UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensásvegur 9,
IS-108 Reykjavík, Iceland

Reports 2009
Number 24

REASSESSMENT OF THE PRODUCTION CAPACITY OF TWO GEOTHERMAL FIELDS IN NICARAGUA

Juana Ruiz Mendieta
Ministry of Energy and Mines
Geothermal Direction
Managua
NICARAGUA
juana.ruiz@mem.gob.ni

ABSTRACT

In this study the production capacity of two geothermal fields in Nicaragua is re-evaluated based on exploration and drilling data collected after the publication of the Nicaraguan Geothermal Master Plan in 2001. The geothermal fields re-evaluated using the volumetric method with Monte Carlo simulation are the Casita – San Cristobal and San Jacinto – Tizate fields. Considerable new surface exploration data are available from the Casita-San Cristobal area; and several deep production and reinjection wells have been drilled in the San Jacinto – Tizate area. The volumetric model for the Casita – San Cristóbal area predicts, with 90% confidence that the estimated power production is in the range of 53-188 MW for 25 years and the cumulative probability distribution shows there is a 90% probability that the resource capacity is at least 70 MW. The volumetric model for San Jacinto – Tizate area predicts with 90% confidence that the estimated power production is in the range of 91-237 MW for 25 years and the cumulative probability distribution shows there is a 90% probability that the resource capacity is at least 100 MW. Comparison of results with the master plan shows that estimates for the San Jacinto – Tizate geothermal field are similar although the current estimate for the Casita – San Cristóbal geothermal field are lower due to the values assigned to the most sensitive parameters in the calculation, such as the reservoir area, the recovery factor, the thickness of the reservoir and the reservoir temperature. This shows the importance of methods used to assign values for the parameters; conservative or optimistic methods will greatly affect the results of the estimated power capacity.

1. INTRODUCTION

Nicaragua is rich in geothermal resources with several high temperature fields in the active volcanic cordillera that extends along the Pacific coast of the country (see Figure 1). A national resource assessment was carried out in 1999-2001 where the status of the geothermal exploration in each of the geothermal fields was reviewed and the generating capacity of the fields for power production was assessed based on volumetric methods. The results were published in 2001 in the *Nicaragua Geothermal Master Plan* (CNE, 2001); according to the master plan the total geothermal potential of Nicaragua to generate electricity is on the order of 1500 MW. This is almost two times the installed capacity in Nicaragua, which today is 767.2 MW, but only 90 MW of which is geothermal. The rest is mainly generated by burning fossil fuel.

FIGURE 1: The volcanic chain that goes through Nicaragua

The Nicaraguan Government has made efforts to promote investments in electricity generation from renewable resources which can be implemented by private companies, by the state or both, for the short and medium term. One of the main priorities of the Nicaraguan state is the urgency of changing the energy matrix since the recent increase in the price of fossil fuel has significantly increased the cost of electricity, affecting the country's economic stability.

The high geothermal potential in Nicaragua is an opportunity for the nation to meet a significant part of its energy demand by using this clean renewable resource. Nicaragua could significantly and gradually achieve a change in the energy matrix and contribute to the environment as geothermal energy is a relatively low carbon-dioxide emitting source of energy, which could contribute significantly to reducing greenhouse gas emissions which contribute to climate change on our planet. Geothermal power is also a good base load with a load factor of up to 95%, not dependent on climatic factors.

Since the publication of the master plan, some geothermal concessions have been awarded in Nicaragua to private foreign companies. Exploration studies have been carried out in a few geothermal fields and a few exploration, production and reinjection wells have been drilled. The first geothermal power plant in Nicaragua was commissioned in Momotombo in 1989. Initial capacity was two units of 35 MW for a total of 70 MW; a 10 MW binary unit was added in 2002. The Momotombo plant has, however, never operated at full load due to a lack of steam and is presently operated at about 30 MW. The second geothermal power plant in Nicaragua started operation in San Jacinto – Tizate in June 2005. The installed capacity of the plant is 10 MW but the developer plans to expand the plant to 72 MW within a few years.

The aim of the present study is to conduct a re-evaluation of the production capacity based on exploration and drilling data achieved after the publication of the master plan. The geothermal fields to be re-evaluated are Casita – San Cristobal and San Jacinto – Tizate. Considerable new surface exploration data are now available from Casita – San Cristobal; and several deep production and reinjection wells have been drilled in San Jacinto – Tizate.

The re-evaluation of the capacity was done using the volumetric method, similar to what was done in the master plan. With the volumetric method, the thermal energy is calculated in the formation and thermal extraction is estimated based on the estimated volume of the resource and the average temperature. Finally, the amount of electricity that can be generated from the extracted energy in a geothermal power plant is calculated from the enthalpy of the fluid above a defined rejection temperature. The results are then analyzed in terms of the probability of occurrence of the reserves and/or equivalent power output in the range of values. The probability distribution function quantifies the upside potential and downward risk in sizing up the field power potential, and gives indications on the probable range of proven, probable and possible reserves.

2. BACKGROUND

2.1 Regional setting

The chain of 18 distinct volcanic centres found in Nicaragua is a part of the Central America Volcanic Arc (CAVA) which extends along the Pacific coastline of the Central American Isthmus, from Guatemala through Belize, El Salvador, Honduras, Nicaragua, Costa Rica to Panama. This Quaternary volcanic arc is formed by an active subduction of the Cocos oceanic plate under the Caribbean continental plate along the Mesoamerican trench (Figure 2). The subsequently formed Nicaraguan depression is thus parallel to the Mesoamerican trench. As seen in Figure 1, the Nicaraguan Depression is on the southern part of the Chortis block, a unit of mainly continental crust belonging to the Caribbean Plate (CNE 2001).

Weinberg (1992) identified three different phases of deformation that accompanied the geological evolution of the Pacific region of Nicaragua: 1) Miocene phase, 2) Pliocene – Lower Pleistocene phase and 3) Upper Pleistocene – Holocene phase. During the first two of these, the tectonic regime was dominated by compression of NE-SW events, normal to the Mesoamerican trench. From the Pliocene – Lower Pleistocene phase the angle of subduction of the Cocos plate is thought to have increased, reducing the speed of convergence of the Cocos and Caribbean plates.

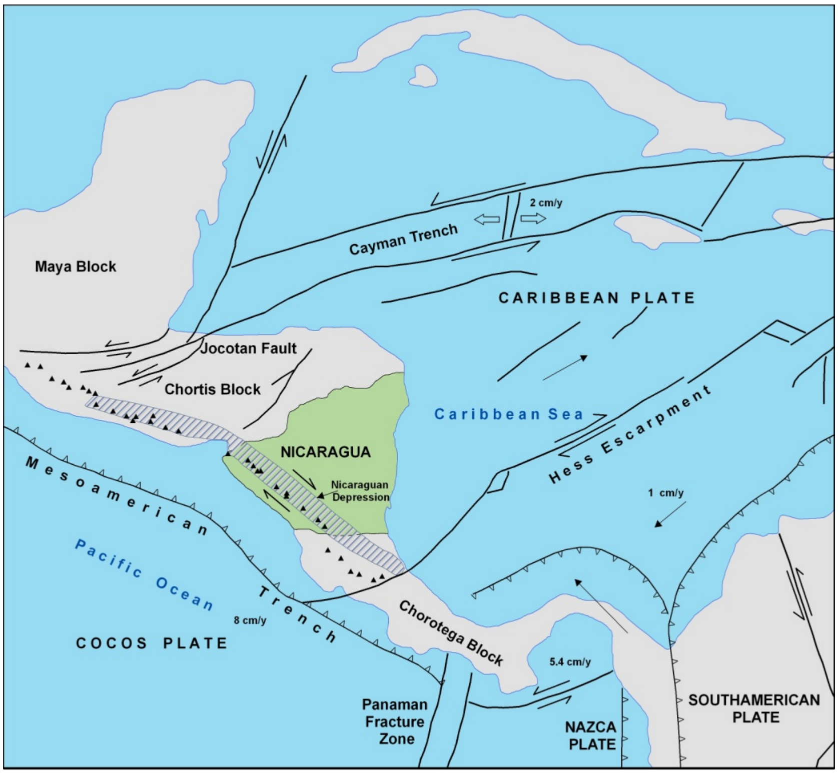

FIGURE 2: Tectonic scheme of the Central American region (CNE, 2001)

This resulted in a migration of volcanism westwards towards the Pacific; the deformation was mainly through normal faults, such as those that led to the Nicaraguan depression (Weinberg, 1992). Subsequently, the terrestrial energy current was high, comprised mainly of magma production and heat conduction to depth levels shallow enough to create geothermal systems with surface manifestations and events of volcanism. From the Upper Pleistocene – Holocene until the present, the tectonic movements can be characterised as a N-S compression which caused the Managua Depression (CNE, 2001).

2.2 Master plan for geothermal energy utilization in Nicaragua

The Federal Government of Nicaragua pursued geothermal development in 1999 when the work for the Master Plan for Geothermal Energy Utilization in Nicaragua started. After three years of extensive research and evaluation, the master plan was published in 2001. The master plan assessed the country's existing and potential geothermal resources in terms of resource quality and environmental issues and ranked the resources in terms of developmental priority. Critical issues included available megawatts, the size of the resources, the potential for transmission access and other pertinent factors such as environmental protection.

Of the 18 volcanic systems in Nicaragua, production capacity of the ten most prominent systems was evaluated, one of which hosted an operating project, i.e. Momotombo, and another which was being developed, i.e. San Jacinto – Tizate. The remaining eight required significant new assessments.

2.2.1 Categorization and theoretical approach

The geothermal systems analysed where categorized into three groups, based on the level of exploration in the area:

1) Fields with a history of drilling in the area with reliable down hole measurements of the physical characteristics of the system and extensive geoscientific surface exploration of the fields;
2) Fields with enough surface exploratory studies, but not verified with drilling; and
3) Fields with few and limited surface exploratory studies.

See a list of the categories in Table 1.

The recoverable reserves and production capacity were estimated by calculating the recovery of the stored heat in the ground using the conventional volumetric method for the parts of the fields that fall under categories 1 and 2. For category 3, the resources were classified where sufficient exploration data existed which allowed estimating the deposit parameters by calculating the amount of heat available at the site based on the presence of magmatic intrusions (CNE, 2001).

For ranking and classification, a risk-weighted factor was introduced. The lowest degree of uncertainty when estimating reserves applies to category 1 while the highest applies to those sites classified in category 3. The risk-weighted reserves were defined to take into account the fact that the estimate of reserves for category 3 resources were made based on the transfer of magmatic heat in volcanoes in a given area, included any category 1 or category 2 reserves in that area. The formula confirmed that the reserves estimate for category 1 was relatively correct, less so for category 2, and still more uncertain for category 3. The weighting factor of 0.5 used for category 2 reserves implied a standard deviation of 50% from the most probable value, while the weighting factor of 0.25 used for category 3 reserves implied a standard deviation of 75% from the most probable value. It should be noted that the risk-weighted reserves are being considered only for purposes of ranking and classification, and do not imply any drop in the reserves that have been estimated (CNE, 2001).

The uncertainty of parameter evaluation for categories 1 and 2 in the volumetric method was done using Monte Carlo simulations. In this method, it is assumed that each variable with uncertainty is a random variable within a given range of values. It should estimate the minimum and maximum potential of each of the uncertain parameters in order to define this range (CNE, 2001).

In the master plan (CNE, 2001), estimates of uncertain parameters were derived from conceptual models. For the average temperature of the reservoir, the reservoir area and the thickness of the reservoir, it was assumed that the two uncertain parameters, porosity and recovery factor, were the same for categories 1 and 2. A uniform probability was chosen, using 3-7% for porosity and 10-20% for the recovery factor. It must be said that the methodology is exactly the same for categories 1 and 2. The only difference between the two categories is the extent of the uncertainty, i.e. the standard deviation of the three variables, the reservoir temperature, area and thickness (CNE, 2001).

Category 3 is based on a model of stored heat for a body of magma, where it recognizes three possible idealized boundary conditions, firstly a magma body cooling down with conduction, secondly a magma body that retains indefinitely its original temperature (constant temperature) and finally a magma body with a continuous discharge of heat due to convection within the magma, so the rate of discharge of the hot magma body remains constant forever (constant heat flux). The first idealization is more conservative than the other two. The differential equations were solved using previously published calculations by Carslaw et al., (1959), Lovering (1935) and Lachenbruch (1957a; 1957b) in the master plan in 2001.

The methodology described above for the area of category 3 is inherently less accurate than the methodology used in the areas of categories 1 and 2. However, it was used in the absence of a direct method for estimating sub-surface temperatures and thickness of the geothermal reservoir. The proposed method is the only consistent and quantitative method for estimating geothermal reserves with limited amounts of data, at least as an upper limit. The estimated reserves, in this way, allow a comparison of category 3 with the other categories and make it possible to conduct a nationwide inventory of the potential of geothermal reserves in unexplored or inadequately explored areas (CNE, 2001).

2.2.2 Results of the resource assessment

When estimating reserves the parameters, such as temperature, deposit area, thickness and deposit porosity are taken into account. However, there are other parameters as well that must be considered in any systematic classification and ranking effort. One limitation is that these parameters are precisely those that are difficult to quantify, such as those used to estimate reserves (i.e. drilling depth, well productivity, potential scale, potential corrosion and complexity of resources).

Table 1 shows the 10 areas identified by the master plan along with the outcome of the potential calculated for each area. It is important to mention that the Caldera Masaya, Caldera Apoyo and Volcán Mombacho areas belong to the Masaya – Granada – Nandaime area, separated for the purpose of calculating the reserves. The ranking and classification of the resources was based on the previously mentioned risk-weighted factor.

2.3 Recent geothermal exploration research

After the publication of the Master Plan in 2001, some concession areas were licensed to international companies for exploration and exploitation. These companies carried out exploration in their concessions areas and a few exploration wells were drilled; a few production and reinjection wells were also drilled in the two areas which are under exploitation. The exploration work carried out in the ten geothermal fields, listed in Table 1, since the publication of the master plan in 2001 is summarized below:

TABLE 1: Results of calculation of reserves for each area in the geothermal master plan (CNE, 2001)

No.	Geothermal areas		Category	Potential (MW)
1	Momotombo		1	154
2	San Jacinto – Tizate		1	167
3	El Hoyo – Monte Galán		2	159
4	Managua – Chiltepe		2	111
5	Telica – El Ñajo		2	78
6	Casita – San Cristóbal		2	225
7	Masaya – Granada – Nandaime	Caldera de Masaya	3	153
		Caldera de Apoyo	2	111.5
		Volcán Mombacho	2	99.5
8	Tipitapa		2	9
9	Volcán Cosigüina		3	106
10	Isla de Ometepe		3	146
	Total potential			**1,519**

The Momotombo field has been operated by Ormat for more than ten years. The installed capacity was 70 MW but only 10 MW were generated when Ormat overtook the operation. Since then Ormat has drilled several production and reinjection wells and carried out work-over and cleaned several of the older wells. A programme has also been implemented for total reinjection; and a 10 MW binary power plant has been constructed and commissioned. Currently the total generation in Momotombo is 27 MW, but Ormat plans to continue to increase the generation towards the installed capacity.

The San Jacinto – Tizate geothermal field is operated by Polaris. Considerable developments have been carried out during the last few years, including some surface explorations and drilling of a few production and reinjection wells. Polaris has constructed a 10 MW geothermal power plant that started operation in June 2005.

For the geothermal fields El Hoyo – Monte Galan and Managua Chiltepe, the international company GeoNica was awarded exploration concessions in 2006. They have carried out an exploration programme in both areas. The first part of it was a detailed surface study in geology, geophysics and geochemistry, summarised in exploration reports. The second phase, ongoing at the moment, is exploration drilling.

The Casita – San Cristobal geothermal field has, since 2001, been explored by two international companies, first by Triton and later by Cerro Colorado Power which now has the exploration licence for this field. The exploration work has focused on geological, geochemical and geophysical studies including structural geology, geothermometry and MT measurements. Exploration drilling is planned in the near future.

For the geothermal areas Telica – Ñajo, Caldera de Apoyo, Volcán Mombacho and Isla de Ometepe an international tender for exploration studies is currently being processed. No exploration work has been carried out since 2001. The geothermal master plan study of 2001 is, therefore, still the best geothermal evaluation of these fields. The geothermal areas Volcán Cosigüina, Tipitapa and Caldera de Masaya have not undergone any geothermal exploration since 2001. The results of the master plan are, therefore, still the best knowledge base for these fields.

The exploration and development work have added new knowledge on these geothermal fields which can be used to reassess their geothermal potential and update the results from the master plan (CNE, 2001). The initial idea for this project work was to reassess the two concession areas of GeoNica, i.e. El Hoyo – Monte Galan and Managua Chiltepe. However, GeoNica is now completing their exploration programme for both fields, both surface exploration and exploration drilling and could not provide the required data when needed, as they had not fully evaluated it themselves. It was, therefore, decided to reassess two other fields, Casita – San Cristobal and San Jacinto – Tizate, to evaluate the main results of the recent geothermal exploration in these two fields and carry out a new volumetric assessment.

3. PRODUCTION CAPACITY ASSESSMENT

3.1 Volumetric methodology

Geothermal resource evaluation (*resource assessment*) is a process of evaluating all available exploratory and drilling data for the geothermal field, and integrating it with other geoscientific information obtained from geological, geophysical and geochemical measurements. The main focus of geothermal resource assessment is to confirm that there exists a geothermal resource that could be exploited at a certain capacity for a certain period with well defined fluid characteristics and resource management strategies to ensure production sustainability over a long period (Sarmiento, 2008).

A volumetric assessment with Monte Carlo simulation allows variable parameters. The results are then analysed in terms of the probability of occurrence of the reserves and/or equivalent power output in the range of values. The probability distribution function quantifies the upside potential and downward risk in sizing up the field power potential, and gives indications on the probable range of proven, probable and possible reserves (Sarmiento and Steingrímsson, 2008).

3.1.1 Thermal energy calculation

The volumetric method refers to the calculation of the thermal stored energy in the rock and in the fluid. The total energy stored in the reservoir is the sum of the energy in the rock and the energy in the fluid.

The equation used in calculating the thermal energy for a liquid-dominated reservoir is as follows:

$$Q_T = Q_r + Q_w \quad (1)$$

and

$$Q_r = A\,h\,[\rho_r \times C_r \times (1-\varphi) \times (T_i - T_f)] \quad (2)$$

$$Q_w = A\,h\,[\rho_w * C_w * \varphi * (T_i - T_f)] \quad (3)$$

where Q_T = Total thermal energy (kJ);
Q_r = Heat in rock (kJ);
Q_w = Heat in water (kJ);
A = Area of the reservoir (m^2);
h = Average thickness of the reservoir (m);
C_r = Specific heat of rock at reservoir conditions (kJ/kgK);
C_w = Specific heat of liquid at reservoir conditions (kJ/kgK);
φ = Porosity;
ρ_r = Rock density (kg/m^3);
ρ_{si} = Steam density (kg/m^3);
ρ_{wi} = Water initial density (kg/m^3);
T_i = Average temperature of the reservoir (°C);
T_f = Final or rejection temperature (°C).

However, a comparison made by Sanyal and Sarmiento (2007) indicates that if only water is produced from the reservoir, only 3.9% of the energy is contained in the fluids; the rest is in the rock matrix; and if only steam is produced from the reservoir, only 9.6% is contained in the fluids. If both water and steam are produced from the reservoir, the heat content in the fluids is somewhere between 3.9 and 9.6%. Conclusively, all the fluids are in the rock and it doesn't matter whether one distinguishes between the stored heat in the water and steam, respectively. This approach is illustrated by the following set of equations to separately account for the liquid and steam components in the reservoir:

$$Q_T = Q_r + Q_s + Q_w \tag{4}$$

$$Q_r = A\,h\left[\rho_r \times C_r \times (1-\varphi) \times \left(T_i - T_f\right)\right] \tag{2}$$

$$Q_s = A\,h\left[\rho_{si} \times \varphi \times (1-S_w) \times \left(H_{si} - H_{wf}\right)\right] \tag{5}$$

$$Q_w = A\,h\left[\rho_{wi} \times \varphi \times S_w \times \left(H_{wi} - H_{wf}\right)\right] \tag{6}$$

where Q_s = Heat in steam (kJ);
C_s = Specific heat of steam at reservoir conditions (kJ/kgK);
H_{si} = Steam enthalpy at reservoir temperature (kJ/kg);
H_{wi} = Water enthalpy at reservoir temperature (kJ/kg);
H_{wf} = Final or water enthalpy at base temperature (kJ/kg);
S_w = Water saturation.

The above calculations only provide for the total thermal energy in place in the reservoir. To size the power plant that could be supported by the resource, the following equation is also introduced:

$$P = \frac{Q_t \times R_f + C_e}{P_f \times t} \tag{7}$$

where P = Power potential (MWe);
R_f = Recovery factor;
C_e = Conversion efficiency;
P_f = Plant factor;
T = Time in years (economic life).

The *recovery factor* refers to the fraction of the stored heat in the reservoir that could be extracted to the surface. It is dependent on the fraction of the reservoir that is considered permeable and on the efficiency by which heat could be swept from these permeable channels.

The *conversion efficiency* takes into account the conversion of the recoverable thermal energy into electricity.

The *economic life* of the project is the period it takes the whole investment to be recovered within its target internal rate of return. This is usually 25-30 years.

The *plant factor* refers to the plant availability throughout the year taking into consideration the period when the plant is scheduled for maintenance, or whether the plant is operated as a base-load or peaking plant. The good performance of many geothermal plants around the world places the availability factor to be between 90 and 97 %.

Sarmiento and Steingrímsson (2008) used the results of the Monte Carlo simulation to determine the proven, probable and possible or inferred reserves based on the resulting percentiles obtained from the cumulative frequency or the probability density function. The percentile value indicates the value of probability that the quantities of reserves to be recovered will actually equal or exceed.

The Monte Carlo simulation, using the @RISK spreadsheet-based software (Palisade Corp., 2007), performs the calculation on the generation level or reserve estimates by extracting each of the uncertain parameters (random value) within the span of the minimum, most likely and maximum (triangular distribution). The random sampling and calculations are done for 1000 to 10,000 iterations and each result is sent to the bin to be compiled for the frequency distribution. Knowing the range of minimum, most likely and maximum values from the various input parameters, the risk and the probability of occurrence can thus be evaluated when a decision is made on the generation level (Sarmiento and Steingrímsson, 2008).

According to Sarmiento and Steingrímsson (2008), for the estimation of the reserves, the most important output of the programme is related to the frequency plot of the thermal energy or its equivalent power plant size capacity. The thermal energy or the plant capacity is usually plotted using the relative frequency histogram and the cumulative frequency distribution. The relative frequency of a value or a group of numbers (intervals or bins) is calculated as a fraction or percentage of the total number of data points (the sum of the frequencies).

3.1.2 Recovery factor

The Recovery factor is the fraction of the stored heat in the reservoir that could be extracted to the surface. It is dependent on the fraction of the reservoir that is considered permeable and on the efficiency by which heat could be swept from these permeable channels.

The recovery factor cannot be measured directly, but a few crude indirect methods have been applied to roughly estimate or guess how much of the energy of a geothermal system can be recovered. A constant value for the recovery factor was often applied in earlier reservoir assessments and a typical value was 0.25 (Muffler, 1979). Sometimes the recovery factor is estimated to be a function of the reservoir porosity as shown in Figure 3. Notice that 10% reservoir porosity will result in a recovery factor of 0.25.

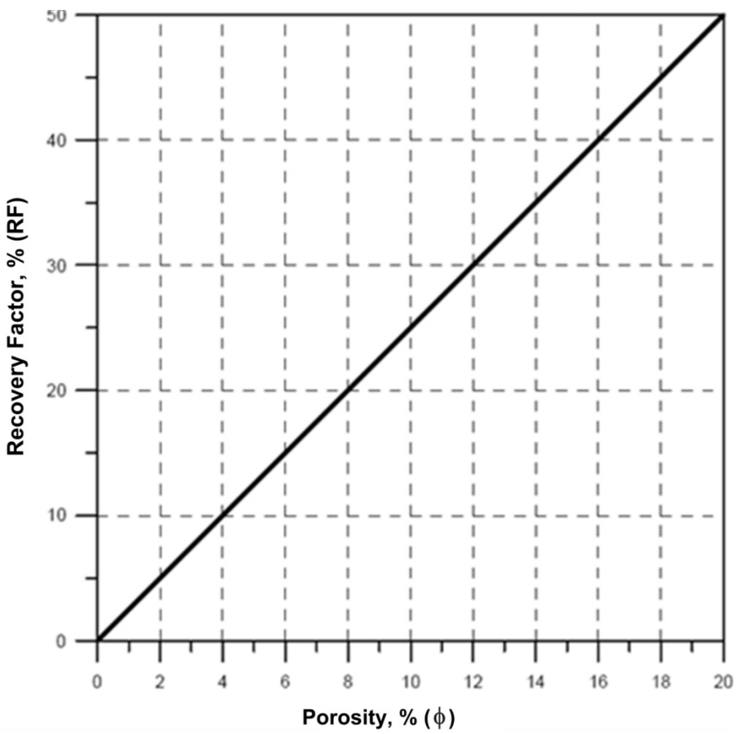

FIGURE 3: Correlation between recovery factor and porosity (after Muffler, 1979)

Today it is generally believed that earlier assessments overestimated the recoverable fraction of the stored energy at least for fractured reservoirs. Recent analyses of data from fractured reservoirs indicate much lower values for the recovery factor, maybe as low as 0.1 for a reservoir of a typical 10% porosity (Williams, 2007). The geothermal reservoirs in Nicaragua are fractured volcanic systems. In the present study it was, therefore, decided to use 0.1, 0.15 and 0.25 for minimum, most likely and maximum values for the recovery factor, respectively, in the volumetric assessment of the geothermal fields.

3.2 Casita – San Cristóbal Field

The Casita – San Cristóbal volcanic massif is made up of three main edifices: the regular cone of the active San Cristóbal stratovolcano (1,745 m a.s.l.); the Casita volcanic edifice (1,405 m a.s.l.), which occupies the central part with a more complex and eroded topography, particularly to the south; and La Pelona caldera, located to the extreme southeast and formed by an edifice of lesser altitude with a broad flat-base crater, which partially underlies the Casita volcano edifice. In addition to these three main edifices, the volcanic complex includes some minor volcanoes to the north-northeast and west of San Cristóbal volcano, as well as several cones and other subsidiary volcanic structures.

Volcanoes Casita and San Cristóbal are mainly constituted of lava, lahars and pyroclastic deposits which range in composition mainly from basaltic to basaltic-andesitic, with a less significant presence of andesitic and dacitic rocks. San Cristóbal volcano is active. It is uncertain if Casita volcano has been active in historical time, but a sample of lava collected at the lower part of the crater was dated at 12,000 ± 1,000 years. The rocks at La Pelona caldera range from basaltic to dacitic, thus reflecting a higher degree of differentiation with respect to the other edifices of the volcanic complex. It is probable that this edifice began its formation and to a large extent completed it before the growth of Casita and San Cristóbal, and has not been active in historical time.

3.2.1 Conceptual model

According to results of geophysical study, the conductive zone is at an elevation above 200 m b.s.l. and the highest point of its base, which reaches up to 300 m a.s.l., lies directly below the Casita ridge. This very strong change in the topography of the base of the conductive layer under the Casita ridge is suggestive of the presence of a vapour-dominated zone.

Geochemistry of the Casita fumaroles is characteristic of discharge from a vapour-dominated reservoir, bur geothermometry temperatures range from 225 to 275°C. While purely vapour-dominated resources tend to have reservoir temperatures of 240°C, there can be variability in geothermometry temperatures from such systems. This, in combination with the absence of chloride rich springs with geothermal character in close proximity to the Casita ridge, means that there is some uncertainty about the presence of a deeper water reservoir.

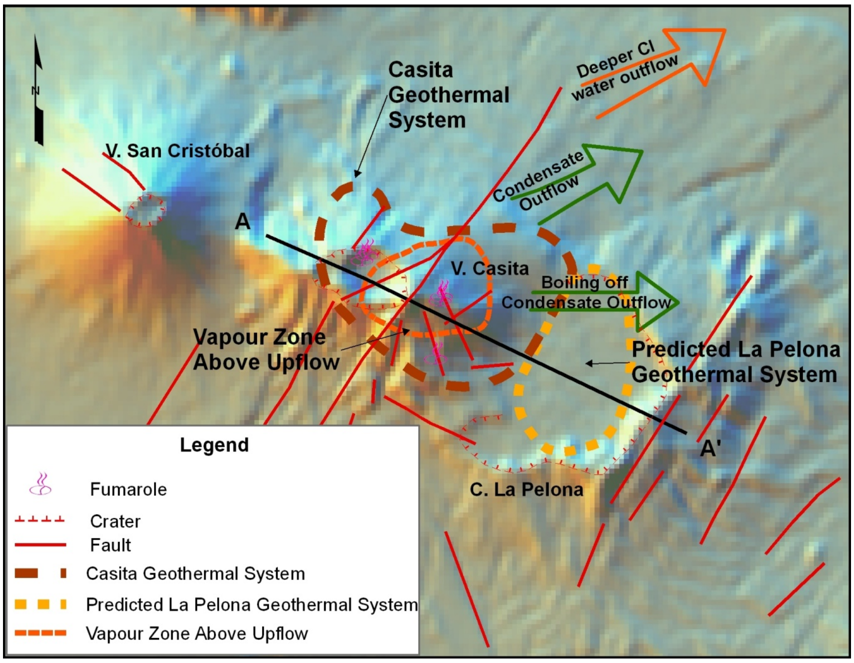

FIGURE 4: Map showing the area of geothermal reserves for the Casita – San Cristóbal field (SKM, 2005)

According to SKM (2005), the La Pelona caldera hosts a significant doming of the conductive layer at similar elevation levels to the broader anomaly around Casita and this could indicate the presence of an extension to the Casita system or a separate geothermal upflow zone in this area in the east. The separate area of up doming of the base of the conductive layer within the La Pelona caldera has some characteristics that support the possibility that this feature is an extension of the Casita geothermal system (see Figure 4).

The fact that the conductive layer there is both thick (500 m) and domed argues against this resistivity feature being due to lake sediments (which are very unlikely to be this thick given the youth of the caldera) or to be due to relict alteration (which tends to have low resistivity persisting to depth). Therefore, there could possibly be a separate upflow beneath the La Pelona caldera.

Geological evaluation indicates that there is probably a highly permeable pumice layer across much of the area (derived from an eruption of La Pelona) with its top at approximately 500 m a.s.l. in the La Pelona caldera and probably lying deeper and thinner to the west. This has the potential to act as a permeable horizon in the steam zone. This permeable layer and potential resource may extend east of the Casita ridge beneath the La Pelona caldera, where the pumice layer is likely to be deeper and thicker.

As the base of the conductor reaches up to 500 m below the Casita ridge, there is potential for the vapour-dominated zone to be hosted by the pumice breccias, beneath the ridge. Therefore, there is potential for a widespread stratigraphic drilling target to be present beneath the ridge. If the deeper neutral Cl liquid reservoir is to be exploited beneath the ridge, then structural targets must be sought as previously discussed (SKM, 2002).

This geothermal conceptual model for Casita – San Cristóbal field is summarised in Figures 4 and 5. Geothermal isotherms on the cross-section have been assumed to be based on the shape of the conductive layer; the vapour-dominated or two-phase steam zone within the mountain is guided by the shape of the conductor and the distribution of steaming ground. Isotherms within the La Pelona caldera are more speculative than under Casita. The thickness of the vapour-dominated zone at Casita is unknown, but estimated to be on the order of a few hundred metres.

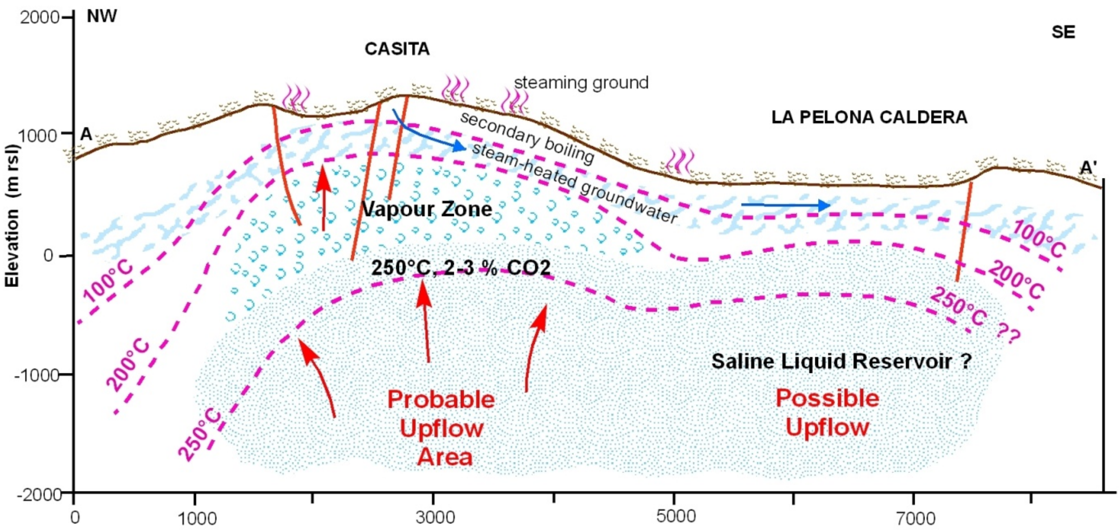

FIGURE 5: Conceptual model of the Casita – San Cristóbal field (SKM, 2005)

3.2.2 Parameter evaluation

The area was defined by considering the surface thermal activity, the interpretation of geophysical cross-sections and the topography of the area. The absolute minimum area of the deeper layer at Casita is assumed to be a small zone surrounding the most active fumaroles. The most likely area is taken to be defined approximately by the 0 m (sea level) elevation contour of the conductor, which also takes in all of the main thermal activity. The maximum area is estimated to correspond approximately to the -200 m elevation contour of the base of the conductors in the north, west and south, and in the east by drawing a boundary half way to the La Pelona anomaly. This maximum area coincidentally encloses, by a few hundred metres, all of the outermost surface thermal activity (SKM, 2005).

Since the upper layer at Casita is ascribed to the steam zone, and on the basis of the geophysical cross-sections and general topographical considerations, it is considered unlikely that the steam zone underlies the whole area of the deeper resource, the most likely and maximum areas for the upper layer are down rated (see Table 2). However, because most of the energy is stored in the much thicker and hotter underlying zone this makes little difference to the overall estimate (SKM, 2005).

At La Pelona the minimum area was taken to be zero, since it has not been confirmed that any thermal resource actually exists there. The most likely area was taken to be that enclosed by the 0 m (sea level) elevation contour at the base of the conductor (see Table 3). The maximum possible area was defined by the 200 m b.s.l. contour, and by the boundary half way to the Casita area (SKM, 2005).

At Casita the thickness of the steam zone is quite tightly constrained. Based upon experience from the reservoirs at San Jacinto – Tizate and Momotombo, where the pressure within the liquid reservoir is regulated by the local hydrological base level, it is likely that the liquid reservoir at Casita will also have a piezometric level at approximately sea level. Therefore, unless the reservoir at Casita is isolated from the regional hydrology, the deepest that the vapour-dominated zone could extend is about 300 m b.s.l. Based on consideration of the lithostatic and hydrostatic pressure necessary to provide a cap to a vapour-dominated zone, the top of the vapour-dominated reservoir could at its highest be at about 900 m a.s.l., but it could be significantly deeper. The thickness of the underlying layer is then the remainder of what is considered to be a reasonable maximum economic drilling depth plus an underlying drainage volume, taking into account the fact that the outlying part of the resource is at significantly lower elevation than the centre (SKM, 2005).

Regarding fluid saturation, the vapour zone in Casita is considered to have 45% liquid by volume. This is a typical calculation of an untapped area of steam, taking into account the geochemistry of the area because it has characteristics of a very mature field and, therefore, may be relatively dry. In the case of Casita, the porosity of the rock is considered high, as steam zones cannot form where porosity is low; a value of 15% is assumed. For La Pelona, the same value of 15% was assumed, although it may be a little lower than for Casita. Both areas are suspected of a large volcanic formation at depth and this causes some reduction in porosity with depth, assumed to be due to the consolidation of the rock.

The temperature in the steam zone in the Casita area is considered very tightly constrained, because the higher temperature is approximately 245°C. There is little justification for the selection of a much lower minimum temperature. However, a higher temperature was suggested in the geochemistry of gases, thus allowing a maximum temperature of 290°C, although there is a possibility that the temperatures at depth are higher (SKM, 2005). In La Pelona, there is no geothermometry available to estimate an appropriate value of the temperature; however, a minimum value of 180 °C was assumed for the evaluation of the resource.

The recovery factor calculated in the Casita – San Cristobal area was conducted separately for the Casita area which was calculated as a two-phase reservoir, resulting in a recovery factor of 15%; the area of Cerro La Pelona was calculated as a liquid-dominated phase reservoir with a recovery factor of 15%. The difference in both areas is minimal.

For the assessment of the wider resource, the Casita and La Pelona areas were assessed separately, to account for the fact that there is less clear evidence for the existence and nature of the La Pelona resource; the results were, however, combined for the overall assessment. Tables 2 and 3 list the input parameters used in the analyses.

TABLE 2: Parameters used in the Casita area resource assessment

Input parameters	**Units**	**Probability distribution**			
		Minimum	**Most likely**	**Maximum**	**Type of distribution**
Area: upper layer	km^2	1	4	8	Triangular
Area: lower layer	km^2	1	6	12	Triangular
Thickness: upper layer	m	300	500	500	Triangular
Thickness: lower layer	m	1300	1700	2000	Triangular
Fluid saturation, upper layer	%		45		Constant
Fluid saturation, lower layer	%		100		Constant
Rock density	kg/m^3		2700		Constant
Rock specific heat	kJ/kg°C		0.9		Constant
Porosity: upper layer	%	6	15	20	Triangular
Porosity: lower layer	%	5	10	12	Triangular
Temperature: upper layer	°C	240	250	275	Triangular
Temperature: lower layer	°C	250	260	290	Triangular
Fluid density	kg/m^3		784		f (temp)
Fluid specific heat	kJ/kg°C		4.98		f (temp)
Recovery factor	%	10	15	25	f (por), triang.
Conversion efficiency	%		13		f (temp)
Plant life	years		25		Single value
Load factor	%		90		Constant
Rejection temperature	°C		180		Constant

TABLE 3: Parameters used in La Pelona area resource assessment

Input parameters	**Units**	**Probability distribution**			
		Minimum	**Most likely**	**Maximum**	**Type of distribution**
Area	km^2	0	3	10	Triangular
Thickness	m	1000	2000	2000	Triangular
Fluid saturation	%		100		Constant
Rock density	kg/m^3		2700		Constant
Rock specific heat	kJ/kg°C		0.9		Constant
Porosity	%	6	15	18	Triangular
Temperature	°C	180	250	260	Triangular
Fluid density	kg/m^3		799.2		f (temp)
Fluid specific heat	kJ/kg°C		4.87		f (temp)
Recovery factor	%	10	15	25	f (por), triang
Conversion efficiency	%		13		f (temp)
Plant life	years		25		Single value
Load factor	%		90		Constant
Rejection temperature	°C		180		Constant

3.2.3 Production capacity

The results were obtained through simulations with the @RISK software (Palisade Corp., 2007) as shown in Figure 6 with 10,000 iterations to obtain the frequency distribution and the cumulative probability distributions.

The calculated parameters indicate that the capacity of the whole Casita – San Cristóbal resource has a mean value of 114 MW for 25 years, with a standard deviation of 42 MW. It can also be seen in

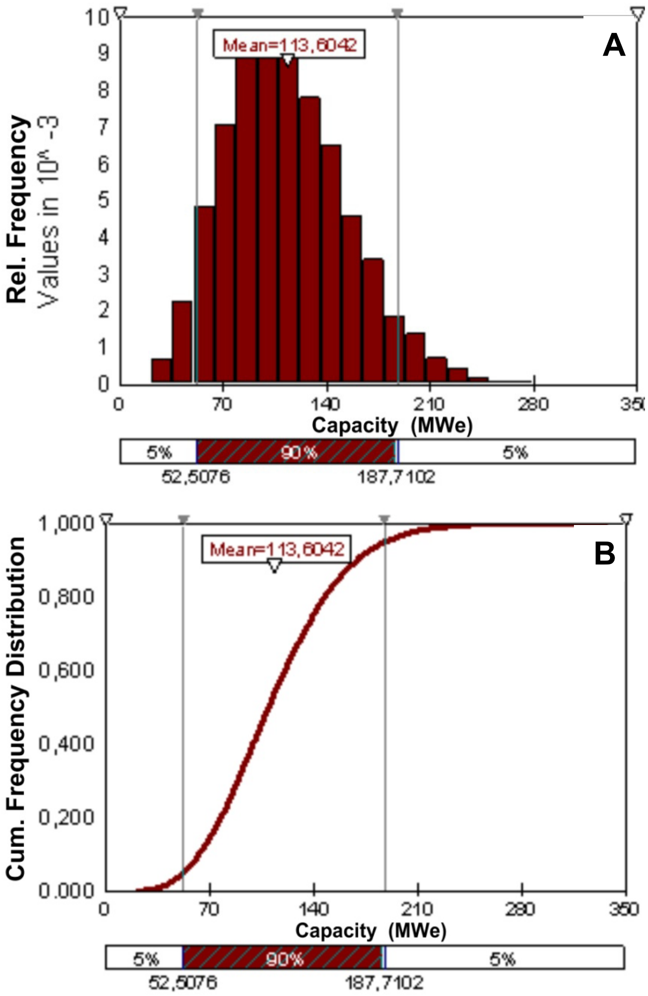

FIGURE 6: Casita – San Cristóbal field; a) Frequency distribution, and b) Cumulative probability distribution for the electric power production

Figure 6 that the volumetric model predicts with 90% confidence that the estimated power production will be in the range 53-180 MW for 25 years. The cumulative probability distribution shows there is a 90% probability that the resource capacity will be at least 70 MW.

3.2.4 Comparison of present study and the master plan

In the assessment of 2001, as seen in Table 4, which shows the results for the Casita – San Cristobal field, in the volumetric calculation high values were assumed for the most sensitive parameters: the area, the reservoir thickness and the recovery factor. Also of great importance is that the most likely value of the recovery factor was not known for the 2001 calculation; only the minimum and maximum values were given, which leads us to believe that the result for the power potential, 224 MW, is based on the maximum value.

In the present evaluation (see Tables 2 and 3) the area identified in the conceptual model corresponds to the area that includes both the Casita and La Pelona resources. The recovery factor was calculated according to the

TABLE 4: Estimated probability distribution for Monte Carlo simulation of the Casita – San Cristóbal field, 2001 (for present results, see Tables 2 and 3)

Input parameters	**Units**	**Master plan 2001**		
		Minimum	**Most likely**	**Maximum**
Area	km^2	4	10	24
thickness	m	1000		3000
Rock density	kg/m^3			
Porosity	%	3		7
Recovery factor	%	10		20
Rock specific heat	kJ/kg°C			
Temperature	°C	200		260
Fluid density	kg/m^3			
Conversion efficiency	%			
Fluid specific heat	kJ/kg°C			
Plant life	years		30	
Load factor	%		90	
Rejection temperature	°C			
Volumetric heat capacity	kJ/m3/°C		2280	
Ejection temperature	°C		30	
Utilization factor	%		45	
Summary of results	**MW**	**224.4**		

methodolog suggested by Muffler (1979) and is presented in Section 3.1. Thanks to the additional studies conducted in recent years, it was possible to make an approximation of the area, the thickness of the reservoir, and to define a recovery factor consistent with the characteristics of the field. Once the first drilling has taken place it is possible to do a new reassessment of the field.

To update the Casita – San Cristóbal area, according to the conceptual model, there is a possible two-phase reservoir in the Casita resource; there is also another possible liquid-dominated reservoir in the La Pelona resource. For this reason the two resources were evaluated separately and for the final result, a general value for the entire field was given. The results for the power potential of the area can be seen in Figures 6. The volumetric model predicts with 90% confidence that the estimated power production will be in the range of 53-188 MW for 25 years.

3.3 San Jacinto – Tizate field

The holes drilled in the San Jacinto – Tizate geothermal field have provided extensive information on the subsurface stratigraphy in the area. Lithological samples from wells have been studied primarily by DAL SpA (1995), Ostapenko et al. (1998), and SKM (2008a, b, c and d) who identified a sequence of different units ranging from recent volcanic products of the Quaternary volcanic range to rock volcanic and volcano-sedimentary Tertiary rocks.

In the geothermal field there are two main areas of fumarole activity located, respectively, at El Tizate and at San Jacinto, 3 km from each other. The fumaroles at El Tizate are very weak and reduced to a few spots within an area of hydrothermal alteration, while at San Jacinto the thermals are characterised by hot mud springs and hot soils, intense hydrothermal alteration and steam leaks. In the sector located between the two fumarole areas, there are some springs with temperatures of up to 40°C that represent discharge from the shallow aquifer.

3.3.1 Conceptual model

The stratigraphic sequence consists of lavas and tuffs of variable composition between andesite and basalt and related product epiclastics with thicknesses between 100 and 300 m; in the area of Tizate SJ-2, tuffs and lavas are intercalated with slag (300-400 m). This is the oldest formation of the volcanic range of Maribios Pleistocene. Depths between 850 and 950 m are characterised by sequences of volcanoclastic red shale and sandstone, conglomerates and breccias, with interbedded lavas and tuffs. Inside the sequence, sub-intrusive shaped rocks and small sub-volcanic dykes were also reported from 600 m depth (SKM, 2008a, b, c and d).

The main tectonic lines identified in the San Jacinto – Tizate trend NW-SE and N-S. On the whole, the system of fractures in the area is consistent with the regional tectonic stress field defined by Weinberg (1992), characterised by a compressive principal stress in a N-S direction, which generates a system of fractures that include strike-slip type failures in a N-S direction around NE-SW and NW-SE normal faults. The area has several normal faults with roughly N-S direction, which generate a depression that extends from Tizate to the south and is generally known as the San Jacinto depression. All these structures do not seem to define an emerging N-S rift system.

FMI logging revealed that the deep formations are tightly folded and dip at moderate to steep angles to the west which means that there will not be a close correlation of geology between wells. It also means that permeability must be focused within structures rather than formations because the formations dip to the west, but the highest temperatures are to the east (in SJ5 and SJ6-2). For the hot fluid to ascend to the surface from depth, it must cut across these formations, rather than (or in addition to) flowing up permeable units. (SKM, 2008d)

The upflow zone of the deep fluids that feed the hydrothermal system is located between the La Bolsa faults and Tizate with possible extension to the east. Starting at the upflow zone, the geothermal fluids move laterally to the south, at depths that vary between 400 and 1400 m inside the San Jacinto depression structure (CNE, 2001; SKM, 2008)

From the new information obtained from recently drilled wells (SKM, 2007; SKM, 2008 a, b, c and d), it has been determined that the increased permeability is due to the structures in the eastern part of the field as it is in that direction that the highest temperatures, ranging from 289 to 303°C, were recorded (see Figure 7).

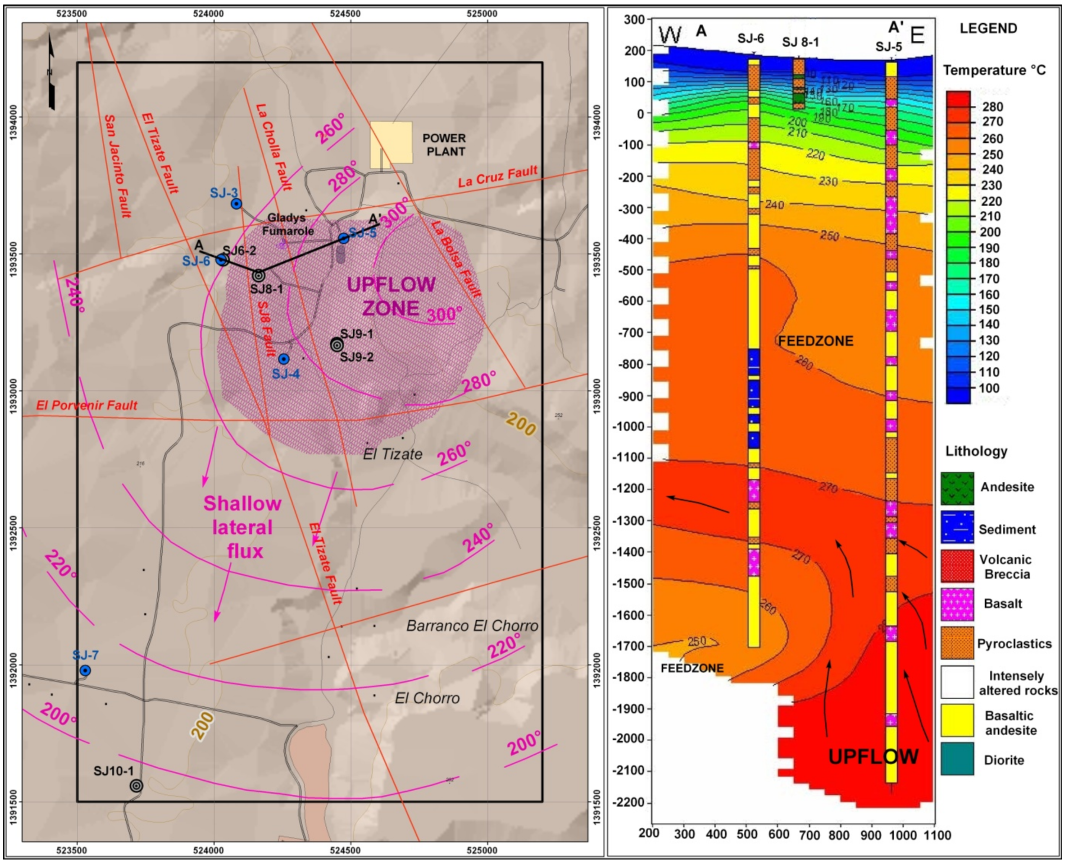

FIGURE 7: Map showing the area of geothermal reserves and the conceptual model of the San Jacinto – Tizate field

3.3.2 Parameter evaluation

The area was defined by taking into account the surface thermal manifestations, the interpretation of geophysical cross-sections and the area where the wells of the fields are located. The thickness of the reservoir was taken from the correlation of pressure and temperature profiles, obtained from recent drilling and existing wells. The minimum thickness was taken as the approximate area of ascent to 2000 m, and 3000 m as the maximum value (see Figure 7 and Table 5). The temperature of the reservoir was determined by the temperature and pressure profiles indicating that the reservoir temperature increases at depth and to the east, towards well SJ6-2, up to 303°C being the maximum temperature recorded in the reservoir.

The current study is to reassess the potential of the field using the Monte Carlo probabilistic volumetric method, explained above. The analysis is based on the conceptual model defined in previous studies and new information obtained from recently drilled wells. The field was evaluated as a liquid-dominate reservoir. The parameters used in the analysis are summarized in Table 5.

TABLE 5: Estimated probability distribution for Monte Carlo simulation of the San Jacinto – Tizate reservoir

Input parameters	Units	Probability distribution			
		Minimum	Most likely	Maximum	Type of distribution
Area	km^2	4	7	10	Triangular
Thickness	m	2000	2500	3000	Triangular
Rock density	kg/m^3	2620	2700	2900	Triangular
Porosity	%	8	12	15	Lognorm
Recovery factor	%	10	15	25	Triangular
Rock specific heat	kJ/kg°C	0.9	0.98	1	Triangular
Temperature	°C	265	300	320	Triangular
Fluid density	kg/m^3		705		f(temp.)
Conversion efficiency	%	10	13	14	f(temp.), triang.
Fluid specific heat	kJ/kg°C		5.76		f(temp.)
Plant life	years		25		Single value
Load factor	%	90	95	100	Triangular
Rejection temperature	°C		180		Single value

The recovery factor in the San Jacinto – Tizate was estimated as 15% for the calculation of thermal energy available in a volume of permeable and porous medium. This value could be changed in the future, in a new estimate of energy reserves. Currently estimated as a reservoir of porous medium, it is possible that the field trends toward fractured media.

3.3.3 Production capacity

The results obtained through simulations with the Monte Carlo volumetric model are shown in Figure 8. The results were obtained using the @RISK software (Palisade Corp., 2007) with 10.000 iterations to obtain the frequency distribution and the cumulative probability distributions that are shown in the figure.

The calculated parameters indicate that the estimated capacity of the whole San Jacinto – Tizate field has a mean value of 155 MW for 25 years, with a standard deviation of 45 MW. It can also be seen in the figures that the volumetric model predicts with 90% confidence that the estimated power production will be in the range of 91-237 MW for

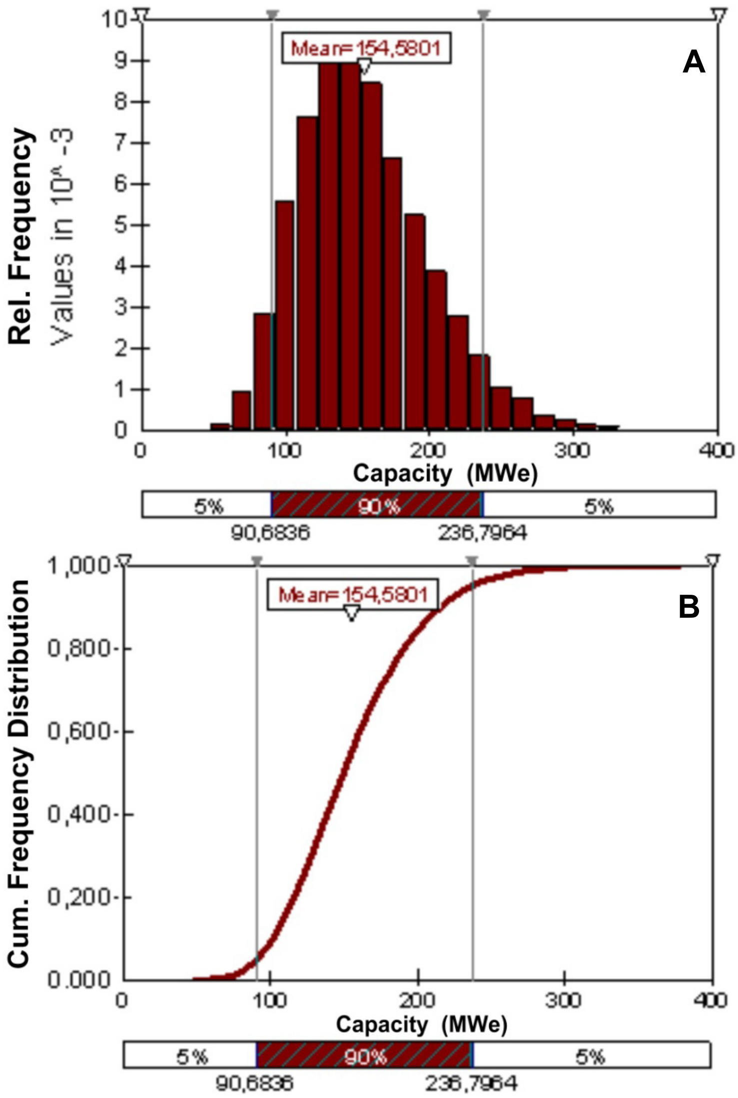

FIGURE 8: San Jacinto – Tizate field; a) Frequency distribution for electric power production; b) Cumulative probability distribution for electric power production

25 years. The cumulative probability distribution shows there is a 90% probability that the resource capacity will be at least 100 MW.

3.3.4 Comparison to previous study

The parameters evaluated for the San Jacinto – Tizate area are presented in Table 6, which compares the parameters used in both the current study and the assessment of 2001, and results for the power potential. The San Jacinto – Tizate is being reconsidered as being a liquid-dominated reservoir. Comparing the present results with the master plan from 2001, one can see that the difference is 6 MW. This is because the values of the parameters used for the calculation are almost the same, such as in area and the recovery factor. One could also say that the values assumed in the recent evaluation are somewhat more accurate due to data obtained with new methods and technology.

TABLE 6: Estimated probability distribution for Monte Carlo simulation in the San Jacinto – Tizate reservoir

Input parameters	Units	Master plan 2001			Present study			
		Min.	Most likely	Max.	Min.	Most likely	Max.	Type of distribution
Area	km^2	2.5	6.5	13	4	7	10	Triangular
thickness	m	2000		3000	2000	2500	3000	Triangular
Rock density	kg/m^3				2620	2700	2900	Triangular
Porosity	%	3		7	8	12	15	Lognorm, tria.
Recovery factor	%	10		20	10	15	25	Triangular
Rock specific heat	kJ/kg°C				0.9	0.98	1	Triangular
Temperature	°C	225		235	265	300	320	Triangular
Fluid density	kg/m^3					705		f(temp.)
Conversion efficiency	%				10	13	14	f(temp.), tri.
Fluid specific heat	kJ/kg°C					5.76		f(temp.)
Plant life	years		30			25		Single value
Load factor	%		90		90	95	100	Triangular
Rejection temperature	°C					180		Single value
Volum. heat capacity	$kJ/m^3/°C$		2,280					
Ejection temperature	°C		30					
Utilization factor	%		45					
Summary of results	**MW**		**161**			**155**		

4. OFFICIAL MONITORING OF GEOTHERMAL UTILIZATION

The objective of assessing national resources is to facilitate policy makers and authorities in decision making and licensing. It is thus important that resource assessments be regularly revised in accordance with recent studies, technical merit, protection, and energy prices, all with regard to the estimated reserves. Official monitoring is an important factor enabling relevant authorities to assess the geothermal systems under development. In this study the production capacity of two geothermal systems was revised from a previous official study using up-to-date information. This study has revealed that parameter estimation of previous studies is unclear in detail. For an official monitoring body, it is important to structure reports and assessments from the developer so as to facilitate the authorities in independently assessing a country's reserves.

According to the work of Steinsdóttir et al. (2009), the information which the developers in Iceland are obliged to hand in once a year to the official monitoring body includes:

i. The amount of geothermal fluid extracted from the geothermal reservoir each month (kg/s);
ii. The amount of geothermal fluid extracted from each well in the geothermal area each month (kg/s);
iii. The amount of fluid re-injected into the geothermal reservoir each month (kg/s);
iv. The temperature of the water re-injected into the geothermal reservoir each month (°C);
v. Results of water level measurements in wells in which the water level can be measured and are within the geothermal area (m);
vi. The pressure changes or drawdown determined in the geothermal reservoir (bar);
vii. The results of measurements of the enthalpy of the fluid from every production well in the geothermal area (kJ/kg);
viii. Chemical analyses of the geothermal water (and steam, if appropriate);
ix. Results from simulations of the geothermal reservoir;
x. Results of measurements made to monitor changes in the geothermal reservoir;
xi. Information on drilling in the industrial area;
xii. A resume of improved understanding of the physical characteristics of the geothermal reservoir based on the results of the latest drilling.

The data that should be turned in includes, information regarding wells as a construction, and information regarding wells and the geothermal heat as a resource.

Constructional information e.g.:
i. Location of the well (coordinate, place, area);
ii. Depth of well and casing;
iii. Drilling year.

Resource information e.g.:
i. Flow from the hole;
ii. Temperature of the well fluid;
iii. Locations of water veins in the well;
iv. Chemical combination of the well fluid;
v. Temperature and pressure in the geothermal reservoir.

For the official monitoring bodies in Nicaragua, i.e. the Ministry of Energy and Mines (MEM) and the Ministry of Environment and Natural Resources (MARENA), structured reporting from the developers can facilitate estimates of reserves. Regular reassessment of reserves in the country is then easier to execute.

5. CONCLUSIONS AND RECOMMENDATIONS

The methodology in the master plan 2001 was used to assign priority levels to different areas studied. In the assessment of 2001 a variation of the principles governing the calculation of heat stored in a geothermal system were considered and evaluated to get an idea of the amount of available energy stored in a geothermal system and the amount of electricity that could be converted from the recoverable heat.

The volumetric method with Monte Carlo simulation has demonstrated the validity of its application to geothermal systems but depends to some extent on the quality of information on the values assigned to parameters.

For Casita – San Cristobal area, the analysed data are the result of surface exploratory studies and should be checked once deep exploratory wells are drilled. Therefore, the uncertainty in the results obtained in the calculation of energy reserves is considerable. The conceptual model shows a possible two-phase reservoir in the Casita field and another liquid-dominated reservoir in the La Pelona field. For this reason the two resources were evaluated separately and then the results were combined for the entire field.

The calculated parameters indicate that the estimated capacity of the entire Casita – San Cristóbal resource has a mean value of 114 MW for 25 years, with a standard deviation of 42 MW. The volumetric model predicts with 90% confidence that the estimated power production is in the range of 53-188 MW for 25 years and the cumulative probability distribution shows there is a 90% probability that the resource capacity is at least 70 MW.

The San Jacinto – Tizate field was reassessed as a liquid-dominated reservoir. The calculated parameters indicate that the estimated capacity of the San Jacinto – Tizate field has a mean value of 155 MW for 25 years, with a standard deviation of 45 MW. The volumetric model predicts with 90% confidence that the estimated power production is in the range of 91-237 MW for 25 years and the cumulative probability distribution shows there is a 90% probability that the resource capacity is at least 100 MW.

The volumetric assessment of 2001 predicted a power capacity of 224 MW for 30 years for the Casita – San Cristóbal resource and 161 MW for the San Jacinto – Tizate resource. The difference of only 6 MW for the San Jacinto – Tizate geothermal field is due to the similarity of the parameter values used in the calculations in both cases. The difference in the results of the two assessments for the Casita – San Cristóbal geothermal field is due to the values assigned to the most sensitive parameters in the calculation, the reservoir area, the recovery factor, the thickness of the reservoir and the reservoir temperature.

It is important to update the data fields when additional studies are available to enable a better understanding of the behaviour of the reservoir and to assign the most likely values to the parameters in the calculation of the energy resource.

It is recommended that the estimated power production capacity of the Casita – San Cristobal field will be updated after drilling of exploratory wells in the area.

For the San Jacinto – Tizate field it is recommended to estimate the power production capacity with a numerical model, which is more accurate than the volumetric model, since historical production data is available and new well data has been obtained with improved methodology and technology.

ACKNOWLEDGEMENTS

My sincere gratitude is expressed to the Government of Iceland, the United Nations University Geothermal Training Programme and the Government of Nicaragua, for giving me the opportunity to participate in this training. My heartfelt gratitude goes to Dr. Ingvar B. Fridleifsson and Mr. Lúdvík S. Georgsson for their support in completing this training. I also thank very much Ms. Thórhildur Ísberg, Ms. Dorthe H. Holm and Mr. Markús A.G. Wilde for their support during these 6 months.

Sincere thanks to my supervisors, Mr. Jónas Ketilsson and Mr. Benedikt Steingrímsson for their excellent guidance. I also want to thank Ms. Saeunn Halldórsdóttir for providing excellent help and assistance, and Mr. Ari Ingimundarson for reading the paper and giving me good suggestions. I am grateful to the UNU fellows for their support over the last six months.

I extend my thanks to my boss, Magdalena Pérez, for her support and confidence in me. I want to especially thank my family for their invaluable support in my absence. Finally, I want to thank and dedicate this work to the most important person in my life, my son Luis Demetrio, for his understanding and sacrifice during these long six months.

REFERENCES

Carslaw, H.W., and Jaeger, J.C., 1959: *Conduction of heat in solids* (2nd Edition). Clarendon Press, Oxford, 510 pp.

CNE, 2001: *Geothermal master plan of Nicaragua.* National Energy Commission, vols. I, II, III, V.

DAL SpA, 1995: *San Jacinto – Tizate geothermal project, feasibility report, Vol. 1, risk assessment and engineering.* Nicaraguan Electricity Company (ENEL), Managua, Nicaragua, DAL SpA, Milano, Italy, report.

Lachenbruch, A.H., 1957a: Thermal effects of the ocean on permafrost. *Geological Society of America Bulletin, 68,* 1515-1530.

Lachenbruch, A.H., 1957b: Three dimensional heat conduction in permafrost beneath heated buildings. *US Geological Survey, Bulletin, 1052-B,* 51-69.

Lovering, T.S., 1935: Theory of heat conduction applied to geological problems. *Geological Society of America, Bulletin, 46,* 69-94.

Muffler, L.P.J. (editor), 1979: *Assessment of geothermal resources of the United States - 1978.* USGS Circular 790, Arlington, VA.

Ostapenko, S.V., Spektor, S.V., and Netesov, Y.P., 1998: San Jacinto – Tizate geothermal field Nicaragua: Exploration and conceptual model. *Geothermics, 27,* 361-378.

Palisade Corp., 2007: *@RISK program and decision tools suite. Risk analysis, decision analysis and statistical analysis.* Palisade Corporation

Sanyal, S.K., and Sarmiento, Z.F., 2005: Booking geothermal energy reserves. *Geoth. Resourc. Council, Trans., 29,* 467-474.

Sarmiento, Z.F., 2008: Geothermal resource evaluation: Key elements. In: Georgsson, L.S., Holm, D.H., Simiyu, S.M., and Bahati, G. (eds.), *Short course on Geothermal Project Management and Development*. UNU-GTP, KenGen, DGSM, CD SC-08, 11 pp.

Sarmiento, Z.F., and Steingrímsson, B., 2008: Computer programme for resource assessment and risk evaluation using Monte Carlo simulation. In: Georgsson, L.S., Holm, D.H., Simiyu, S.M., and Bahati, G. (eds.), *Short course on Geothermal Project Management and Development*. UNU-GTP, KenGen, DGSM, CD SC-08, 11 pp.

Sarmiento, Z.F., and Steingrímsson, B., 2007: Review on estimated power potential and realistic development of geothermal resources in leading geothermal countries. In: Fridleifsson, I.B., Holm, D.H., Henriquez, J.L, Torio, E.C. (eds.), *Short course on Geothermal Development in Central America: Resource Assessment and Environmental Management.* UNU-GTP, LaGeo, CD SC-04, 11 pp.

SKM, 2002: *Structural study of the Casita geothermal field.* Sinclair Knight Merz, unpublished report for Sajenco, February.

SKM, 2005: *Casita geothermal prospect. Scientific assessment.* Sinclair Knight Merz, unpublished report for Triton Power S.A., June.

SKM, 2007: *Geology and petrology report on well SJ8-1.* Sinclair Knight Merz, unpublished report for Polaris Energy Nicaragua S.A., November.

SKM, 2008 a: *Geology and petrology report on well SJ9-1.* Sinclair Knight Merz, unpublished report for Polaris Energy Nicaragua, February.

SKM, 2008 b: *Geology and petrology report on well SJ9-2.* Sinclair Knight Merz, unpublished report for Polaris Energy Nicaragua S.A., April.

SKM, 2008 c: *Geology and petrology report well SJ10-1.* Sinclair Knight Merz, unpublished report for Polaris Energy Nicaragua, San Jacinto – Tizate geothermal power project. April.

SKM, 2008 d: *Geology and petrology report on well SJ6-2.* Sinclair Knight Merz, unpublished report for Polaris Energy Nicaragua S.A., April.

Steinsdóttir, G., Kristjánsson, S., and Ketilsson, J., 2009: *Public monitoring of geothermal utilisation: lessons learned in Iceland considered for geothermal development in Nicaragua.* Orkustofnun, Reykjavík, prepared for ÍSOR – Iceland GeoSurvey, report OS-2009/006, 41 pp.

Weinberg, R., 1992: Neotectonic development of western Nicaragua. *Tectonics, 11,* 1010-1017.

Williams, C.F., 2007: Updated methods for estimating recovery factors for geothermal resources. *Proceedings of the 32nd Workshop on Geothermal Reservoir Engineering, Stanford University, California,* SGP-TR-183, 7 pp.