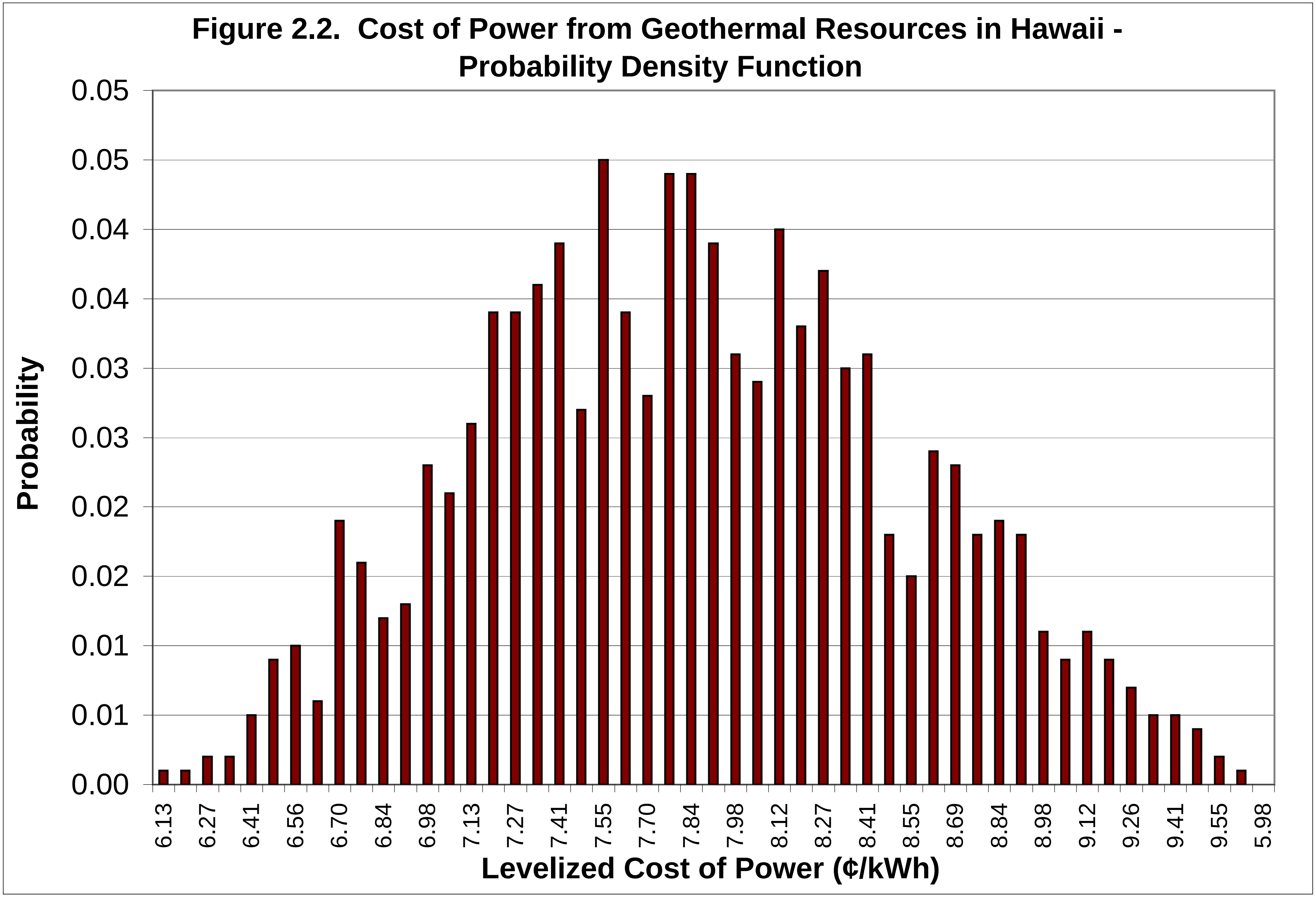


Figure 2.2. Cost of Power from Geothermal Resources in Hawaii -
Probability Density Function
Probability
0.05
0.05
0.04
0.04
0.03
0.03
0.02
0.02
0.01
0.01
0.00
6.13
6.27
6.41
6.56
6.70
6.84
6.98
7.13
7.27
7.41
7.55
7.70
7.84
7.98
8.12
8.27
8.41
8.55
8.69
8.84
8.98
9.12
9.26
9.41
9.55
5.98
Levelized Cost of Power (¢/kWh)

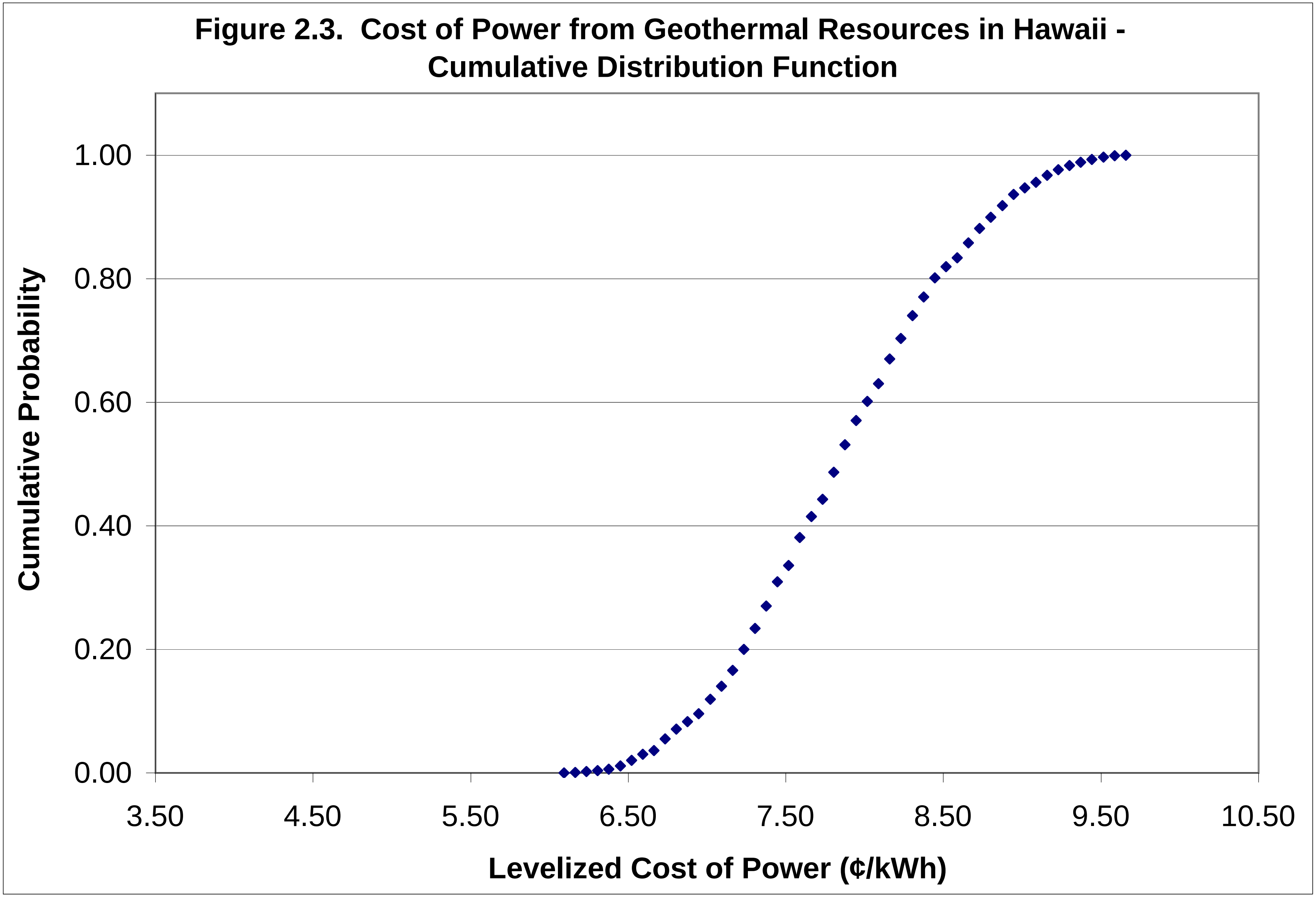


Figure 2.3. Cost of Power from Geothermal Resources in Hawaii -
Cumulative Distribution Function
Cumulative Probability
1.00
0.80
0.60
0.40
0.20
0.00
3.50
4.50
5.50
6.50
7.50
8.50
9.50
10.50
Levelized Cost of Power (¢/kWh)

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APPENDIX A

Probabilistic Reserve Estimates by Area

Estimate of Geothermal Energy Reserves,
Lower Kilauea East Rift Zone

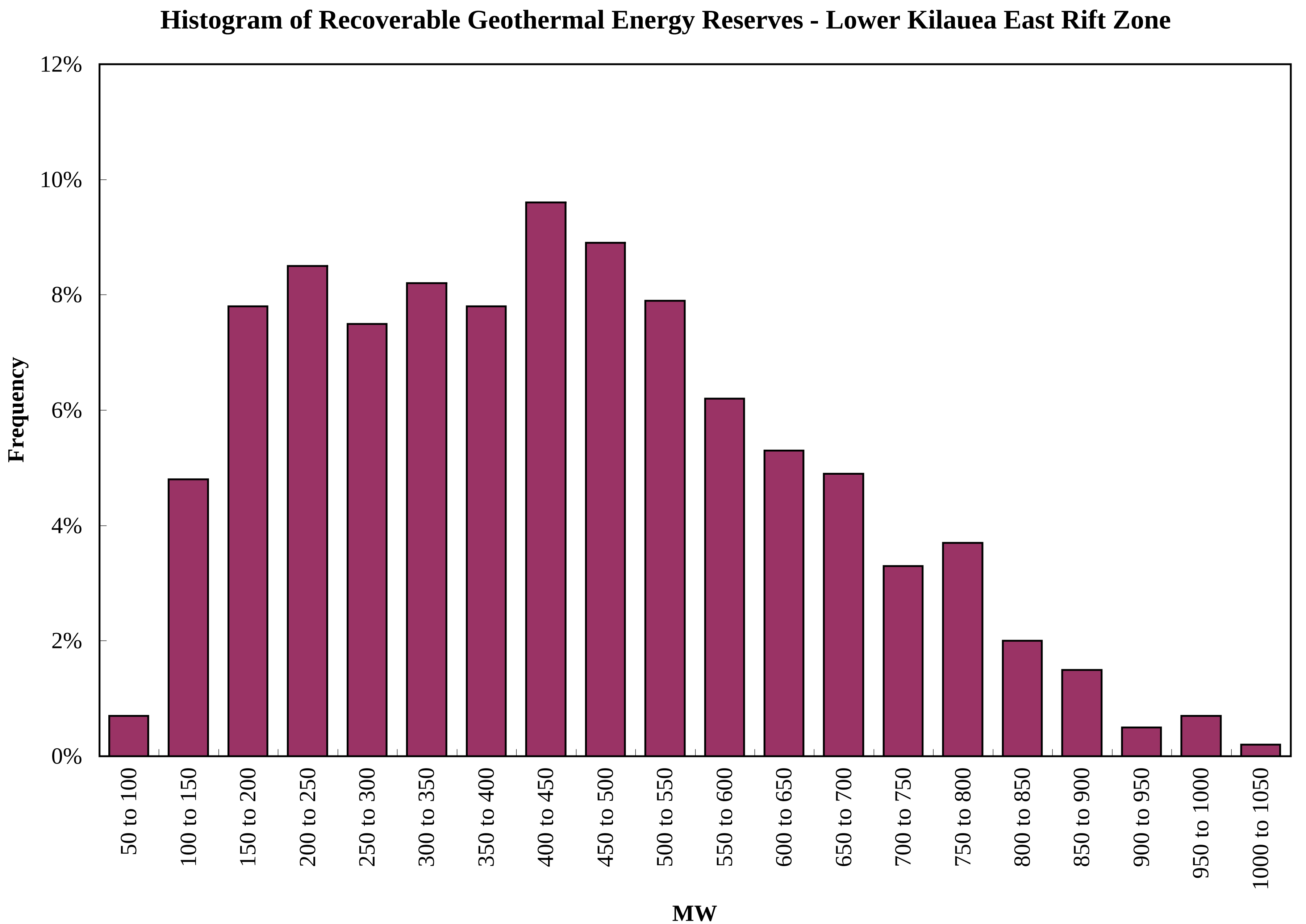
Summary of Input Parameters

Variable Parameters	Minimum	Most Likely	Maximum
Reservoir Area (square miles)	5.75		11.5
Reservoir Thickness (feet)	6,350		6,350
Rock Porosity	3%		7%
Reservoir Temperature (°F)	580		650
Recovery Factor	2.5%		15%

Fixed Parameters	
Rock Volumetric Heat Capacity (BTU/ft^3°F)	34.0
Rejection Temperature (°F)	65
Utilization Factor	45%
Plant Capacity Factor	95%
Power Plant Life (years)	30

Summary of Results

	MW	MW / square mile	Recovery Efficiency
Mean Value	438.4	51.1	1.26%
Standard Deviation	202.7	20.9	0.51%
10th Percentile	180.7	22.1	0.54%
Median Value	423.0	51.1	1.26%



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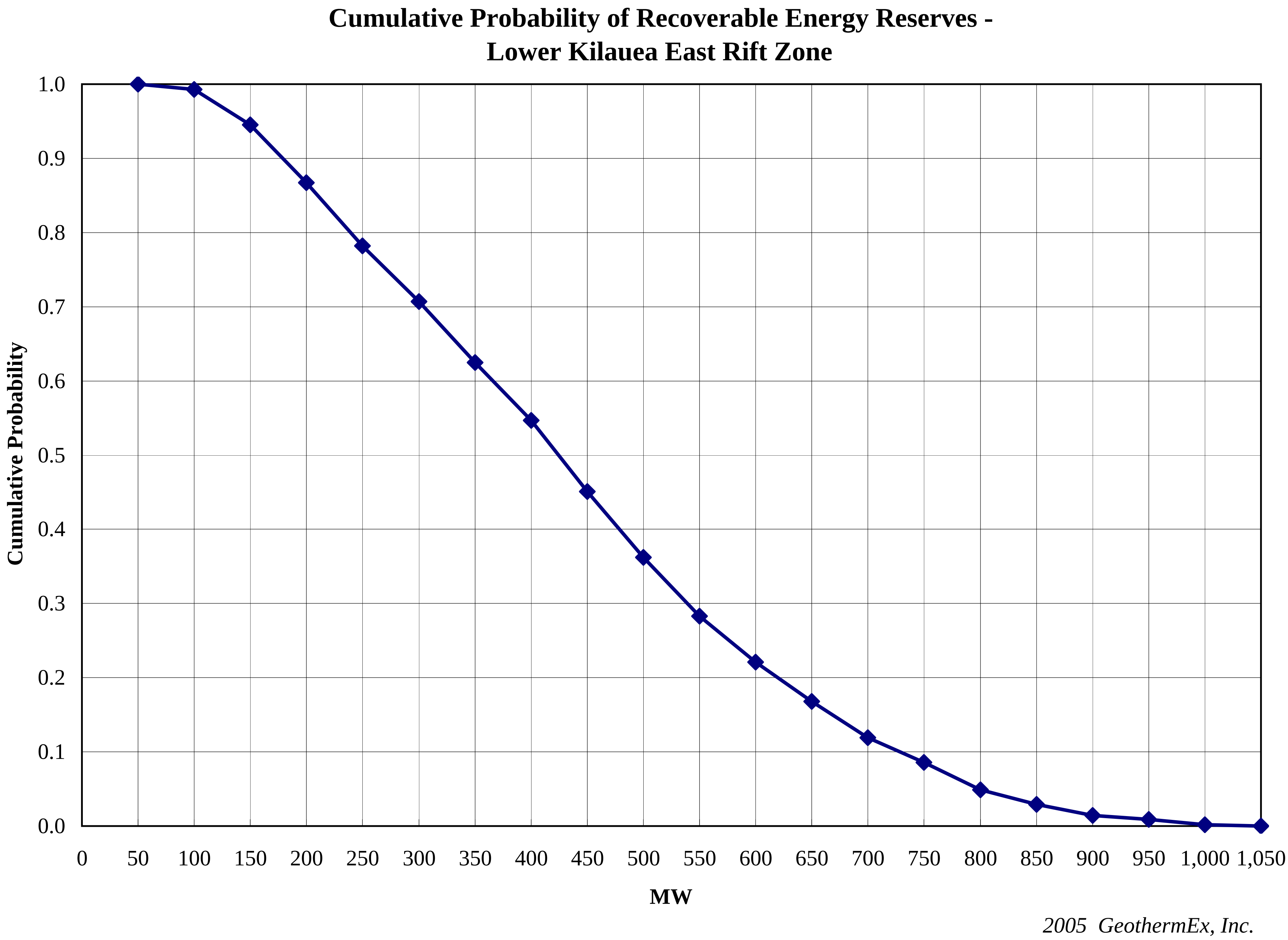

Cumulative Probability of Recoverable Energy Reserves -
Lower Kilauea East Rift Zone
Cumulative Probability
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1,000
1,050
MW
2005 GeothermEx, Inc.

Estimate of Geothermal Energy Reserves, Upper Kilauea East Rift Zone

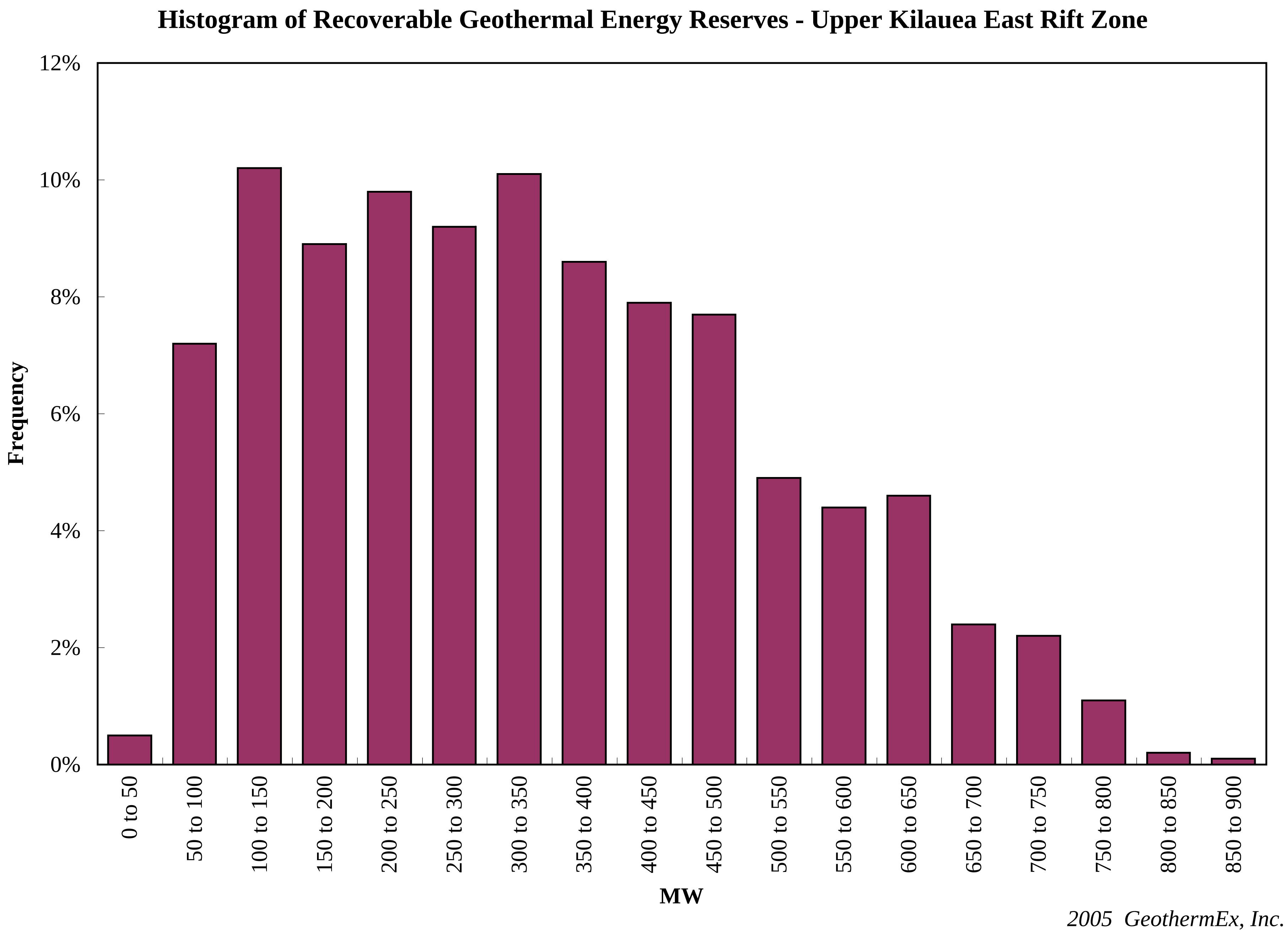
Summary of Input Parameters

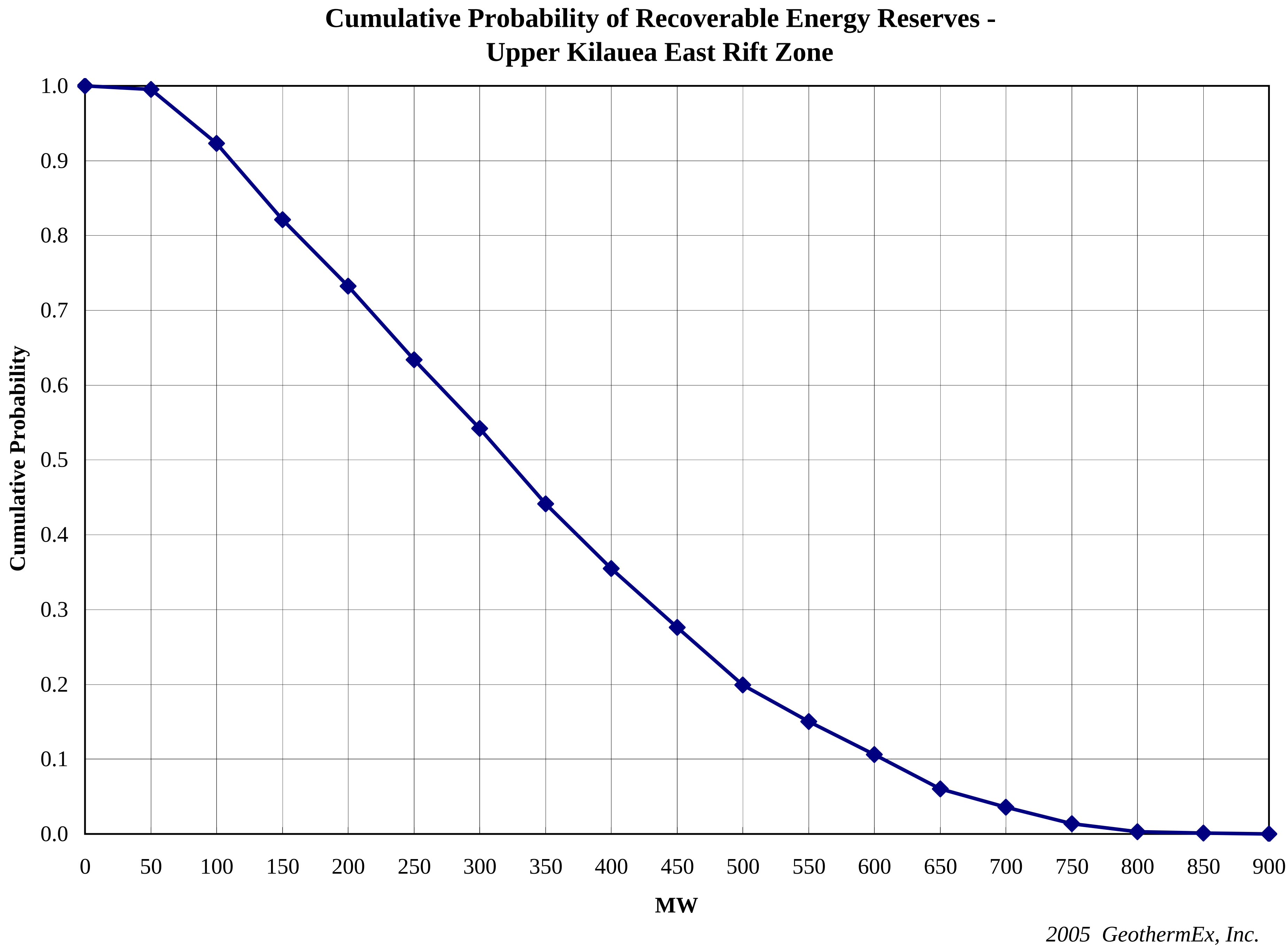
Variable Parameters	Minimum	Most Likely	Maximum
Reservoir Area (square miles)	10.25		20.5
Reservoir Thickness (feet)	4,450		4,450
Rock Porosity	3%		7%
Reservoir Temperature (°F)	580		650
Recovery Factor	1.0%		10%

Fixed Parameters	
Rock Volumetric Heat Capacity (BTU/ft^3°F)	34.0
Rejection Temperature (°F)	65
Utilization Factor	45%
Plant Capacity Factor	95%
Power Plant Life (years)	30

Summary of Results

	MW	MW / square mile	Recovery Efficiency
Mean Value	339.2	22.1	0.78%
Standard Deviation	180.9	10.9	0.38%
10th Percentile	110.3	7.2	0.26%
Median Value	319.1	21.5	0.75%


Histogram of Recoverable Geothermal Energy Reserves - Upper Kilauea East Rift Zone
12%
10%
8%
6%
4%
2%
0%
Frequency
0 to 50
50 to 100
100 to 150
150 to 200
200 to 250
250 to 300
300 to 350
350 to 400
400 to 450
450 to 500
500 to 550
550 to 600
600 to 650
650 to 700
700 to 750
750 to 800
800 to 850
850 to 900
MW
2005 GeothermEx, Inc.


Cumulative Probability of Recoverable Energy Reserves -
Upper Kilauea East Rift Zone
Cumulative Probability
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
MW
2005 GeothermEx, Inc.

Estimate of Geothermal Energy Reserves, Lower Kilauea Southwest Rift Zone

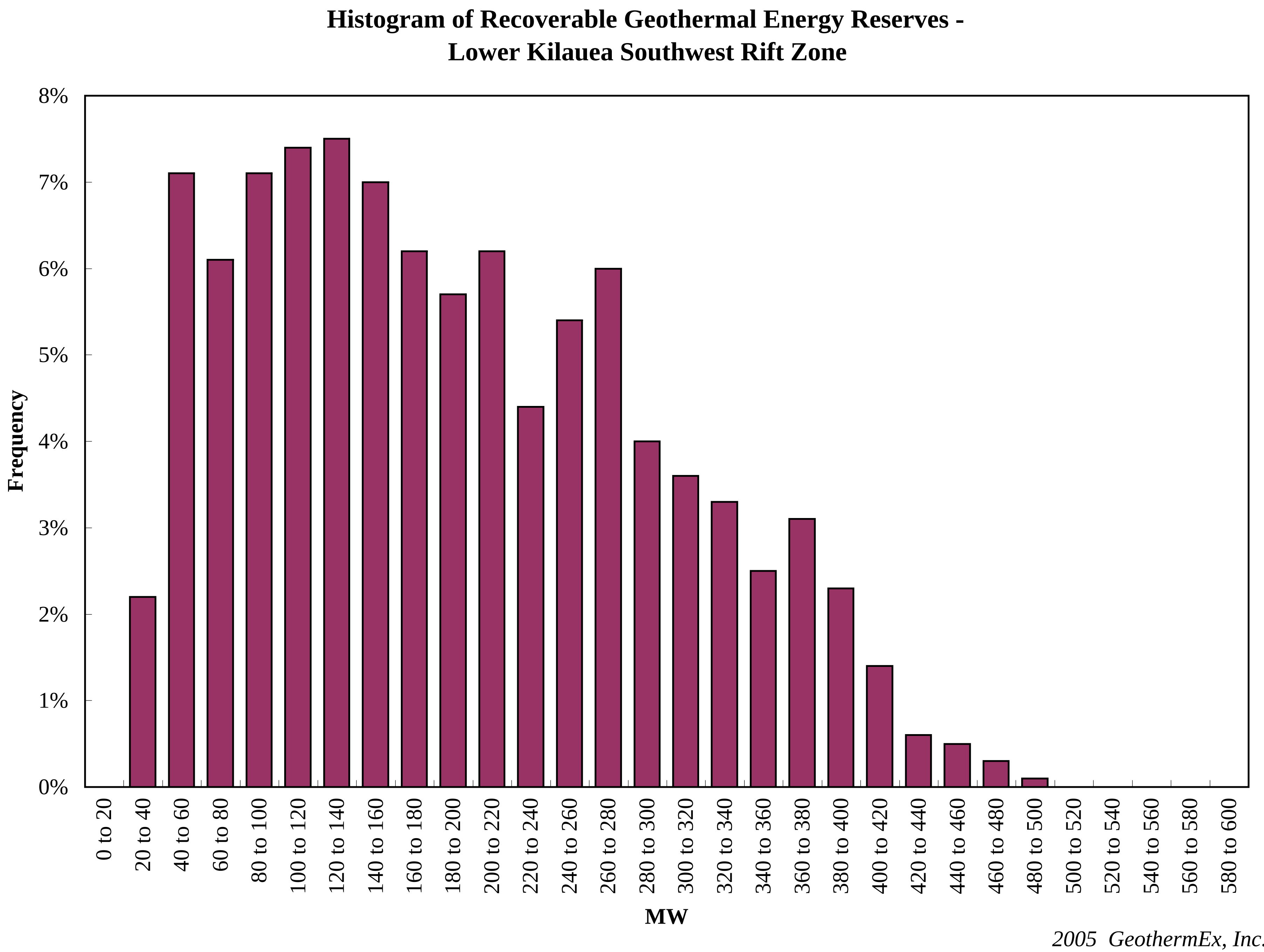
Summary of Input Parameters

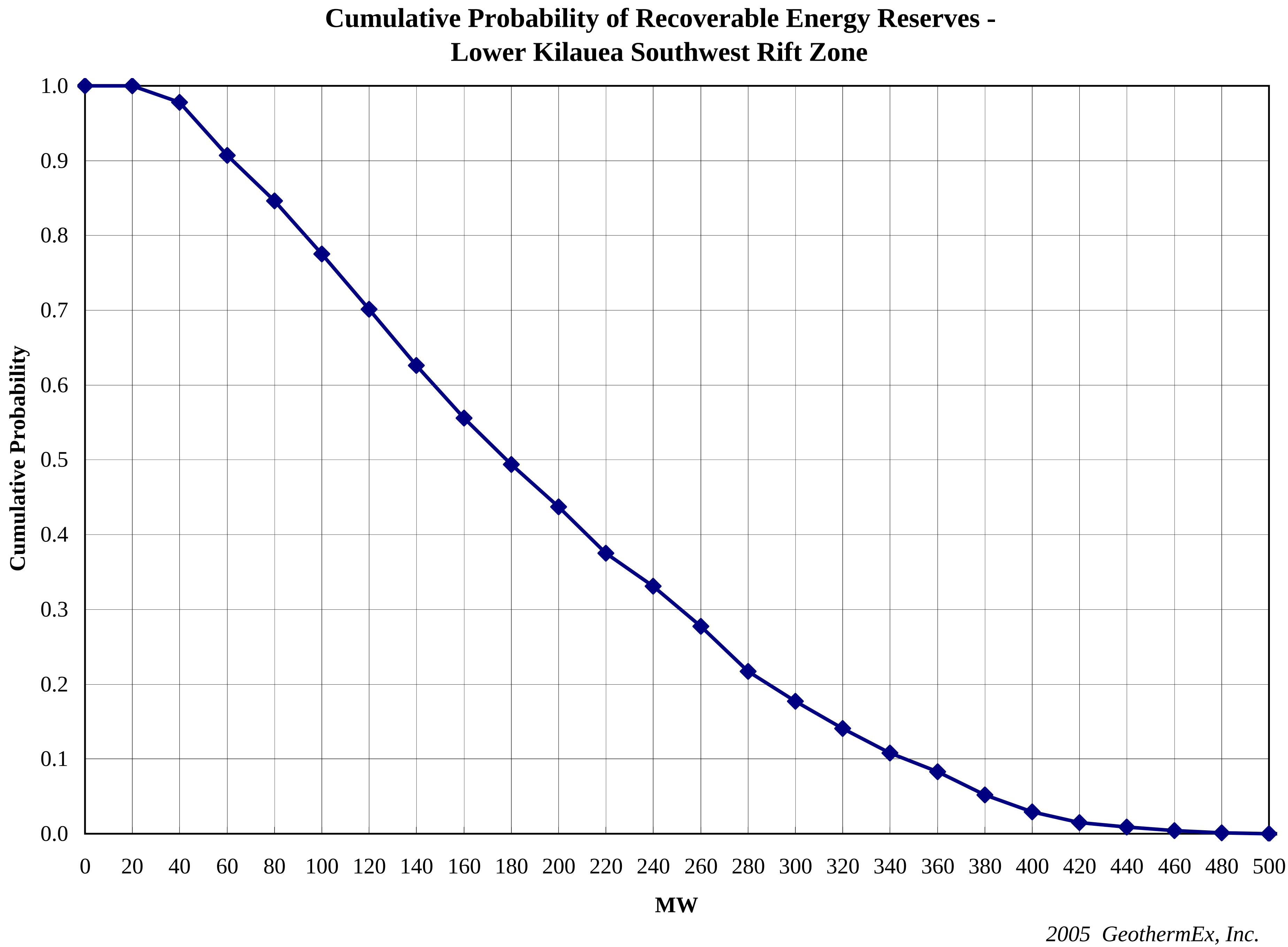
Variable Parameters	Minimum	Most Likely	Maximum
Reservoir Area (square miles)	4.25		8.5
Reservoir Thickness (feet)	6,200		6,200
Rock Porosity	3%		7%
Reservoir Temperature (°F)	580		650
Recovery Factor	1.0%		10%

Fixed Parameters	
Rock Volumetric Heat Capacity (BTU/ft^3°F)	34.0
Rejection Temperature (°F)	65
Utilization Factor	45%
Plant Capacity Factor	95%
Power Plant Life (years)	30

Summary of Results

	MW	MW / square mile	Recovery Efficiency
Mean Value	192.7	30.1	0.76%
Standard Deviation	104.1	14.8	0.37%
10th Percentile	64.4	10.4	0.26%
Median Value	178.5	29.1	0.73%


Histogram of Recoverable Geothermal Energy Reserves -
Lower Kilauea Southwest Rift Zone
Frequency
8%
7%
6%
5%
4%
3%
2%
1%
0%
0 to 20
20 to 40
40 to 60
60 to 80
80 to 100
100 to 120
120 to 140
140 to 160
160 to 180
180 to 200
200 to 220
220 to 240
240 to 260
260 to 280
280 to 300
300 to 320
320 to 340
340 to 360
360 to 380
380 to 400
400 to 420
420 to 440
440 to 460
460 to 480
480 to 500
500 to 520
520 to 540
540 to 560
560 to 580
580 to 600
MW
2005 GeothermEx, Inc.


Cumulative Probability of Recoverable Energy Reserves -
Lower Kilauea Southwest Rift Zone
Cumulative Probability
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420 440 460 480 500
MW
2005 GeothermEx, Inc.

Estimate of Geothermal Energy Reserves, Upper Kilauea Southwest Rift Zone

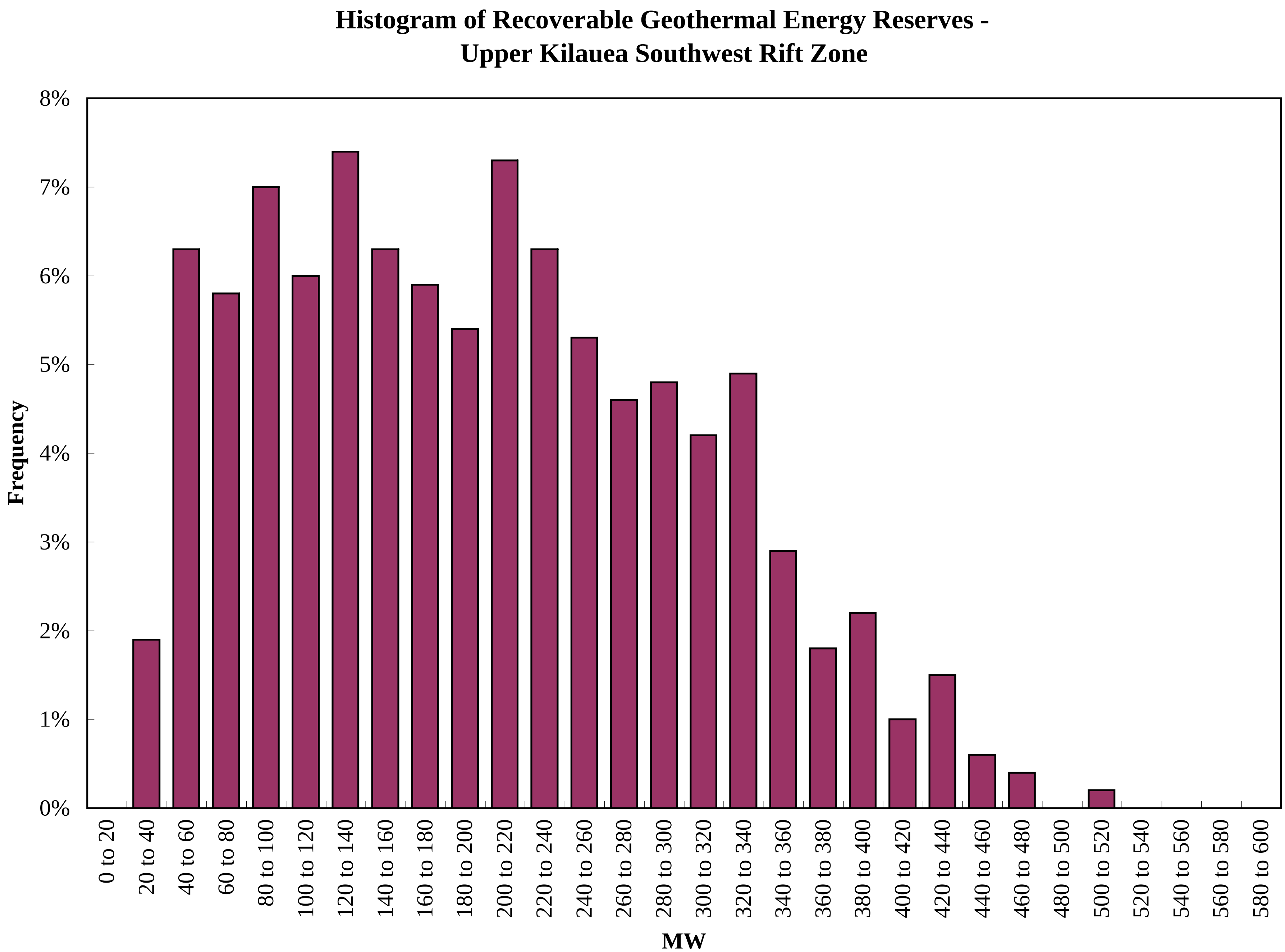
Summary of Input Parameters

Variable Parameters	**Minimum**	**Most Likely**	**Maximum**
Reservoir Area (square miles)	6.25		12.5
Reservoir Thickness (feet)	4,300		4,300
Rock Porosity	3%		7%
Reservoir Temperature (°F)	580		650
Recovery Factor	1.0%		10%

Fixed Parameters	
Rock Volumetric Heat Capacity (BTU/ft^3°F)	34.0
Rejection Temperature (°F)	65
Utilization Factor	45%
Plant Capacity Factor	95%
Power Plant Life (years)	30

Summary of Results

	MW	**MW / square mile**	**Recovery Efficiency**
Mean Value	200.6	21.4	0.78%
Standard Deviation	104.9	10.4	0.37%
10th Percentile	68.4	7.4	0.27%
Median Value	192.6	21.0	0.77%



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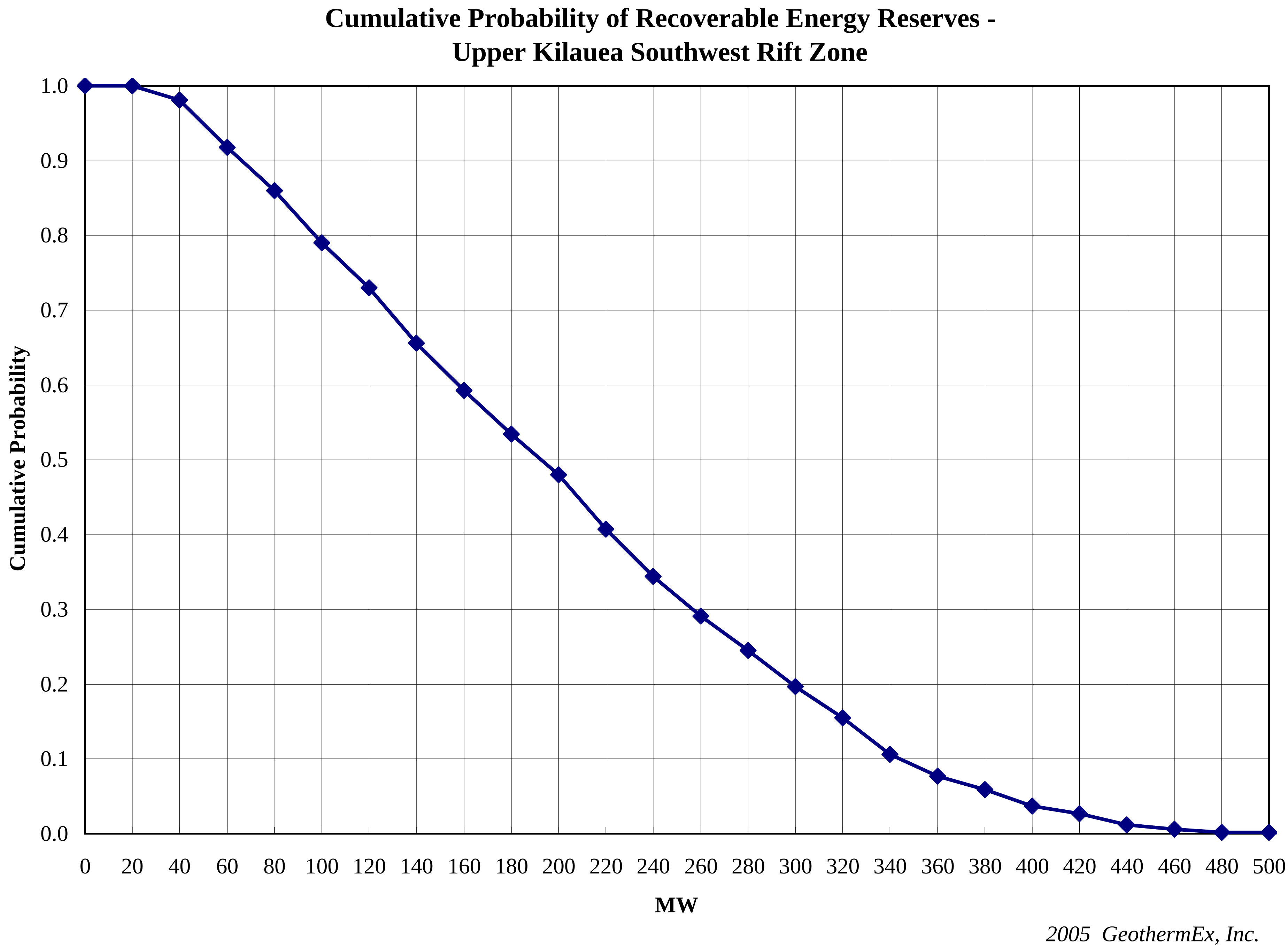


Cumulative Probability of Recoverable Energy Reserves -
Upper Kilauea Southwest Rift Zone
Cumulative Probability
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420 440 460 480 500
MW
2005 GeothermEx, Inc.

Estimate of Geothermal Energy Reserves, Mauna Loa Southwest Rift Zone

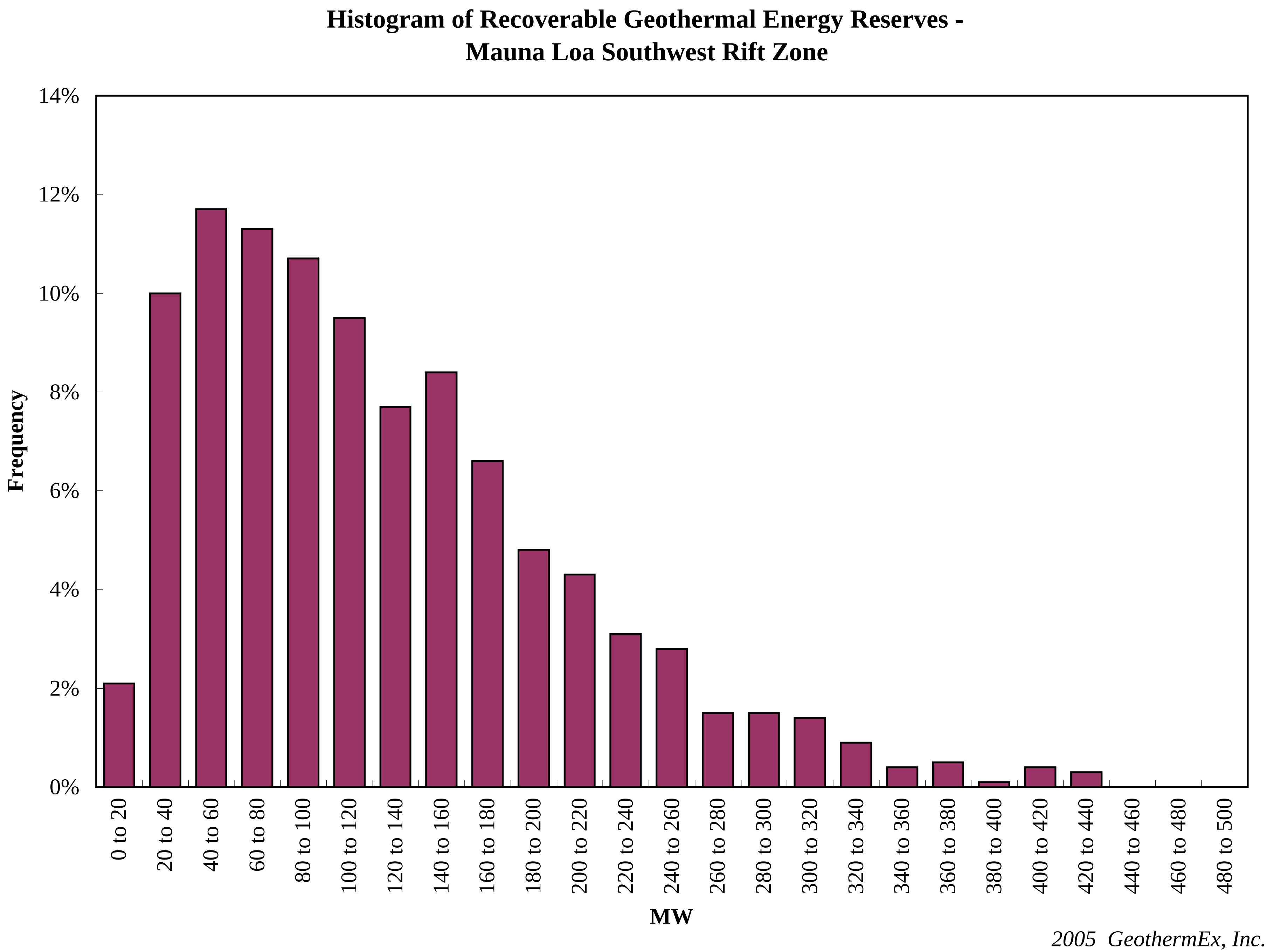
Summary of Input Parameters

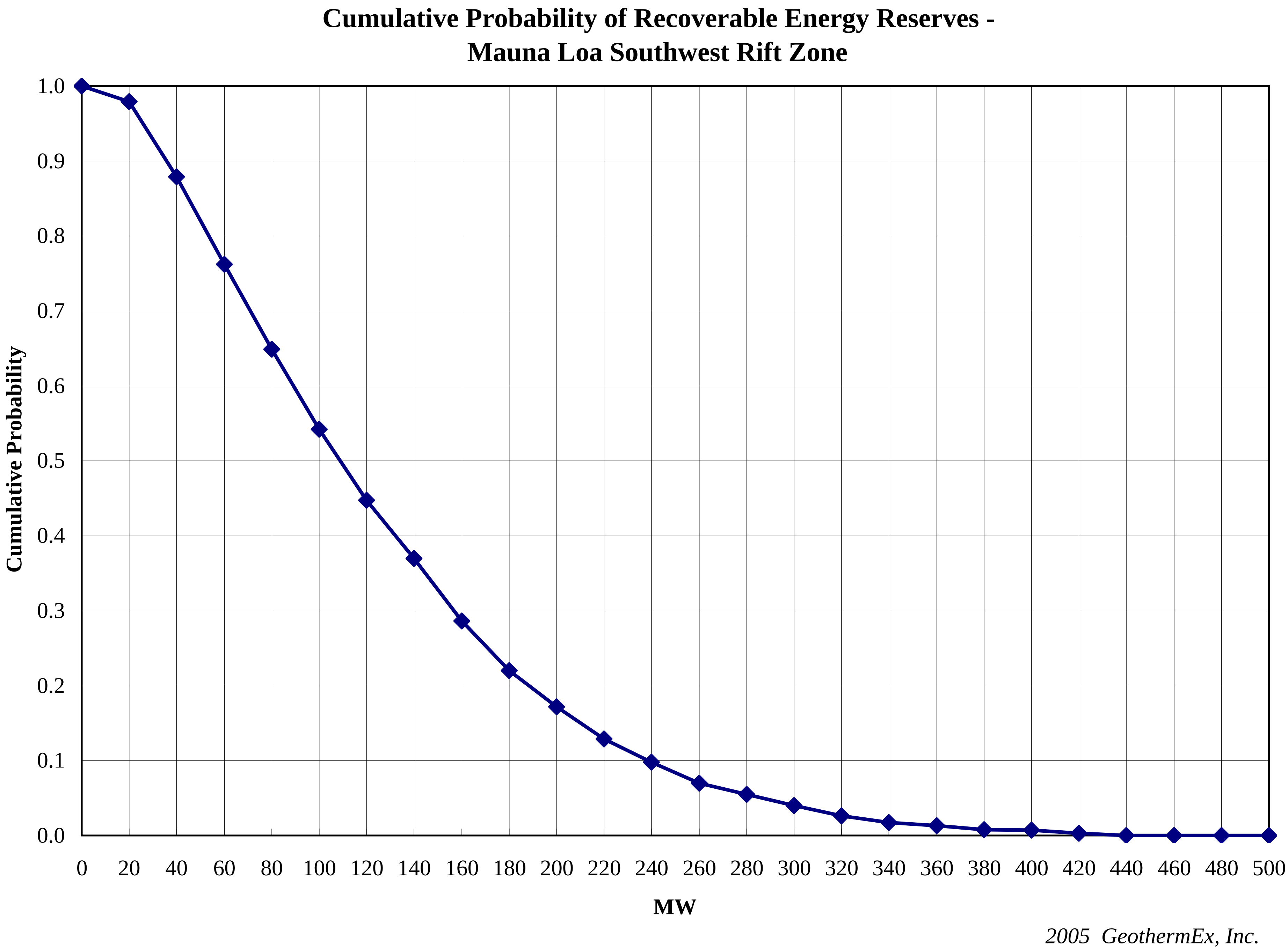
Variable Parameters	**Minimum**	**Most Likely**	**Maximum**
Reservoir Area (square miles)	5.75		11.5
Reservoir Thickness (feet)	2,400		5,400
Rock Porosity	3%		7%
Reservoir Temperature (°F)	400		650
Recovery Factor	1.0%		10%

Fixed Parameters	
Rock Volumetric Heat Capacity (BTU/ft^3°F)	34.0
Rejection Temperature (°F)	65
Utilization Factor	45%
Plant Capacity Factor	95%
Power Plant Life (years)	30

Summary of Results

	MW	**MW / square mile**	**Recovery Efficiency**
Mean Value	125.6	14.5	0.69%
Standard Deviation	81.1	8.8	0.34%
10th Percentile	35.2	4.3	0.24%
Median Value	108.1	13.1	0.69%


Histogram of Recoverable Geothermal Energy Reserves -
Mauna Loa Southwest Rift Zone
Frequency
14%
12%
10%
8%
6%
4%
2%
0%
0 to 20
20 to 40
40 to 60
60 to 80
80 to 100
100 to 120
120 to 140
140 to 160
160 to 180
180 to 200
200 to 220
220 to 240
240 to 260
260 to 280
280 to 300
300 to 320
320 to 340
340 to 360
360 to 380
380 to 400
400 to 420
420 to 440
440 to 460
460 to 480
480 to 500
MW
2005 GeothermEx, Inc.


Cumulative Probability of Recoverable Energy Reserves -
Mauna Loa Southwest Rift Zone
Cumulative Probability
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420 440 460 480 500
MW
2005 GeothermEx, Inc.

Estimate of Geothermal Energy Reserves, Mauna Loa Northeast Rift Zone

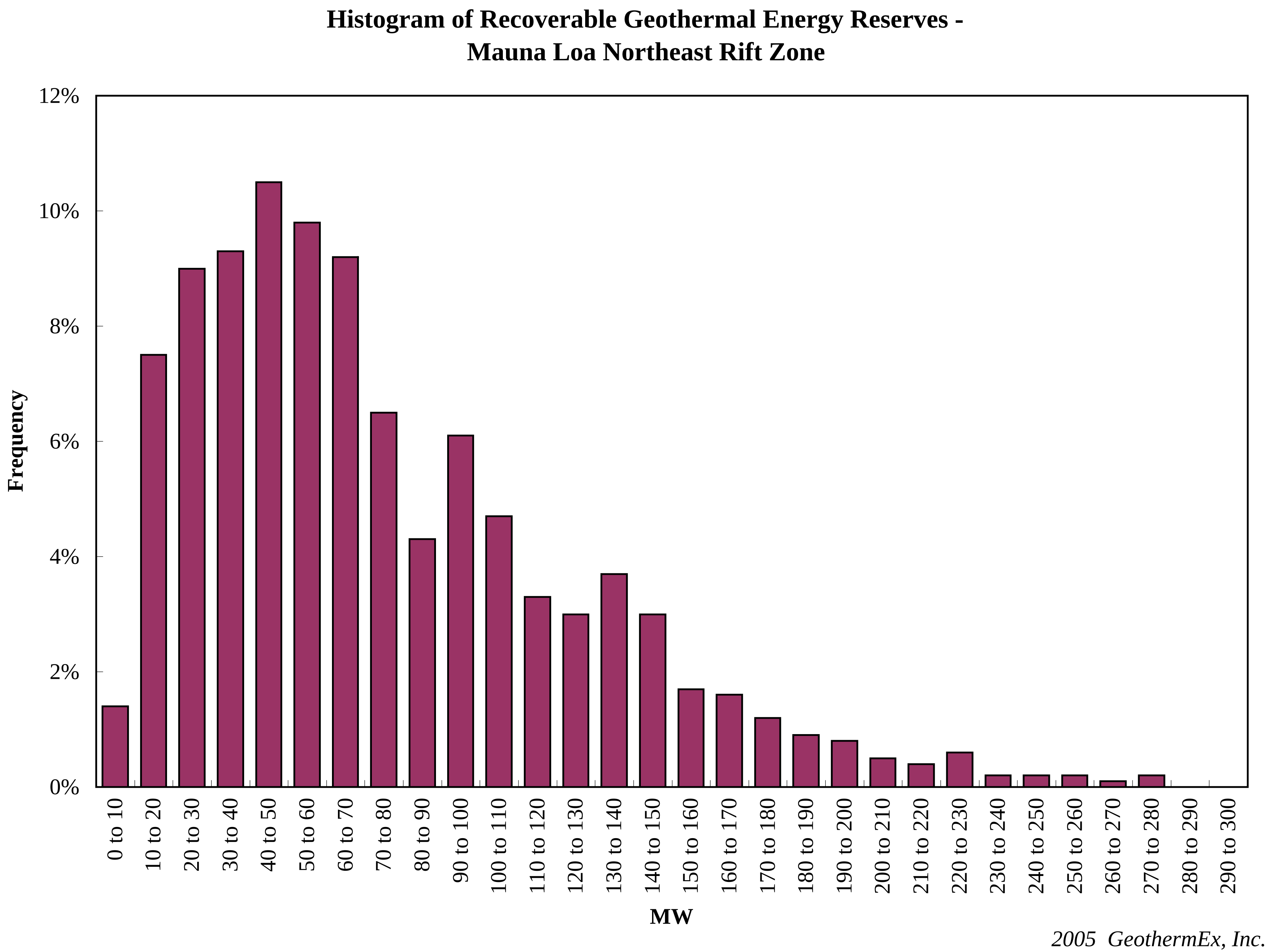
Summary of Input Parameters

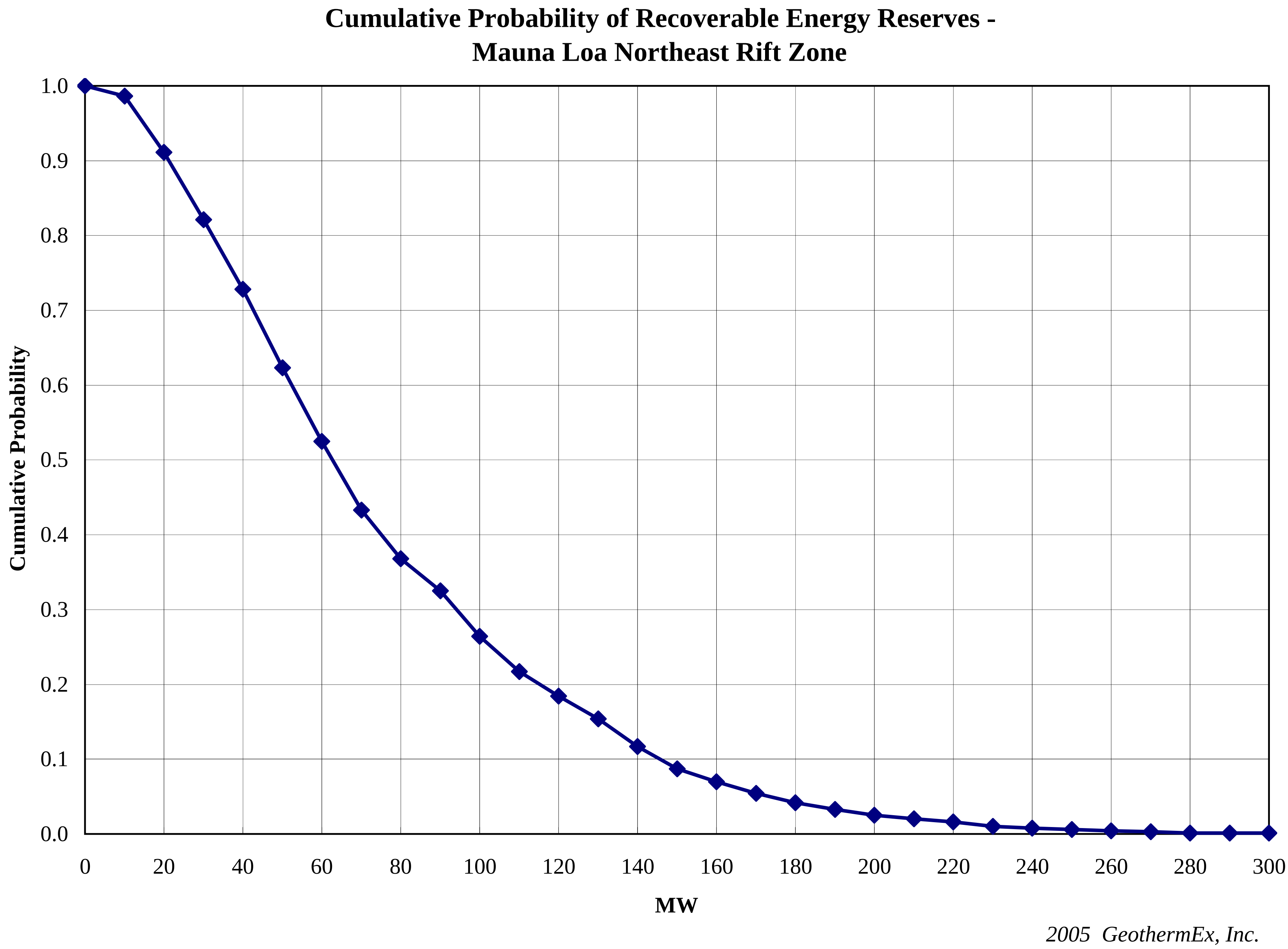
Variable Parameters	**Minimum**	**Most Likely**	**Maximum**
Reservoir Area (square miles)	4.25		8.5
Reservoir Thickness (feet)	1,600		4,600
Rock Porosity	3%		7%
Reservoir Temperature (°F)	400		650
Recovery Factor	1.0%		10%

Fixed Parameters	
Rock Volumetric Heat Capacity (BTU/ft^3°F)	34.0
Rejection Temperature (°F)	65
Utilization Factor	45%
Plant Capacity Factor	95%
Power Plant Life (years)	30

Summary of Results

	MW	**MW / square mile**	**Recovery Efficiency**
Mean Value	75.4	12.0	0.71%
Standard Deviation	50.4	7.7	0.34%
10th Percentile	22.0	3.6	0.25%
Median Value	62.2	10.1	0.71%


Histogram of Recoverable Geothermal Energy Reserves -
Mauna Loa Northeast Rift Zone
Frequency
12%
10%
8%
6%
4%
2%
0%
0 to 10
10 to 20
20 to 30
30 to 40
40 to 50
50 to 60
60 to 70
70 to 80
80 to 90
90 to 100
100 to 110
110 to 120
120 to 130
130 to 140
140 to 150
150 to 160
160 to 170
170 to 180
180 to 190
190 to 200
200 to 210
210 to 220
220 to 230
230 to 240
240 to 250
250 to 260
260 to 270
270 to 280
280 to 290
290 to 300
MW
2005 GeothermEx, Inc.


Cumulative Probability of Recoverable Energy Reserves -
Mauna Loa Northeast Rift Zone
Cumulative Probability
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
MW
2005 GeothermEx, Inc.

Estimate of Geothermal Energy Reserves, Hualalai

Summary of Input Parameters

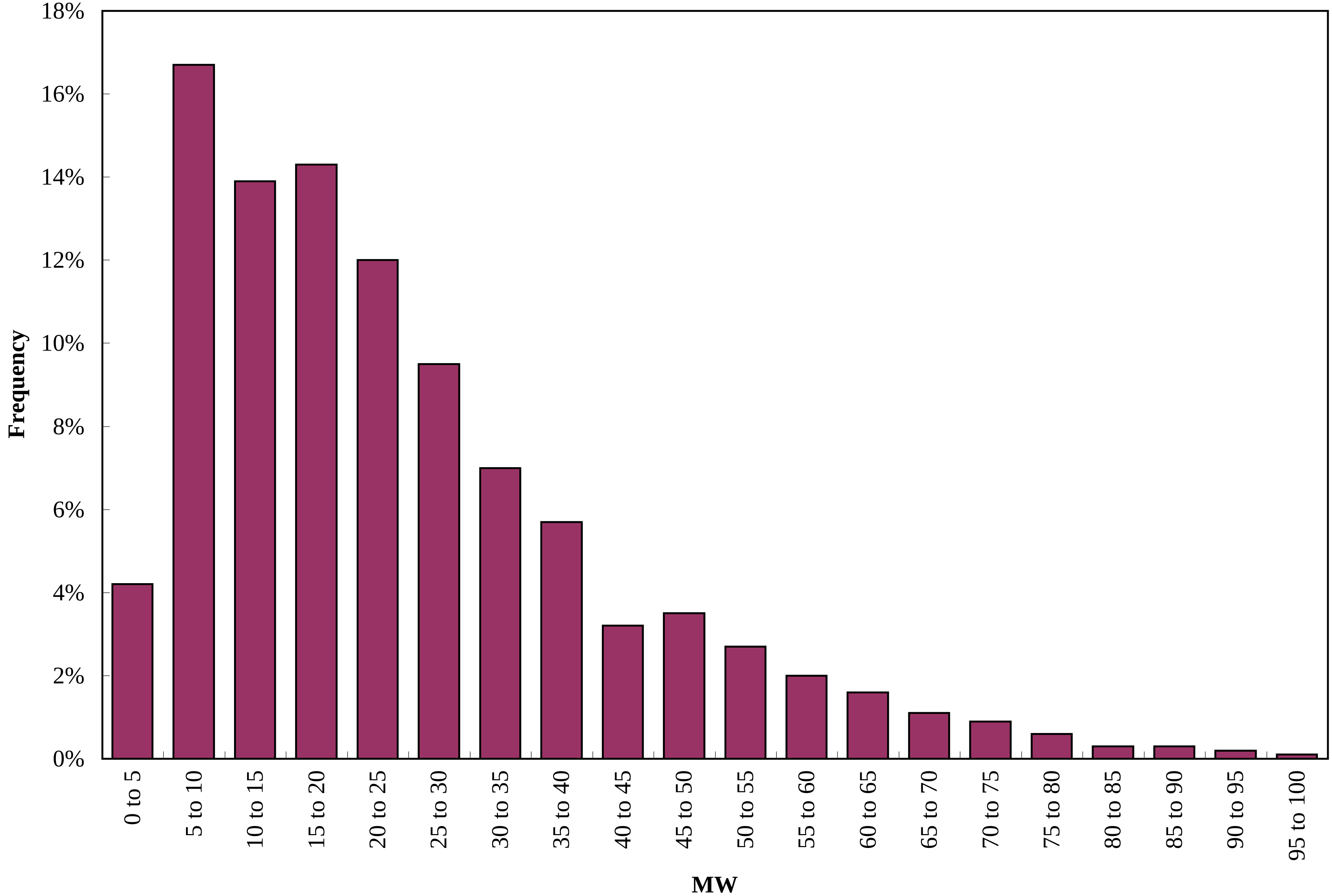
Variable Parameters	Minimum	Most Likely	Maximum
Reservoir Area (square miles)	2.50		5.0
Reservoir Thickness (feet)	1,800		4,800
Rock Porosity	3%		7%
Reservoir Temperature (°F)	257		500
Recovery Factor	1.0%		10%

Fixed Parameters	
Rock Volumetric Heat Capacity (BTU/ft^3°F)	34.0
Rejection Temperature (°F)	65
Utilization Factor	45%
Plant Capacity Factor	95%
Power Plant Life (years)	30

Summary of Results

	MW	MW / square mile	Recovery Efficiency
Mean Value	24.8	6.6	0.53%
Standard Deviation	17.7	4.5	0.26%
10th Percentile	6.7	1.8	0.19%
Median Value	20.4	5.6	0.50%

Histogram of Recoverable Geothermal Energy Reserves - Hualalai



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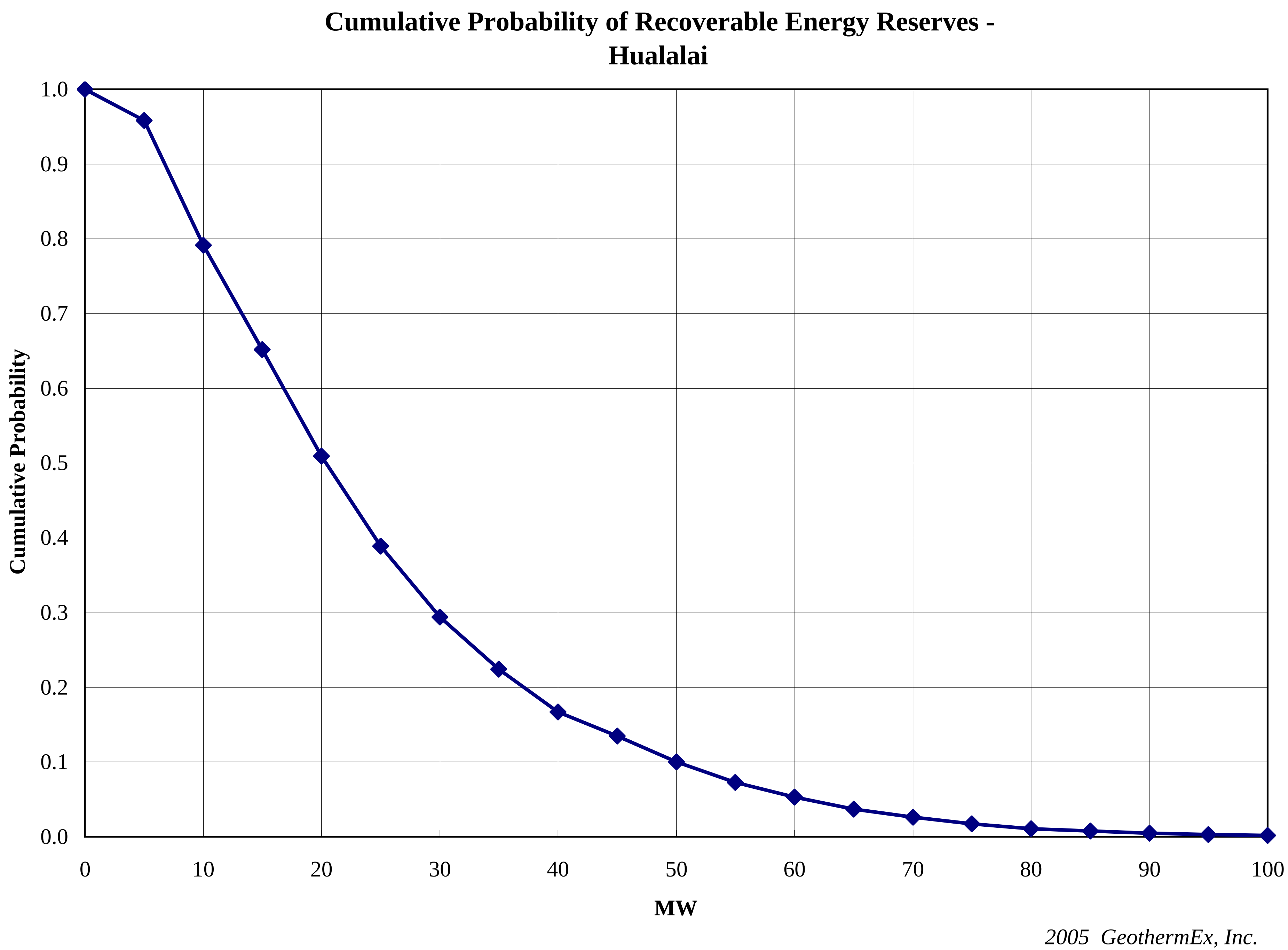

Cumulative Probability of Recoverable Energy Reserves -
Hualalai
Cumulative Probability
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
10
20
30
40
50
60
70
80
90
100
MW
2005 GeothermEx, Inc.

Estimate of Geothermal Energy Reserves, Haleakala Southwest Rift Zone

Summary of Input Parameters

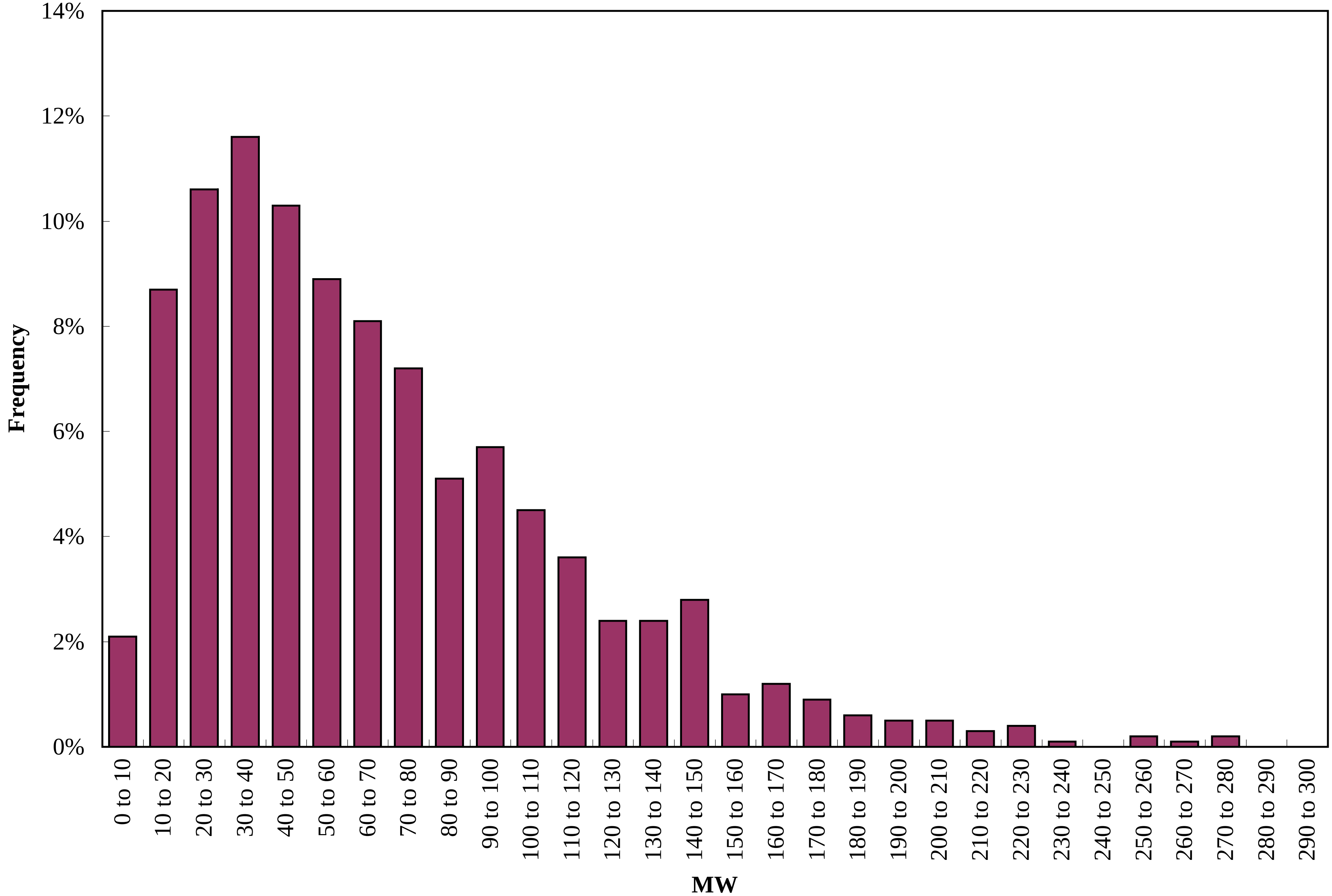
Variable Parameters	Minimum	Most Likely	Maximum
Reservoir Area (square miles)	4.50		9.0
Reservoir Thickness (feet)	3,500		6,500
Rock Porosity	3%		7%
Reservoir Temperature (°F)	257		500
Recovery Factor	1.0%		10%

Fixed Parameters	
Rock Volumetric Heat Capacity (BTU/ft^3°F)	34.0
Rejection Temperature (°F)	65
Utilization Factor	45%
Plant Capacity Factor	95%
Power Plant Life (years)	30

Summary of Results

	MW	MW / square mile	Recovery Efficiency
Mean Value	68.6	10.1	0.53%
Standard Deviation	47.0	6.6	0.27%
10th Percentile	19.6	2.8	0.18%
Median Value	57.7	8.5	0.53%

Histogram of Recoverable Geothermal Energy Reserves -
Haleakala Southwest Rift Zone



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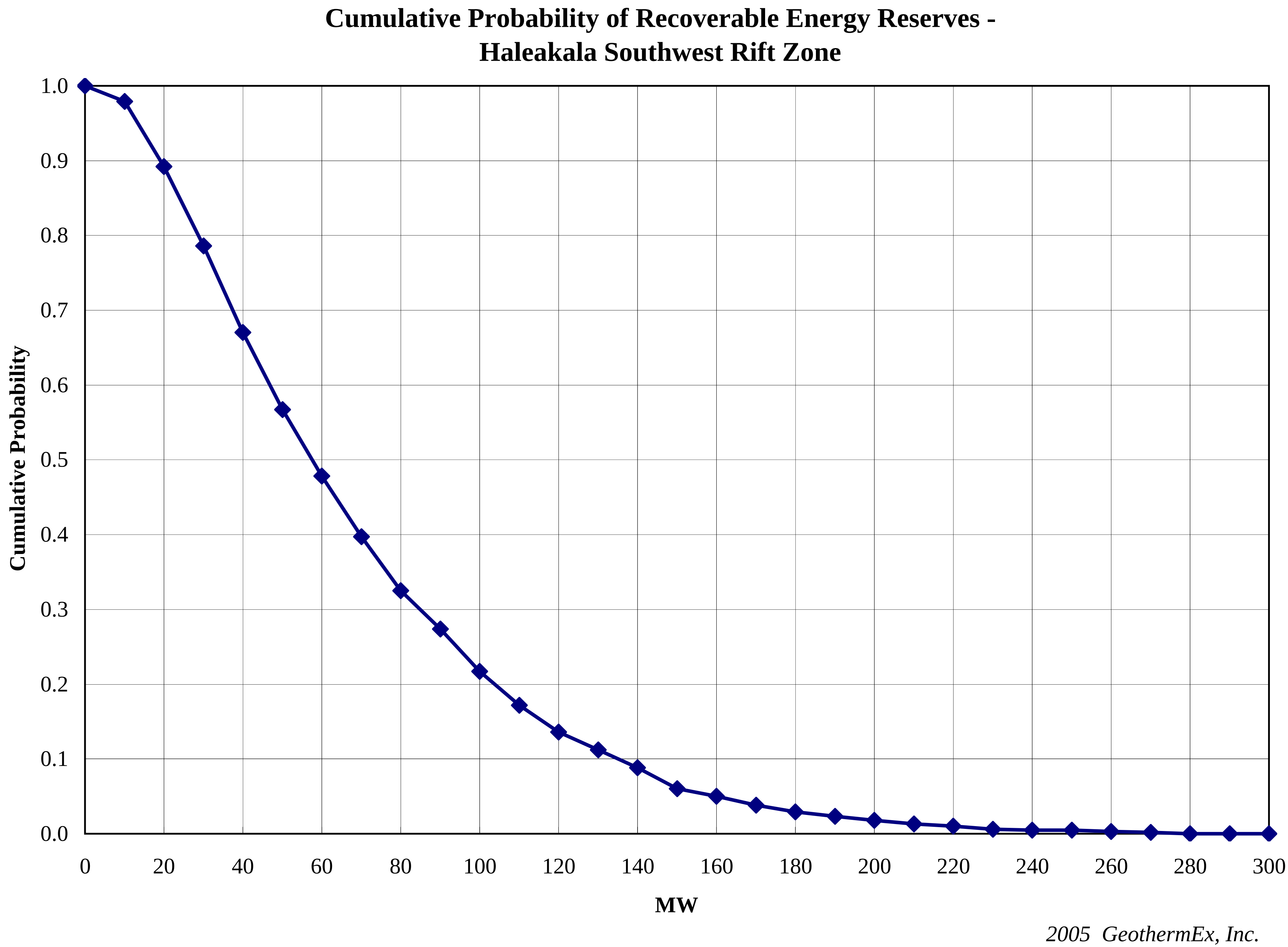

Cumulative Probability of Recoverable Energy Reserves -
Haleakala Southwest Rift Zone
Cumulative Probability
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
MW
2005 GeothermEx, Inc.

Estimate of Geothermal Energy Reserves,
Haleakala East Rift Zone

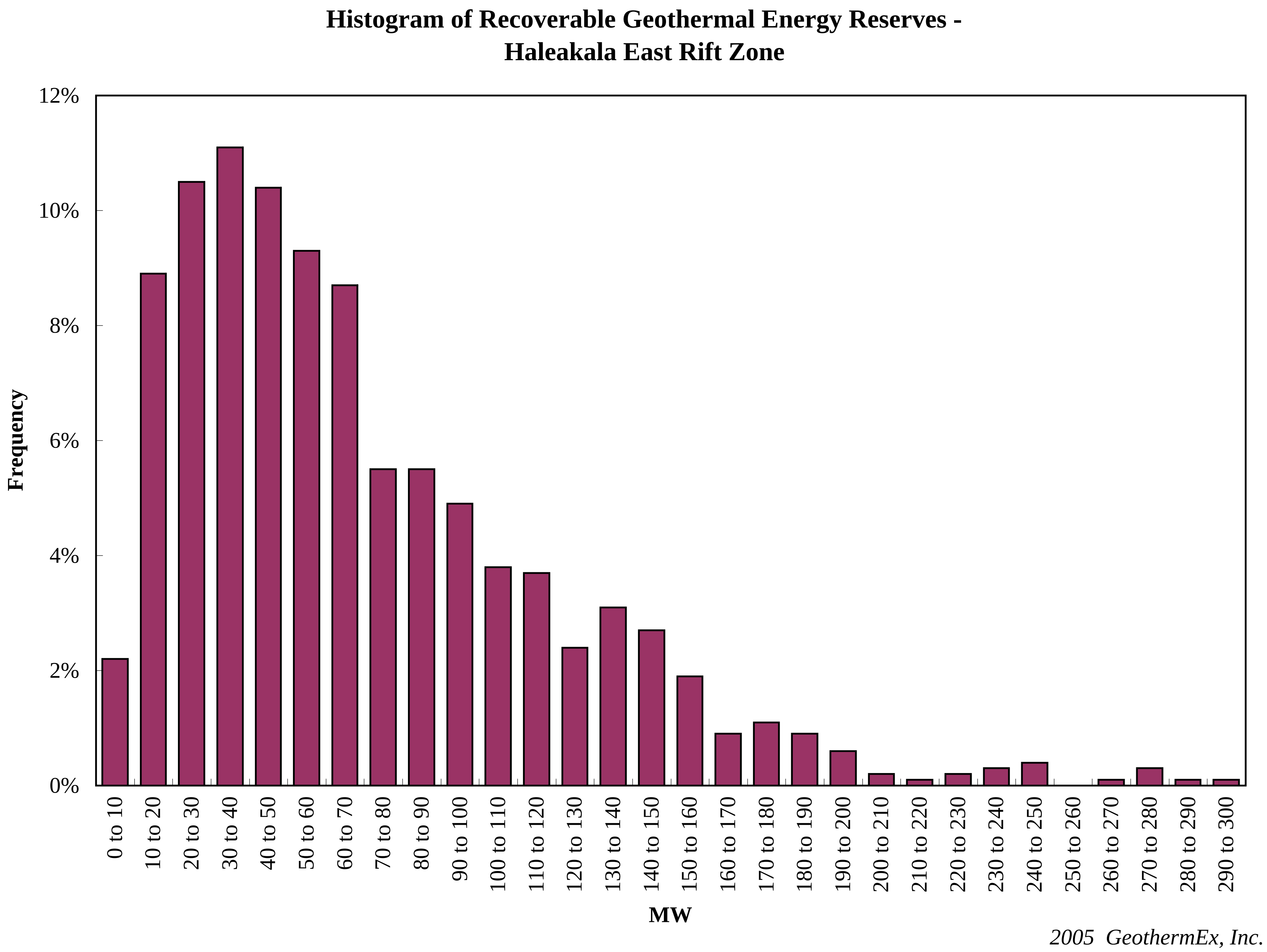
Summary of Input Parameters

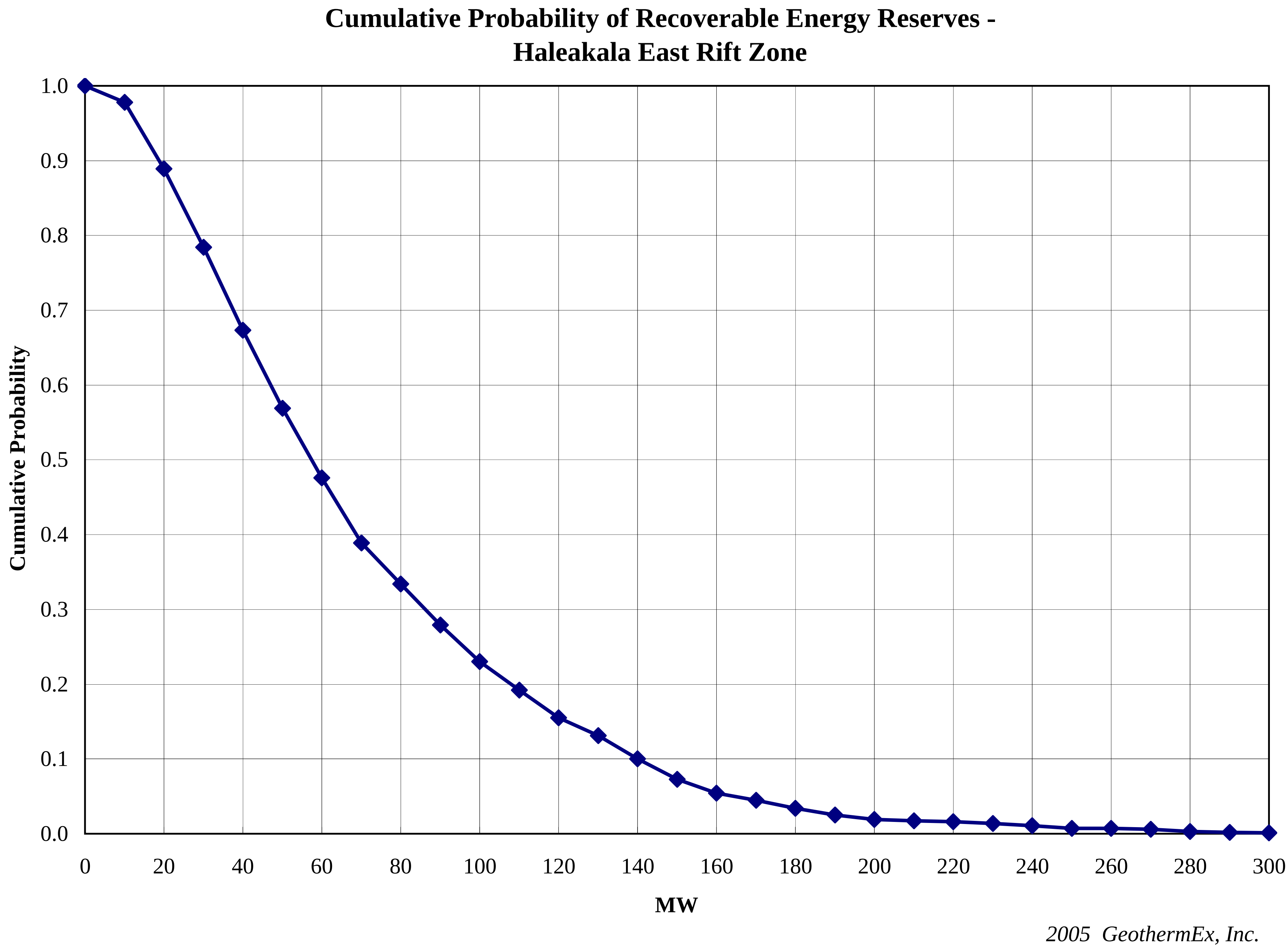
Variable Parameters	**Minimum**	**Most Likely**	**Maximum**
Reservoir Area (square miles)	4.75		9.5
Reservoir Thickness (feet)	3,500		6,500
Rock Porosity	3%		7%
Reservoir Temperature (°F)	257		500
Recovery Factor	1.0%		10%

Fixed Parameters	
Rock Volumetric Heat Capacity (BTU/ft^3°F)	34.0
Rejection Temperature (°F)	65
Utilization Factor	45%
Plant Capacity Factor	95%
Power Plant Life (years)	30

Summary of Results

	MW	**MW / square mile**	**Recovery Efficiency**
Mean Value	69.9	9.8	0.52%
Standard Deviation	50.1	6.6	0.27%
10th Percentile	18.0	2.9	0.17%
Median Value	56.7	8.1	0.50%


Histogram of Recoverable Geothermal Energy Reserves -
Haleakala East Rift Zone
Frequency
12%
10%
8%
6%
4%
2%
0%
0 to 10
10 to 20
20 to 30
30 to 40
40 to 50
50 to 60
60 to 70
70 to 80
80 to 90
90 to 100
100 to 110
110 to 120
120 to 130
130 to 140
140 to 150
150 to 160
160 to 170
170 to 180
180 to 190
190 to 200
200 to 210
210 to 220
220 to 230
230 to 240
240 to 250
250 to 260
260 to 270
270 to 280
280 to 290
290 to 300
MW
2005 GeothermEx, Inc.


Cumulative Probability of Recoverable Energy Reserves -
Haleakala East Rift Zone
Cumulative Probability
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
MW
2005 GeothermEx, Inc.