Low- to medium-temperature Mexican geothermal reserves: first assessment

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Abstract

In this work we make a first, partial, assessment of the low- to medium-temperature geothermal reserves of Mexico. The assessment covers about 30% of the identified geothermal surface manifestations. For reserve assessment we use the volume method, supplemented with Montecarlo simulations and statistics, in order to quantify the inherent uncertainties. We estimate these reserves as lying between 7.7 10^{16} and 8.6 10^{16} kJ, with 90% confidence. The distribution of most likely reservoir temperatures ranges 60-180°C, with a mean equal to 111°C. These massive amounts of recoverable energy and the associated temperatures are potentially important for the economic development of the associated geothermal localities.

Keywords: Geothermal reserves, Mexico, low-temperature reserves, geothermal direct applications.

Introduction

Due to its particular geological conditions Mexico is blessed with abundant geothermal resources. Most of its high-temperature (T>200°C) resources, suitable for electric power generation, have been explored and assessed, because of its perceived economic value.

For the low- to medium-temperature resources (T<200°C), appropriate mainly for direct heat applications, the situation is quite different. The installed capacity of all direct heat applications in Mexico was slightly more than 164 MW_t in the year 2000 [1], and was mainly in balneology. No significant improvement has taken place since. The international experience indicates (e.g., [2]) that these geothermal resources are orders of magnitude more abundant than their high-temperature counterparts. Thus we can fairly assume that the low- to medium- temperature geothermal resources are vastly underexploited in Mexico. One important reason for the prevalence of this situation is that there is essentially no quantitative information about their potential.

In this work we make a first, partial, assessment of Mexico's low- to medium-temperature geothermal reserves. We define geothermal reserves, following [3] and [4], as the "identified geothermal energy that can be extracted legally today at a cost competitive with other energy sources". Thus, this work focuses on the present technical and economical possibilities.

Method

Following [5] we chose the volume method for the present reserve assessment. With this method one first calculates the thermal energy contained in a given volume of rock and water. Then one estimates how much of this energy is recoverable. The thermal energy is calculated as (e.g. [2])

$$q_R = \rho_C \, A \, h \, (T - T_{ref}) \tag{1}$$

where q_R = reservoir thermal energy in kJ, ρ_C = volumetric specific heat of rock plus water (2700 kJ/m^3°C), A = reservoir area (m^2), h = reservoir thickness (m), T = mean reservoir temperature (°C), and T_{ref} = reference temperature (local mean annual temperature, °C). The volumetric specific heat was calculated assuming the rock volumetric specific heat to be 2500 kJ/m^3°C and the reservoir porosity to be 15 percent. Since most of the heat is stored in the rock (e.g. [6]), our estimates depend only weekly on the magnitude assumed for the porosity.

To quantify the uncertainty in the reserve assessments, we used statistical methods in the calculation of the thermal energies, following [2] and [7]. The uncertainty in the thermal energy results mainly from the uncertainties in the values estimated for A, h, T and T_{ref}. With the exception of T_{ref}, these values result from educated judgment based on geology, geophysics, geochemistry, down-hole measurements and geothermometry. The uncertainty in the reference temperature arises from using regional long-term averages that, for topographic or other reasons, may differ significantly from local mean temperature.

To determine the uncertainty in these estimates we assume, for each variable, a triangular probability density that represents our subjective judgment of the true density, e.g. Figure 1. The parameters in Figure 1 are defined as: T_1 = minimum reservoir temperature; T_2 = most likely reservoir temperature; T_3 = maximum reservoir temperature. The mean $\overline{T}$ and standard deviation σ_T are also represented. The area of the solid vertical band gives the probability that the characteristic reservoir temperature lies between the values T and $T+\Delta T$.

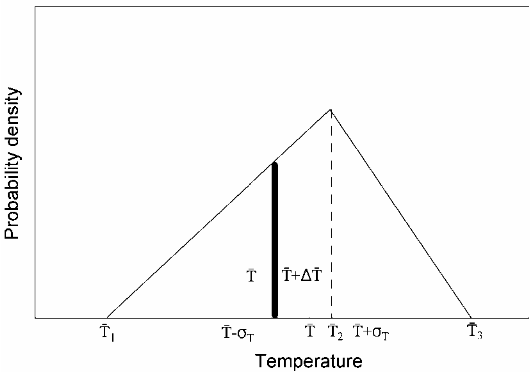


Fig. 1. Example of triangular distribution

We use these triangular probability densities to compute the probability densities of the thermal energy for each geothermal locality, as defined in equation (1), by means of the Montecarlo method. In this way we obtain histograms and fits, and a variety of statistics that include mean, mode, median, standard deviation, variance, etc. Thus, we can determine confidence intervals for the estimated thermal energy. In this way, we quantify the uncertainty in this inferred variable.

Using the Montecarlo method to compute individual locality's thermal energy we have significantly improved the method used by previous authors (e.g. [2]). These authors used products of mean values of area, thickness and the difference between mean values of T and T_{ref} to compute mean values of thermal energy for individual localities. Multiplication of mean values is valid only if the variables *A*, *h* and *T* are statistically independent in the reservoir considered. A statistical dependence of some or all of these variables in the reservoir can hardly be discarded. Using the Montecarlo method removes the necessity to assume statistical independence of the variables.

After computing the distributions of thermal energy for the individual localities included in this assessment, we calculated, from them, the distribution of total thermal energy corresponding to all localities. This problem is analytically intractable (e.g. [7]). Therefore we used again the Montecarlo method to compute the distribution of total thermal energy. This entailed first fitting analytical probability densities to the 276 computed distributions of local thermal energy, and then running a Montecarlo simulation with them. Having this distribution we are able to derive confidence intervals to evaluate the uncertainty associated with the total thermal energy.

Montecarlo simulations produce sample distribution functions that converge to the true distributions as the number of iterations increases. By trial and error we arrived at 5000 iterations as the optimal number to use in each Montecarlo simulation: higher numbers of iterations (we tried 500 to 10,000) resulted in minimal changes in the results.

As mentioned, reserves are estimated as the fraction of identified stored accessible thermal energy legally and economically producible today with current technology. The usual approach is to estimate reserves as the product of the stored thermal energy times a so-called recovery factor *R*. This factor summarizes the physical and technological constraints that prevent all the thermal energy in the reservoir from being extracted. Following [8], [9] and [10] we assumed a constant value of 0.25 for *R* in our reserve estimates, as a first approximation.

Finally, all figures derived in this paper should be regarded as order-of magnitude estimates. However, they should be no less reliable than the published estimates of other energy resources, because they probably involve less speculation about unseen evidence (e.g. [11]).

Data

We obtained the necessary data from a compilation by Torres-Rodríguez *et al.* ([12]). This compilation contains detailed information on 1,358 identified geothermal manifestations in Mexico, with sample temperatures greater than 30°C. The available information includes, for each geothermal manifestation: an identification alphanumerical code, geographical coordinates, state, municipality, local name, sample temperature, heat flow, six descriptive alphanumerical codes (listed below), and reservoir temperature inferred from five geothermometers. The descriptive codes indicate: (1) fluid type; (2) type of surface manifestation; (3) inferred heat source; (4) reservoir temperature class based on the SiO_2 geothermometer; (5) type of geothermal system; and (6) geological age of production zone.

A significant number of manifestations in this database lack data on some of the parameters just mentioned. Thus we filtered out all manifestations lacking data on one or more of the following parameters: geographical coordinates, fluid type, type of surface manifestation, inferred heat source, sample temperature, and all manifestations having data in less than two geothermometers. We did this in order to improve the general accuracy of our estimates for reservoir temperature.

We then grouped manifestations in geothermal localities. The main criteria for grouping were that two adjacent manifestations be within a rectangle of 1,000 m by 2,000 m, and that the inferred heat sources be of the same type.

In order to assign values to T_1, T_2 and T_3 for each locality, we set the following rules: (a) T_1 = the maximum of all the *sample* temperatures in the locality; (b) if the temperature indicated by any of the available geothermometers is less than T_1, do not consider that (these) geothermometer(s); (c) if after the previous filtering there are less than two geothermometer estimates left in a locality, drop this locality; (d) T_2 = average of all remaining geothermometer estimates plus sample temperature; (e) T_3 = maximum temperature indicated by available geothermometers.

Accurate reservoir areas are difficult to obtain, even in well-studied reservoirs with extensive drilling in them. Following [2], where the only evidence of the existence of a hot water reservoir is a single surface manifestation, we assigned a minimum area A_1 = 1 km^2, a most likely area A_2 = 2 km^2 and a maximum area A_3 = 3 km^2. For localities that include more than one surface manifestation, we assigned minimum, most likely and maximum areas of 1, 2 and 3 km^2 respectively to each manifestation, and computed A_1, A_2 and A_3 as the superposition of the respective area sets.

We assumed a uniform thickness over the reservoir area, for simplicity. Following [2]) the estimates in this assessment include thermal energy to a maximum depth of 3 km. Because of this, the reservoir bottom is assumed to be at 3 km unless there is evidence to suggest a shallower depth. If data from geophysical surveys or drilling provide any indication of the top of the reservoir, these data were used to estimate the thickness. Otherwise, a minimum depth of 0.5 km, a maximum of 2 km and a most likely depth of 1.5 km to the top of the reservoir are assumed. Depths to the top of reservoirs of drilled geothermal systems typically lie within this range. Therefore our standard thickness estimates are h_1 = 1000 m, h_2 = 1500 m and h_3 = 2500 m. It is worth noting that for most reservoirs the uncertainties in the thickness are small compared to those of the area (e.g. [2]).

Results and discussion

After filtering we ended up with 276 geothermal localities spread over 20 Mexican states (Fig. 2). Therefore, the results of this work represent lower limits to the low- to medium-temperature Mexican geothermal reserves and to the associated thermal energy. About 70% of the identified manifestations in the database were left out of this assessment because of the filtering.

Due to space limitations, it is impossible to present here our results on a locality-by-locality basis. Therefore we present only the main statistics for the localities and our results concerning the total thermal energy and reserves in the 276 localities covered by this assessment. Figure 3 presents the distribution of most likely temperatures for the assessed geothermal localities. The distribution mode equals 110°C, its mean equals 111.25°C and its standard deviation equals 20.53°C. The one locality shown in the extreme upper tail has a most likely temperature of 202.9°C, just barely outside the temperature range (T<200°C) of this assessment, so we left it in.

Figure 4 shows our results for the distribution of mean thermal energy, for the 276 localities. Note the tight grouping of the thermal energy around 0.9 10^{15} kJ and the long tail towards higher values. The main factor contributing to the thermal energy is usually the reservoir area, whereas the reservoir temperature generally plays a lesser role.

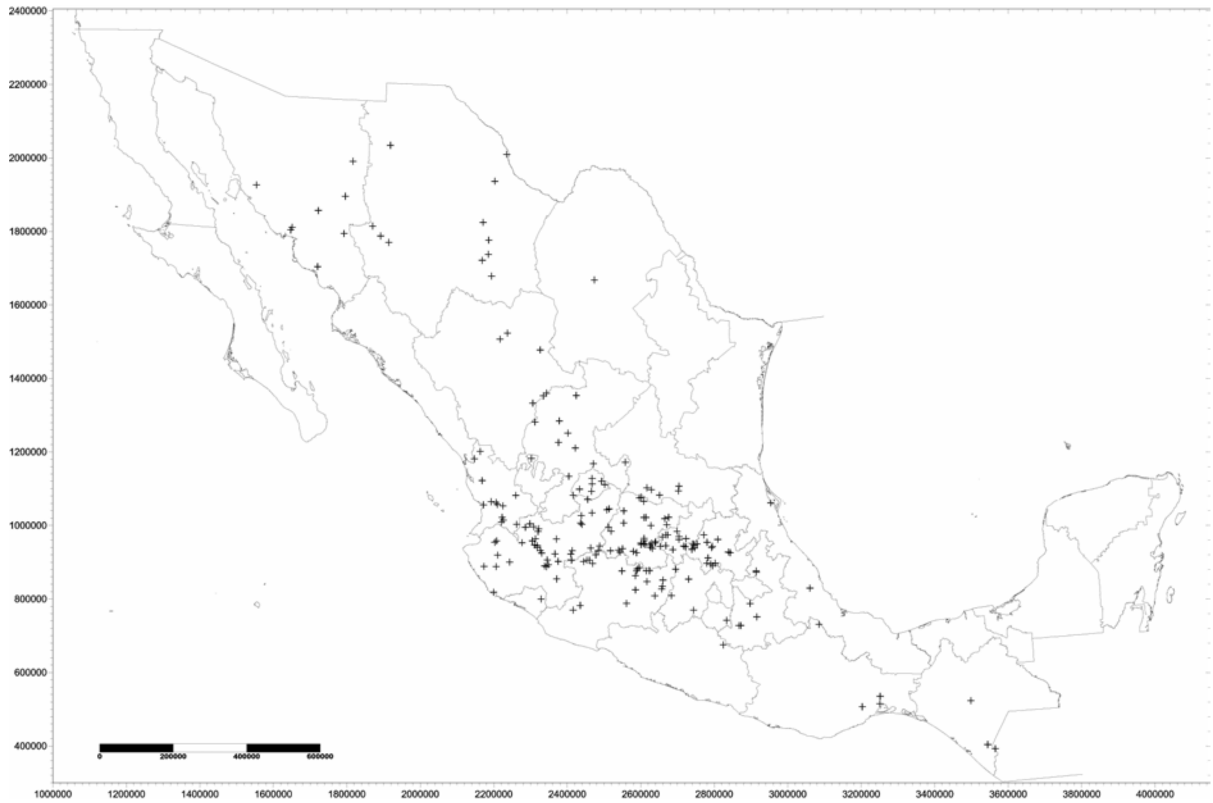
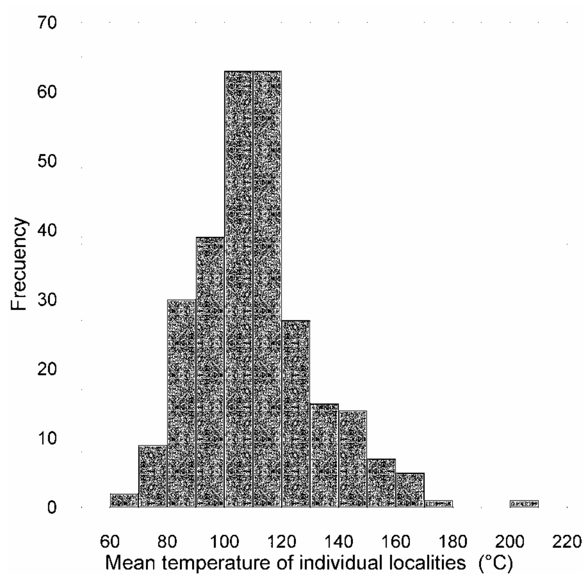


Fig. 2. Geographical distribution of the 276 geothermal localities assessed in this work



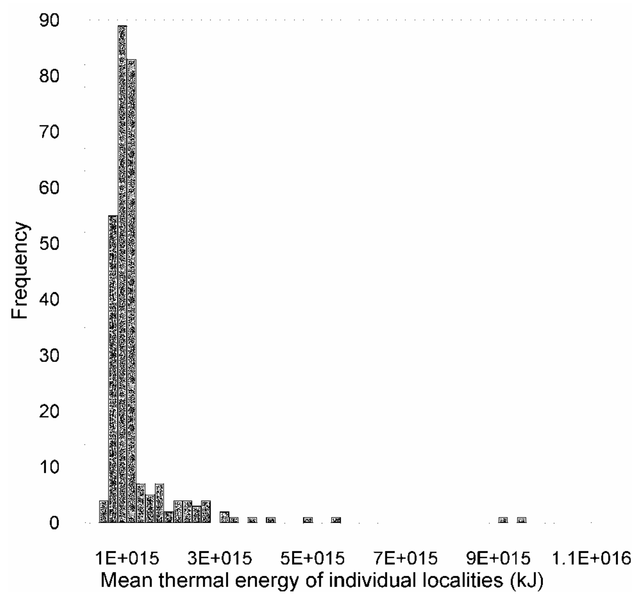


Fig. 3. Distribution of most likely temperatures

Fig. 4. Distribution of thermal energy

Figure 5 presents our results for the total thermal energy stored in the 276 localities. They are very well fitted by a lognormal2 distribution with the values of its μ, σ and shift parameters shown, in that order, at the top of the figure. The estimated total thermal energy is between 3.08 10^{17} and 3.45 10^{17} kJ (8.56 10^{10} to 9.58 10^{10} MW_th), with 90% confidence. The main statistics of the total thermal distribution are: mean = 3.26 10^{17} kJ (9.06 10^{10} MW_th), standard deviation = 1.12 10^{16} kJ (3.11 10^9 MW_th).

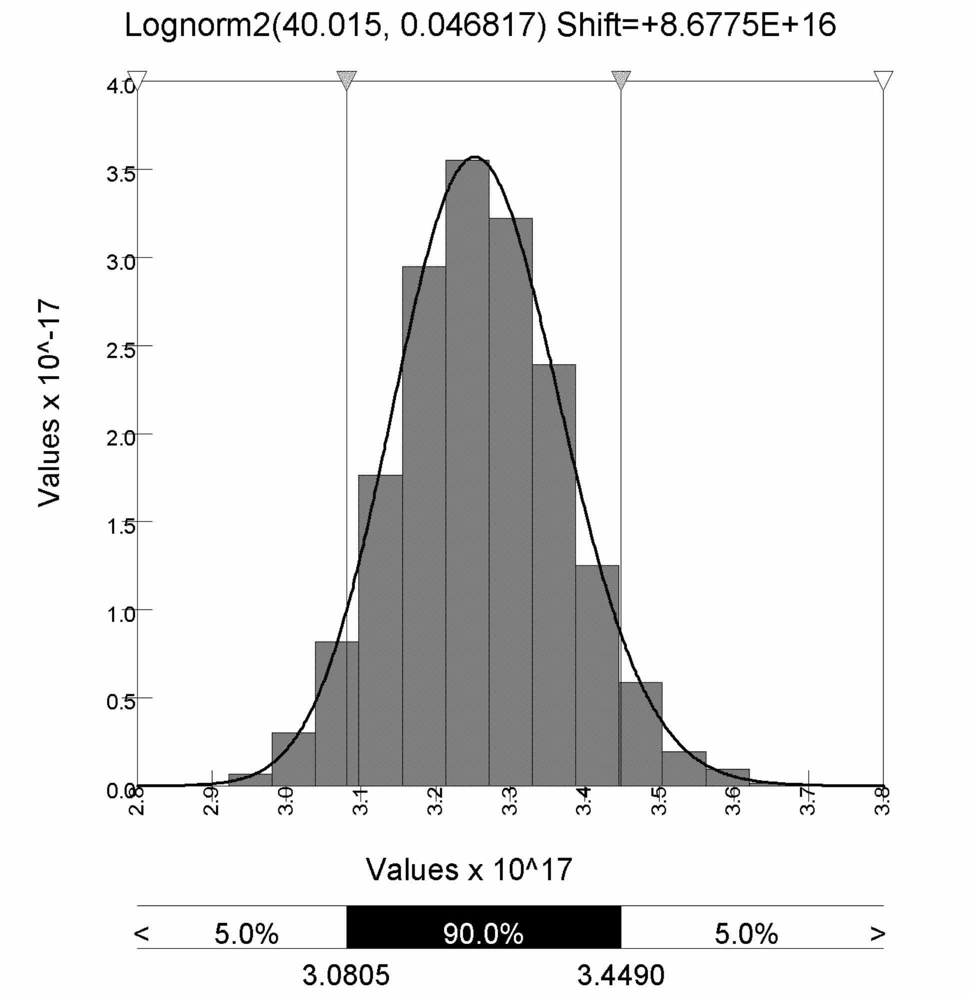


Fig. 5. Distribution of total thermal energy in the 276 geothermal localities

Applying a recovery factor R = 0.25, we estimate the total reserves of the assessed localities as lying between 7.7 10^{16} and 8.6 10^{16} kJ (2.14 10^{10} to 2.39 10^{10} MW_th), with 90% confidence, with a mean equal to 8.15 10^{16} kJ (2.26 10^{10} MW_th) and a standard deviation equal to 0.28 10^{16} kJ (7.78 10^8 MW_th).

Though a lower limit, the reserves assessed in this work hold massive amounts of thermal energy. For example, 8.15 10^{16} kJ, the mean value estimated for the reserves, is equivalent to about 2.14 10^{15} cubic meters of natural gas or to about 1.9 10^9 barrels of Arabian Light oil. With the current installed capacity of 164 MW_t, the mean value of the estimated reserves would last approximately 15,700 years.

This energy is recoverable with current technologies. Therefore, the thermal reserves assessed in this work have the potential to produce a positive and important impact on the local economies.

Summary and Conclusions

This is the first assessment of low- to medium-temperature Mexican geothermal reserves. It includes about 30% of the identified geothermal surface manifestations, because the information available on the rest did not comply with the requisites to obtain quality results.

We found that the thermal energy reserves corresponding to the 276 assessed geothermal localities lies between 7.7 10^{16} and 8.6 10^{16} kJ (2.14 10^{10} to 2.39 10^{10} MW_th), with 90% confidence, with a mean value equal to 8.15 10^{16} kJ (2.26 10^{10} MW_th) and a standard deviation equal to 0.28 10^{16} kJ (7.78 10^{8} MW_th). Its geographical distribution is wide, covering 20 Mexican states.

The total thermal energy corresponding to these reserves lies between 3.08 10^{17} and 3.45 10^{17} kJ (8.56 10^{10} to 9.58 10^{10} MW_th), with 90% confidence, with a mean value equal to 3.26 10^{17} kJ (9.06 10^{10} MW_th) and a standard deviation equal to 1.12 10^{16} kJ (3.11 10^{9} MW_th).

We also found that the distribution of most likely temperature for the geothermal localities ranges from about 60°C to about 180°C, presents a mode equal to 110°C, a mean equal to 111.25°C and a standard deviation equal to 20.53°C.

Though representing only a lower limit, these reserves contain massive amounts of energy, which are recoverable with current technologies. According to the inferred distribution of most likely temperatures, these reserves could be used in an ample variety of direct and electrical applications. Therefore, these reserves have the potential to positively impact the local economies associated with the individual reservoirs.

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