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ASSESSMENT OF THE NORTHERN PART OF THE LOS AZUFRES GEOTHERMAL FIELD, MEXICO, BY LUMPED PARAMETER MODELLING AND MONTE CARLO SIMULATION

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ABSTRACT

The Los Azufres geothermal system is located in the State of Michoacán 80 km east of the city of Morelia and 16 km northwest of Ciudad Hidalgo. It was explored in the mid 1970's and it has been in development since then. At the present time, the Los Azufres is generating 188 MWe and in order to increase its potential it is needed to update the assessment of the area. In the present work, the actual potential of the northern part of the Los Azufres is assessed. The formation temperature of the northern part of the Los Azufres geothermal field was estimated and the thermodynamic parameters were gathered to estimate the potential energy of the field using Monte Carlo simulation. The result shows that there is a 90% probability that the field can sustain a production of 290 MWe for a period of 20 years, 230 MWe for a period of 25 years and 190 MWe for a period of 30 years.

To assess the consequences of such a production increase on the pressure of the Los Azufres system another method called lumped parameter modelling was used. To account for the reinjection, tracer information is used to estimate the amount of water that is recharging the production zone and by subtracting that amount from the total production we get the effective production that is going to be used in the model. The results of the lumped parameter modelling predict a substantial drawdown in pressure for production scenarios of 400 kg/s and 500 kg/s equivalent to approximately 125 and 155 MWe generation, respectively. Comparing the outcomes with previous works, lower values are obtained for the power capacity of the area, which is mainly due to the area chosen being smaller. Also the conservative values used to determine the effect on the production due to injection could cause an overestimation of the pressure response of increased production.

1. INTRODUCTION

1.1 The Los Azufres geothermal field

Mexico is located in Latin America. The coordinates that frame the Mexican territory are to the south N14° 32´ 27´´ on the border with Guatemala, and to the north it is N32° 43´ 06´´ on the border with the United States of America. To the east it is W86° 42´ 36´´, at Isla Mujeres and to the west W118° 22´ 00´´, in the Elephant Rock Island, Pacific Ocean.

Mexico has different sources of energy, including geothermal energy, which is regarded as a clean and renewable energy. Geothermal power production has grown over the years and plays an important role in green power generation as it is called now. In addition it contributes in reducing the greenhouse gas emission and counteracts global climate change. Mexico has four geothermal fields in production: Cerro Prieto, Los Humeros, Las Tres Vírgenes and the one that is discussed here, the Los Azufres which is inside of the Trans-Mexican volcanic belt that stretches in an east-west direction over the southern part of the country (Figure 1).

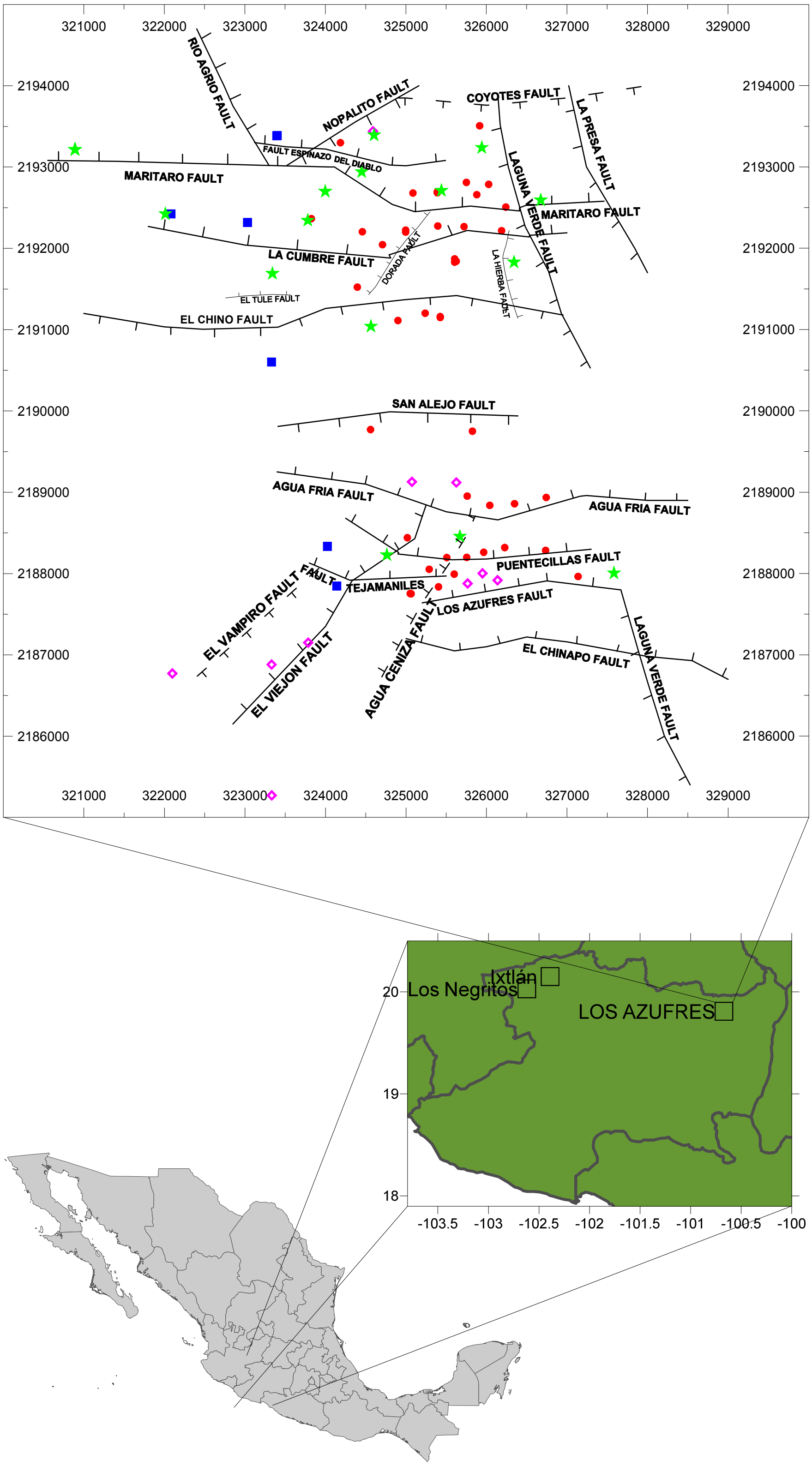

FIGURE 1: Location of the Los Azufres, Michoacán

The Los Azufres geothermal system is located in the State of Michoacán, 80 km east of the city of Morelia and 16 km northwest of Ciudad Hidalgo. The geothermal field was explored in the mid 1970's and since 1982 it has been in development. The natural state was classified as a conventional liquid-dominated high-temperature system but during exploitation several thermodynamic studies have shown that the reservoir now has three zones: dominant vapour in the upper reservoir, liquid saturation in the middle and compressed liquid in the bottom part of the reservoir. The field is located at an altitude above sea level ranging from 2500 to 3000 m, surrounded by valleys.

At the present time the Los Azufres geothermal field has 39 production wells and 6 injections wells producing 14.7

million tonnes of vapour and generating 188 MWe. From the southern part, 93 MWe come from one condensing unit of 50 MWe, one condensing unit of 25 MWe, 3 back-pressure units of 5 MWe each and 2 binary units of 1.5 MWe each. And 95 MWe come from the northern part from 3 condensing unit of 25 MWe each and 4 back-pressure units of 5 MWe each.

1.2 Previous assessments

During the life of the Los Azufres geothermal field it has been evaluated several times, due to the significance of the site, using different approaches. In a paper from 1990, Viggiano and Lopez describe the volume of the liquid available in the northern part of the Los Azufres using the software surfer, the porosity of the site, the isotherms and a proper interpretation of hydrothermal mineralogy. Another volumetric assessment was made using three different methodologies; the first one called "the short method" consists of a total energy assessment available through the simultaneous solution of the equations of mass and energy. The second, called "the rigorous method" is based on the solution of the equations of mass and energy using an iterative algorithm which assesses the thermodynamics of the field with respect to differential pressure. The third and last method, called "the approximate method" is based on calculating the theoretical amount of mechanical work that can be obtained from the total heat content in the reservoir in its initial condition, through the exergy (Flores, 1994).

More complicated assessments have also been made that take into account the adiabatic expansion of the water, expansion with heat transfer fluid-rock, expansion with recharge (Flores, 1995). Or they are based on detailed numerical models, which require a large amount of information in the different disciplines of geothermal energy (geology, geophysics, geochemistry, etc.) and also have a complexity which requires a lot of time for processing (GeothermEx, 2003).

1.3 The work presented here

The Los Azufres geothermal field has been in exploitation for around three decades. This long period of exploitation has carried some problems of decline of the temperature and pressure. Even though the geothermal resource is renewable and sustainable we need to find a balance in where the extraction of the energy is at least equal or less than the time that the system needs for its recovery. Due to the common confusion of the terms "renewable" and "sustainable" in literature and papers, Axelsson et al. (2001) have proposed the following definition for the term "sustainable production of geothermal energy from an individual geothermal system".

*For each geothermal system, and for each mode of production, there exists a certain level of maximum energy production, E_0, below which it will be possible to maintain constant energy production from the system for a very long time (100-300 years). If the production rate is greater than E_0 it cannot be maintained for this length of time. Geothermal energy production below, or equal to E_0, is termed **sustainable production** while production greater than E_0 is termed **excessive production.***

As mentioned above, the amount of energy storage in a geothermal system is not known a priori so methods or techniques are needed to estimate its potential, such as volumetric methods, simple analytical modelling, lumped parameter modelling and detailed numeric modelling, etc. In this work, based on the information available, the production potential of the north part of the Los Azufres will be assessed by using the Monte Carlo volumetric assessment method. This assessment is done for 20, 25 and 30 years of production. In addition, based on pressure profiles and monitoring data, some properties of the reservoir and pressure variation in the future are also estimated by using a lumped parameter model.

2. MONTE-CARLO VOLUMETRIC ASSESSMENT

2.1 Geological settings and the area estimation

The geology of the Los Azufres geothermal field has been studied extensively for about 3 decades by geological exploration and other surface studies and analysis of cores and cuttings from the wells and other borehole studies, etc. Due to its location inside the Trans-Mexican volcanic belt and its linkage to the young volcanism of the area, the rock units observed in the Los Azufres geothermal field are of volcanic origin, consisting mainly of lavas, pyroclastic deposits and volcanic sediments.

The area of the northern part of the Los Azufres geothermal field as defined from resistivity measurements (Figure 2) covers 20 km^2. The surface manifestations of geothermal activity are distributed widely within and around the field, but the main events are grouped within it. Most springs are thermal hot springs of acid-sulphate composition, while some springs located around the periphery of the field are of sodium-chloride type.

The reservoir rocks are fractured andesites, and perhaps other types of rock within the unit Mil Cumbres or andesite Mil Cumbres. The fractures which cause the permeability can be the result of a combination of tectonic, hydrothermal and deposition mechanisms. The position and shape of both sectors of the geothermal reservoir seem to be associated with faults that occur along major structural trends of the area, especially the trends E-W (seem to be the most important) and NE-SW. These are two of the three main structures in the field, the third is NW-SE and the order from old to young is as they are mentioned. Some faults in these groups probably play a role in the increased permeability of the reservoir in the productive zones of the field, however, they could also play a role in forming the lateral boundaries of the field.

Hydrothermal alteration in the Los Azufres field is typical for a high-temperature geothermal system of volcanic origin. Secondary minerals found include clay minerals, calcite, chlorite, pyrite, quartz,

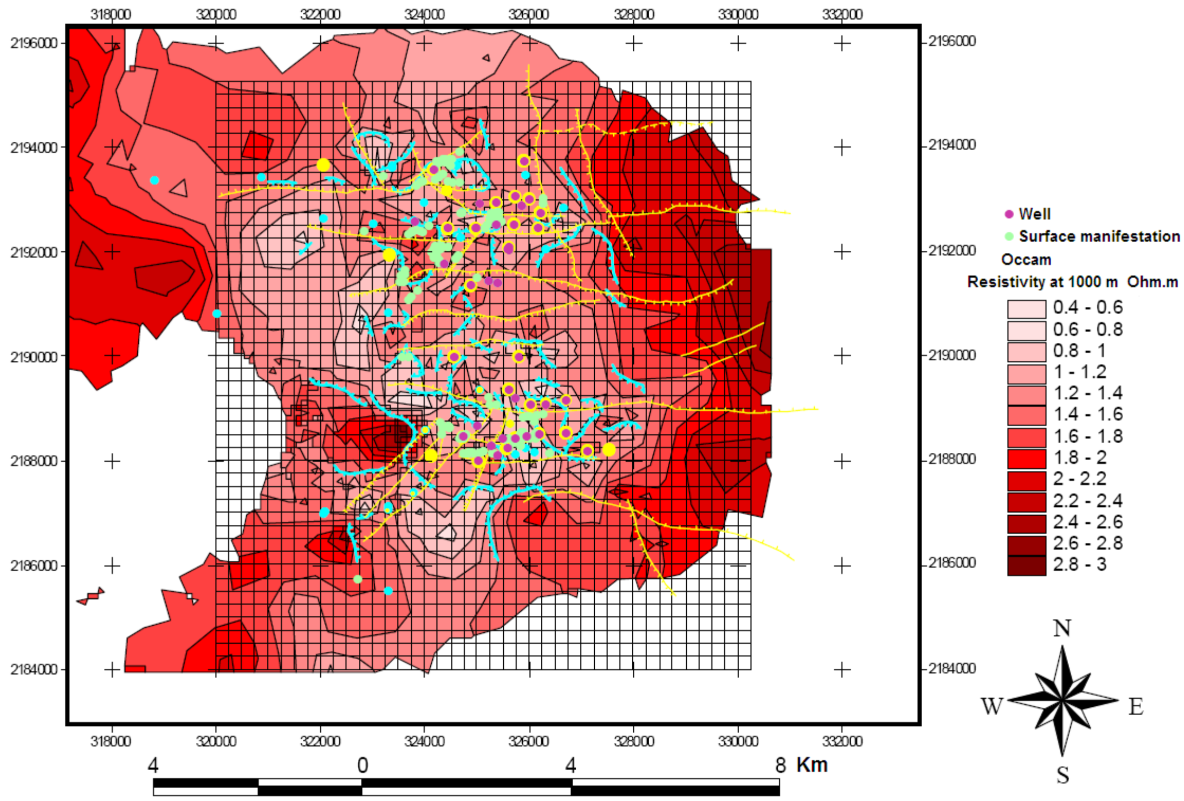

FIGURE 2: Resistivity map at 1000 m depth in the Los Azufres geothermal field (García, 2005)

epidote, hematite and other oxides and hydrothermal amphibole. It is found that the appearance of epidote correlates with formation temperatures near 250°C, whereas the first appearance of amphibole tends to coincide with temperatures approaching 300°C (GeothermEx, 2003).

Further geophysical studies have been conducted in the Los Azufres such as gravity, passive seismic surveys, and geoelectric studies, including vertical electrical soundings and magneto-telluric. Of these methods, the geoelectric studies have been of most direct use to delineate the productive geothermal fields; especially, the distribution of a low-resistivity area has been used to delineate the extent of the geothermal reservoir (Figure 2). This is a reasonable interpretation, considering the good correlation between the resistivity structure and the position of field. Here, the area enclosed by surface manifestations is used as the minimum value for the system area, while the low-resistivity area is used as the maximum value for the geothermal area for the Monte Carlo simulation.

With the information obtained from geology and geophysics, the area to be assessed for its potential is chosen. Three different areas are shown in Figure 3 which represent, the maximum, the most likely and the minimum areas. These are going to be used as input parameters for Monte Carlo simulation. The smallest area is 14 km^2 (4 × 3.5 km) and covers all the geothermal surface manifestations, the maximum area is estimated from resistivity map at 20 km^2 (5 × 4 km) and the most likely area is estimated at 17.5 km^2 (5 × 3.5 km).

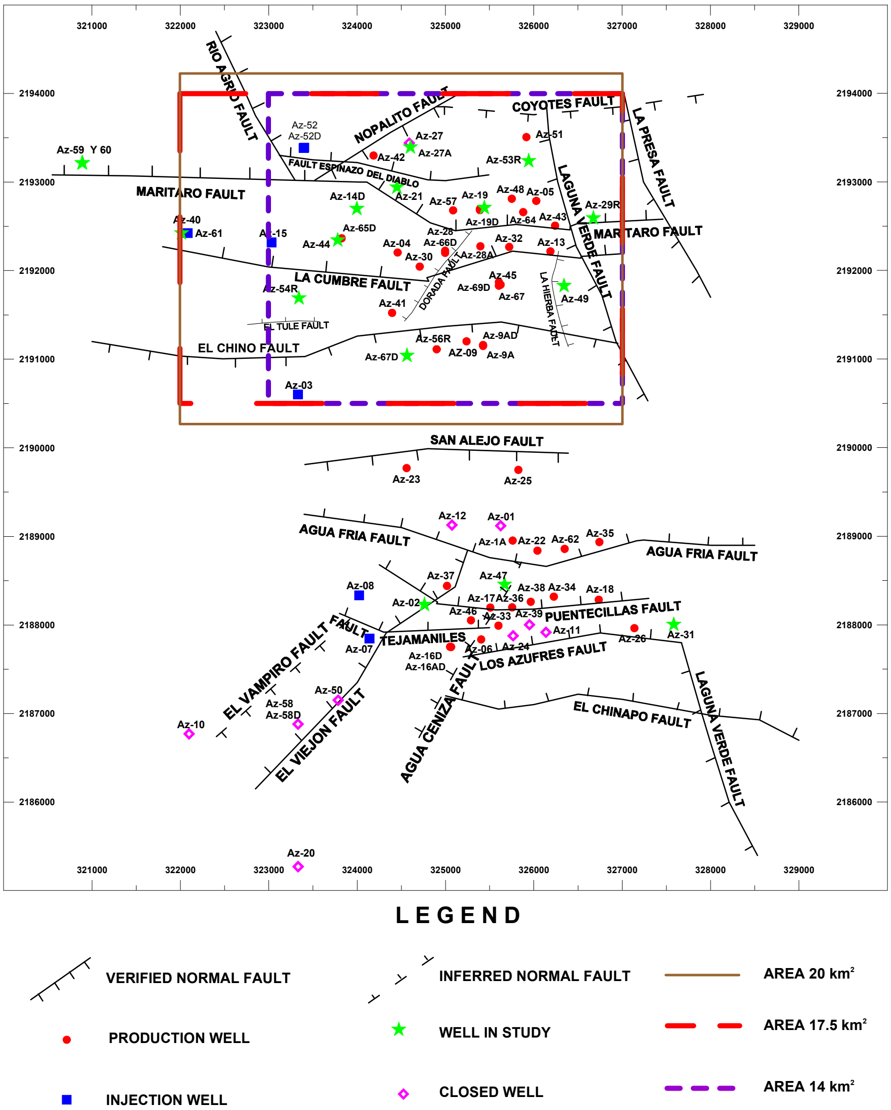

FIGURE 3: Location of the wells in the Los Azufres geothermal field and areas chosen as input parameters for the Monte Carlo simulation

2.2 Formation temperature

When the area of the northern part of the Los Azufres has been assessed, it is necessary to know the formation temperature to estimate the thermal energy that can be utilized on the surface. The temperature profiles of all the wells in the northern part of the Los Azufres were obtained from the

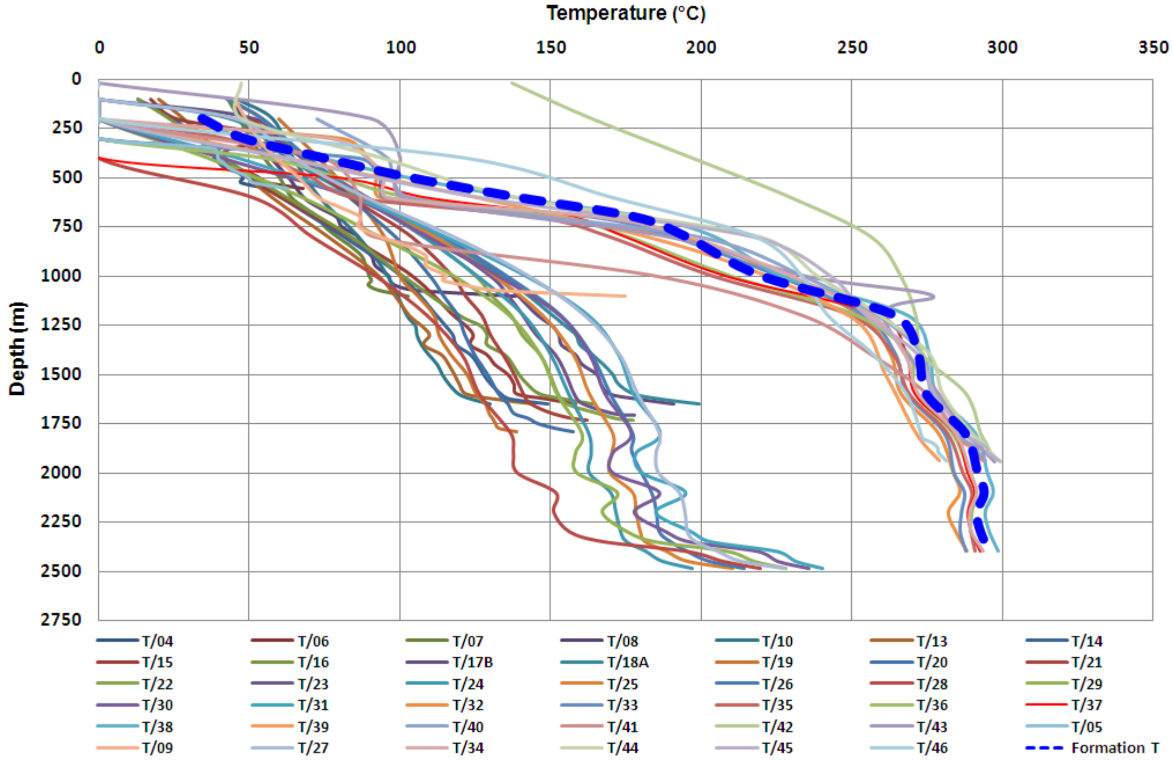

FIGURE 4: Temperature logs from well Az-049

data base *Vulcan Geodata Manager*. The temperature data for each of the wells was graphed to identify or choose the most representative graphs to describe the formation temperature.

Some of the formation temperatures were estimated with the Horner method, while for others the formation temperatures are taken into account, that were estimated for the numerical model made in 2006 for the feasibility study of the Los Azufres III realized by West JEC. The wells that were chosen to represent the estimated area were the Az-03, Az-04, Az-05, Az-09, Az-13, Az-19, Az-28, Az-32, Az-40 and Az-49. The estimated formation temperatures of these wells were used to estimate the temperature range of the system. Figure 4 shows the formation temperature of well Az-49. Once the formation temperatures had been estimated, they were used as input for the method discussed below.

2.3 Method applied

There are different methods to estimate the maximum and minimum thermal energy of a reservoir based on the laws of conservation of mass and energy. The traditional volumetric method is chosen for estimating the thermal energy of the system. The reservoir is normally considered in the volumetric calculations as one body or it is divided into layers and these subdivided into blocks. Each block contains one unique value for each parameter assigned; the main ones being the temperature,, porosity, area, thickness, density and heat capacity of the fluid and rock matrix. In the evaluation of the system, the energy stored in each block is calculated and then summed to obtain the total energy of the reservoir. However, due to the limited number of blocks or layers allowed in this division of the whole reservoir and the use of a constant value in each subsection in calculation, the final results of the traditional volumetric method are often questionable in practice. However, the quantification of the uncertainties in the parameters of the probability distributions can be dealt with quite well by using the Monte Carlo simulation method (Guo Gaoxuan, 2008).

The Monte Carlo (MC) method uses stochastic techniques that are based on the use of random numbers and probability statistics to investigate problems. This method is often used when the model is complex, nonlinear or involves more than just a couple of uncertain parameters. The method uses different approaches but all of them tend to follow a particular pattern. The main requirement to use the Monte Carlo method for simulation of a physical system is that it must be possible to describe the system in terms of a probability density function (PDF). This method determines how random variation, lack of knowledge or error affects the sensitivity, performance or reliability of the system that is being modelled. In other words, it quantifies the uncertainties of the parameters as probability distributions.

In the development of this assessment the reservoir is classified as a box, where the volume is the product between the surface area A in the xy plane and the height (thickness) $z_1 - z_0$ along the z-axis, where z_1 and z_0 are the lower and upper limit of the geothermal system, respectively.

When the volume of the geothermal system has been assessed, the choice has to be made on how to calculate the useable heat that the system contains. For simplicity it can be assumed that the heat capacity and temperature are homogeneous in the xy-plane and are only dependent on depth. The heat content of the system can then be calculated by intergrading the product of the estimated heat capacity per unit-volume $C(z)$ and the difference of the estimated temperature curve $T(z)$ in the system and the cut-off temperature T_0. The cut-off temperature is the temperature of the state from which the heat is integrated from. This can be the outdoor temperature, minimum temperature for electric production, absolute zero temperature etc. The choice of $T(z)$ depends on how one is to calculate the usable energy. The heat energy contained in the geothermal system is calculated with the following equation (Hjartarson et al., 2008):

$$Q = A\int_{z_0}^{z_1} C(z)[T(z) - T_0]dz \tag{1}$$

C is assumed to be homogenous for the whole system and is written as:

$$C = c_r(1-\phi)\rho_r + c_w\phi\rho_w \tag{2}$$

here c_r and c_w are the specific heat of the rock and the water respectively, ρ_r and ρ_w the density of the rock and water, respectively, and ϕ is the porosity.

$T(z)$ is a nonlinear temperature curve that follows a curve shaped like the boiling point curve (Figure 5), and is of the form:

$$T(z) = x \cdot 69.56(z + z_{Delta})^{0.2085} \tag{3}$$

where x is a ratio factor that goes from 0 to 1 and indicates the deviation from the boiling curve and z_{Delta} is transformation in the z direction in order to fulfil the upper boundary conditions, T_{z0} at z_0 (Hjartarson et al., 2008).

There are two way of calculating Equation 1. One is to consider $T(z)$ as a constant mean temperature over the whole depth, but only if the temperature curve seems to be linear. The other is to integrate over the temperature curve if it is believed that the temperature curve is nonlinear. In this case the second method is used. Solving for Equation 1 gives:

$$Q = AC\left[x\frac{69.56}{1.2085}\{(z_1 + z_{Delta})^{1.2085} - (z_0 + z_{Delta})^{1.2085}\} - T_0(z_1 + z_0)\right] \tag{4}$$

Since not all the heat energy contained in the geothermal system can be extracted to the surface, the estimated heat energy is reduced by a recovery factor (R) which is the ratio of the heat which is

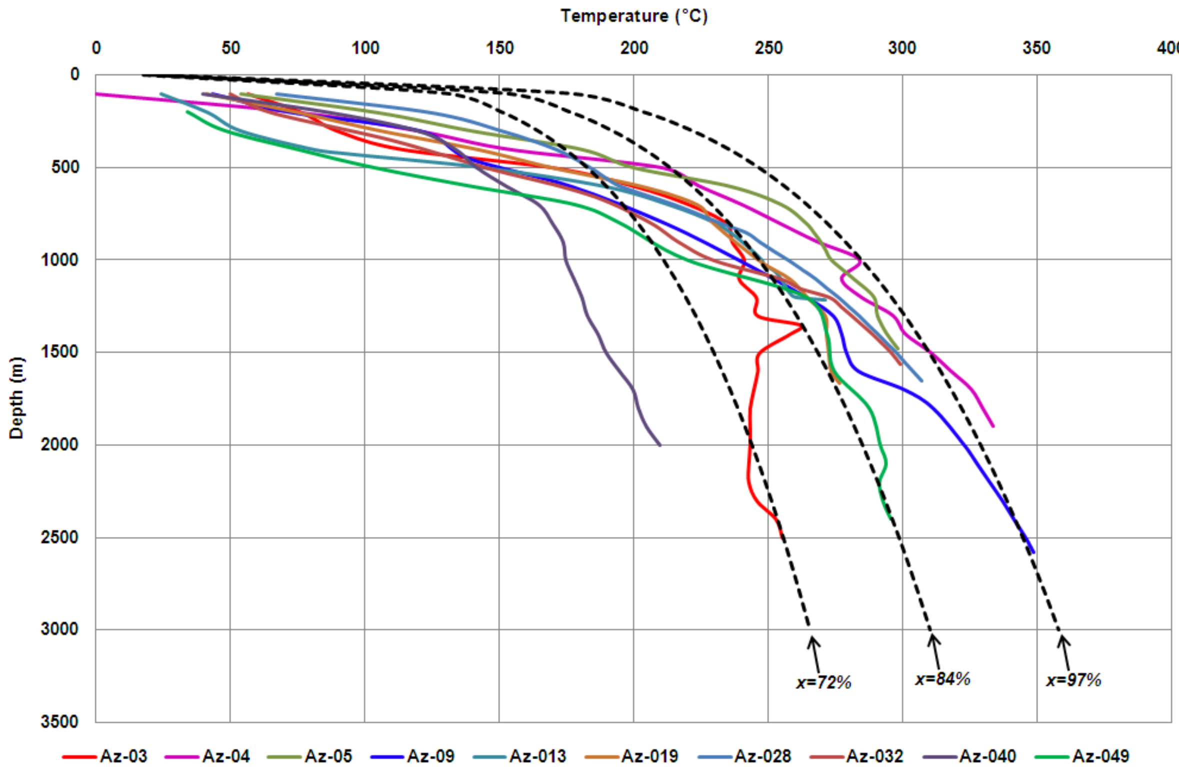

FIGURE 5: Formation temperature (solid lines) and three temperature curves (dotted lines); the values for the different ratios of the boiling curve are 72% for the minimum, 84% for the most likely and 97% for the maximum value

recoverable. And since not all recoverable energy can be transformed into electric energy, the electric utilization constant η_e is defined and gives the electric energy, Q_e as:

$$Q_e = QR\eta_e \tag{5}$$

Then for the electric power, P:

$$P = \frac{Q_e}{t} \tag{6}$$

where P is the power potential in MWe and t is time in years (economic life).

The existent conceptual model in the area was analysed to determine the thermodynamic and petrophysical parameters. Like mentioned before, the formation temperatures are estimated from the temperature profiles of the wells in the northern zone of the Los Azufres (see Figure 5). The area was defined smaller than in previous works based on the results of geophysical resistivity measurements and on the temperatures profiles in the area. The thickness of the reservoir was defined based on the first appearance of epidote, as top of the reservoir and the first appearance of the mineral amphibole as the base of it. Other parameters such as porosity, density, specific heat of the rock, etc. were selected from measurements from cores of different wells (Flores, 1994). The cut-off temperature and the electric conversion coefficient were fixed to 180°C and 12%, respectively (Grant et al., 1982).

Once the minimum, maximum, and most probable values are assigned for each parameter, they define a distribution function (Table 1). This is done because of the uncertainty of the variables and is preferred over the usual deterministic approach which assumes a single value for each parameter to represent the whole reservoir. Instead of assigning a “fixed” value to a reservoir parameter, numbers within the range of the distribution model are randomly selected and drawn for each cycle of calculation over thousand iterations. A Monte Carlo simulation handles this complex scenario which allows extraction of each uncertain variable within the span of the minimum, most likely and maximum value (triangular distribution). The random sampling and calculations are done for thousands of iterations and each result is sent to be compiled for the frequency distribution. Knowing the range of the minimum, most likely and maximum values from the various input parameters, the risk and the probability of occurrence can be evaluated when a decision has been made on the generation level (Sarmiento and Steingrímsson, 2008).

TABLE 1: Best values and the probability distribution used in calculation

Parameters	Variable	Distribution type	Minimum value	Most probable value	Maximum value
Surface area	A	Triangular dist.	14 km^2	17.5 km^2	20 km^2
Upper depth	z_0	Constant	N/A	600 m	N/A
Lower depth	z_1	Constant	N/A	2600 m	N/A
Boling curve ratio	x	Triangular dist.	72%	85%	97%
Cut-off temperature	T_0	Constant	N/A	180 °C	N/A
Porosity	f	Triangular dist.	9%	10%	15%
Specific heat of rock	c_r	Constant	N/A	2.5 (kJ/kg°C)	N/A
Density of rock	r_r	Triangular dist.	2680 kg/m^3	2700 kg/m^3	2720 kg/m^3
Specific heat of water	c_w	Constant	N/A	4.2 (kJ/kg°C)	N/A
Density of water	r_w	Constant	N/A	826 kg/m^3	N/A
Recovery factor	R	Triangular dist.	9%	10%	11%
Electric conversion coefficient	η_e	Constant	N/A	12%	N/A
Production time	t	Constant	N/A	20/25/30 years	N/A

2.4 Results

The results of the volumetric calculations using Monte Carlo simulation are presented as a discreet probability distribution and as a cumulative probability distribution, in Figures 6 and 7, respectively. For this study three operational scenarios were used: a generation period of 20, 25 and 30 years. Each figure consists of 100,000 random outcomes. From these results different statistical parameter can be calculated, like the most likely values, 90% confidence interval, mean and median outcomes, standard deviation and where the 90% limit for the cumulative probability lies. These statistics for the three production periods are presented in Table 2.

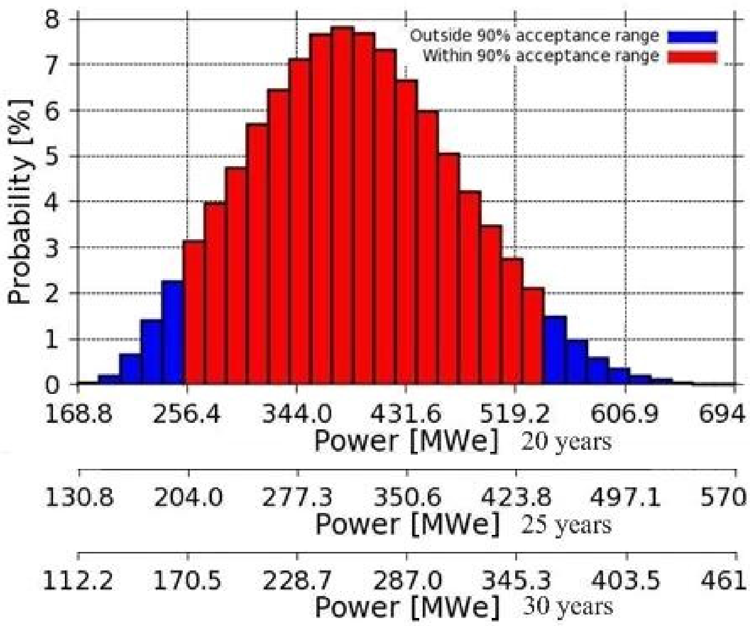

FIGURE 6: The probability distribution for possible electric power generation in MWe; the width of each column corresponds to 16.5 MWe for 20 years, 13.7 MWe for 25 years and 11.4 MWe for 30 years

From the probability distribution in Figure 6, it can be seen that the most probable values (with a probability of 7.8%) for the electrical power capacity lie between about 370 and 390 MWe for a period of 20 years, between

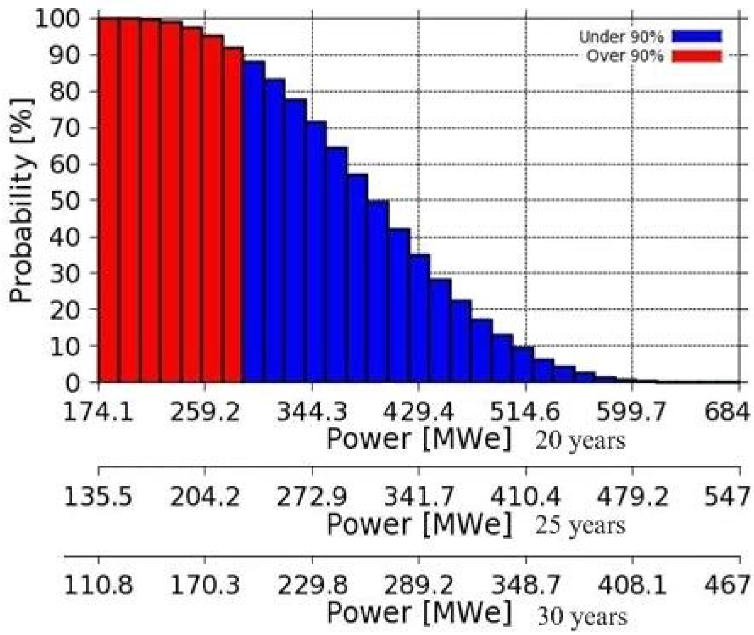

FIGURE 7: Cumulative probability distribution for possible electricity power generation in MWe with each column having the same width as given for Figure 6; each column represents the probability that the result is in or below the interval of the column

300 and 315 MWe for a period of 25 years and between 250 and 260 MWe for 30 years. It is also seen that the volumetric model predicts with 90% confidence that the power production lies between 250 and 540 MWe for 20 years, between 200 and 430 MWe for 25 years and between 170 and 360 MWe for 30 years.

From the cumulative probability distribution in Figure 7 it can be seen that the volumetric model predicts with 90% probability that at least 290 MWe can be produced for a production period of 20 years, at least 230 MWe for 25 years and at least 190 MWe for 30 years. This study presents lower values than previous volumetric analyses and this is caused by the area selected being smaller. For further studies, the analysis should include the north and northwestern part of the field. Worth mentioning here is that if effective reinjection will be applied during utilization to supplement natural recharge higher values for the recovery factor can be used, raising the production capacity estimated.

TABLE 2: Statistical parameters for the probability distribution for electric power production (MWe) for the northern part of the Los Azufres field, estimated by Monte Carlo method

	Production for 20 years	**Production for 25 years**	**Production for 30 years**
7.8% probability	372.2-389.1	301.2-315.4	249-260.4
90% confidence interval	253.5-541.8	201.6-428.5	168.6-360.3
Mean	389.4	311.4	259.7
Median	386.8	309.8	258.1
Standard deviation	82.8	66.2	55
90% limit	289.4	228.6	191.4

3. LUMPED PARAMETER MODEL

3.1 General

One of the main tools for efficient management of a geothermal field is modelling. It seeks to study the behaviour of a phenomenon, in our case the geothermal system, and obtain its properties in the natural state and during the life of utilization. Once the system has been modelled, the model is used to predict this behaviour with different scenarios of future exploitation and with those actions choose the best option for utilization of the geothermal energy as well as estimate the production potential of the system.

There are different techniques that can be used to model geothermal systems and that currently are used by the scientific community. These approaches implicate a mathematical model being developed that simulates most of the physicochemical and thermodynamic properties of the geothermal system involved. These can be simple analytical models, lumped parameter models or detailed numerical models (Axelsson et al., 2005). The most convenient method, for a particular modelling study, is determined by the available data as well as the objectives of the study. In situations where available funds, field data and time are limited, detailed modelling may not be feasible. Lumped parameter modelling is in such cases a viable alternative (Axelsson, 1989).

In this paper lumped parameter modelling will be used, being an effective technique that has been utilized successfully for different geothermal systems in the world (such as in China, Turkey, Eastern Europe, Central America, Iceland and The Philippines). It focuses on the pressure response of the system in terms of its production. This method tackles the simulation problem as an inverse problem. It automatically fits analytical response functions of lumped models to the observed data by using a non-linear iterative least-squares technique for estimating the model parameters (Axelsson, 1989). The theoretical background of this method will briefly be presented, but the details are given by Bodvarsson and Axelsson (1986) and Axelsson (1985).

3.2 Theory

Lumped parameter modelling is usually based on the production history of a geothermal system and used to simulate the available pressure (or water level) decline history, preferably from a centrally located observation well. The aim is to end up with two models, one open and the other closed, that simulate the data accurately. The closed and open model results are the optimistic and pessimistic extremes of lumped parameter modelling. It is likely that the real behaviour of a reservoir is somewhere between these two simulated responses (Rezvani-Khalilabad and Axelsson, 2008).

The main basic components of lumped models are a tank (capacitor) κ that simulates the storage in a reservoir and a resistor (conductor) σ that simulates the flow resistance in the reservoir, controlled by the permeability of its rocks. The parameter κ manifests the storage mechanics that are controlled by the liquid/formation compressibility or the surface mobility and response to a load of liquid mass m with pressure increase $p=m/\kappa$ and the parameter σ controls the mass conductance between tanks (and one-tank open model) for transfer of $q=\sigma\Delta p$ units of liquid mass, per unit time, at the impressed pressure differential Δp.

In general, lumped parameter models consist of series of tanks and resistors that simulate the storage capacity of various parts of a geothermal system. In practice, most of the reservoirs can be modelled with two or three tanks in either of two modes open or close model. The open models are connected by a resistor to an infinitely large imaginary reservoir which maintains a constant pressure. In contrast, closed models are isolated from any external reservoir (see Figure 8). As an example, the first tank in the model can be looked upon as simulating the innermost (production) part of the geothermal reservoir, the second can be the outer part of the reservoir and the third tank simulates both the deeper parts of the reservoir and the overlaying groundwater system (Axelsson, 1989).

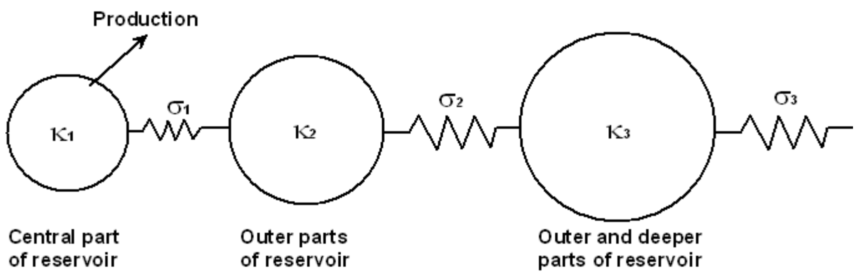

FIGURE 8: An open 3-tank lumped parameter model used to simulate water level or pressure changes in a geothermal system (Axelsson, 1989)

Thereby, in a general lumped network, the basic equations of the conservation of mass and mass flow are as follows:

$$\kappa_i \frac{dp_i}{dt} = \sum_{j=1}^{N} q_{ij} - \sigma_i (p_i - p_0) - Q_i \tag{7}$$

$$q_{ij} = \sigma_{ij}(p_j - p_i) \tag{8}$$

Here, N is the number of tanks, κ_i is the mass capacitance of the i-th tank; Q_i is the production in the i-th tank, p_i is the pressure in the i-th tank, q_{ij} is the mass flow from the j-th tank to the i-th tank and σ_{ij} is the flow resistance from the j-th tank to the i-th tank; in addition, the capacitors are serially connected by up to $N(N\text{-}1)/2$ resistors and the conductance of the same element to itself is equal to zero (σ_{ii}).

Now the general solutions of the lumped models are two, one for the open N-tanks model and the one for the closed N-tanks model, respectively:

$$p(t_i) = p(t_0) - \sum_{j=1}^{N} Q(t_i) \frac{A_j}{L_j} [1 - e^{-L_j t_i}] \tag{9}$$

$$p(t_i) = p(t_0) - \sum_{j=1}^{N-1} Q(t_i) \frac{A_j}{L_j} [1 - e^{-L_j t}] - QBt \tag{10}$$

The coefficients A_i, L_i and B are functions of the storage coefficients of the tanks (κ_i) and the conductance coefficients of resistors (σ_i) of the model. And they can be estimated by the program Lumpfit (included in the *ICEBOX* package). Lumpfit tackles the simulation problem as an inverse problem and will automatically fit the analytical response functions of lumped models to the observed data by using a nonlinear iterative least-squares technique for estimating the model parameters (Axelsson, 1989).

There is a methodology described by Axelsson et al. (2005) that is applied for lumped parameter modelling in Iceland. Here some of the steps are summarised for finding the best fitting parameters for a specific model, which could best fit the observed data. First, begin with a one-tank closed model, and then turn to a one-tank open model. After that, a two-tank closed model and a two-tank open model follow. Each model will give suggestions on the initial guesses of the model coefficients for following more complex one. This should be continued step by step until expanded to a three-tank open model, which is the most complicated model allowed by the program and is sufficient for most systems (Guo Gaoxuan, 2008).

Once the values for the storage coefficients κ and conductance coefficients σ are obtained by the Lumpfit program, some of the properties of the reservoir like the volume and permeability can be calculated. The volume is estimated from the parameter κ which in turn depends on one of two storage mechanism for liquid-dominated systems. The storage is either controlled by the liquid/formation compressibility described by Equation 11 or by the mobility of the free surface as described by Equation 12. These equations are defined for a liquid-dominated system as follows:

$$\kappa = V\rho C_t \tag{11}$$

$$\kappa = A\phi/g \tag{12}$$

where V is the reservoir volume (m^3);
ρ is the liquid density (kg/m^3);
C_t is the total compressibility of the liquid-saturated formation (Pa^{-1});
A is the surface area (km^2);

$\o$ is the formation porosity; and
g is the acceleration of gravity (m/s^2).

The total compressibility of the liquid-saturated formation C_t can be calculated by Equation 13:

$$C_t = \phi C_w + (1 - \phi) C_r \tag{13}$$

where C_w is the compressibility of water (Pa^{-1}) and C_r is the compressibility of the rock matrix (Pa^{-1}).

The permeability is estimated with the parameter σ that depends on the geometry and structures in the reservoir as follows:

$$k = \sigma \frac{ln\left(\frac{r_2}{r_1}\right) v}{2\pi h} \tag{14}$$

where k is the permeability (m^2);
h is the thickness of the reservoir (m);
v is the kinematic viscosity of the fluid (m^2/s); and
r is the radius of the tanks (m).

Lumped parameter models can in general be considered as distributed parameter models with a very coarse spatial discretization. The Lumpfit approach, however, tackles the modelling as an inverse problem, which requires much less time and operator intervention than direct or forward modelling. Reservoir modelling by using Lumpfit is therefore highly cost effective and has been shown to yield quite acceptably accurate results (Axelsson et al., 2005).

3.3 Pressure model

As discussed above the purpose of the lumped parameter modelling is to estimate the production potential of geothermal system through pressure response predictions and estimate the effects of various production scenarios. Therefore it is necessary to know the reservoir pressure data during its production history to study the pressure behaviour and with that fit a model that can be used to forecast.

The pressure information was obtained from static pressure logs of all the wells in the north area of the Los Azufres and from records obtained with the chamber static pressure monitoring well Az-19D and Az-53R. For the utilization of the information the following criteria were considered:

- The elevation at which the analysis should be performed.
- Temperature logs were plotted of each well to locate permeable zones.
- Pressure logs were plotted of each well to determine variations in time.
- Pressure logs in shut in conditions of the wells.
- Wells were chosen with more and better pressure data.

Here it is tried to model the whole area, but in previous works the area has been separated into the following sectors as listed here below (Valencia, 1996):

- La Cumbre sector (wells Az-13 and Az-32);
- Marítaro sector (wells Az-21, Az-42, Az-52, Az-59, Az-60, Az-57, Az-19, Az-48 and Az-29);
- Laguna Verde sector (wells Az-49, Az-53, Az-43, Az-05 and Az-51);
- El Chino sector (wells Az-03, Az-09 and Az-56); and
- La Cumbre Bis sector (Az-04, Az-28 and Az-30).

The depth at which the pressure was obtained depended on the depth at which pressure monitoring chambers were stationed. Here, the well that has the most relevant data is the Az-019D and has an elevation of 2876.7 m above sea level. The pressure monitoring chamber was stationed at 1100 m from the surface, which represents an elevation of 1776.7 m a.s.l. This elevation was considered for the rest of the wells.

Once the pressure measurements were in hand, the pressure was correlated with the production at the time that the pressure measurement was made. This is required by the format of the file that the Lumpfit program needs for its execution. Worth mentioning is that the pressure data were somewhat scattered and therefore data following a similar trend had to be chosen (Figure 9).

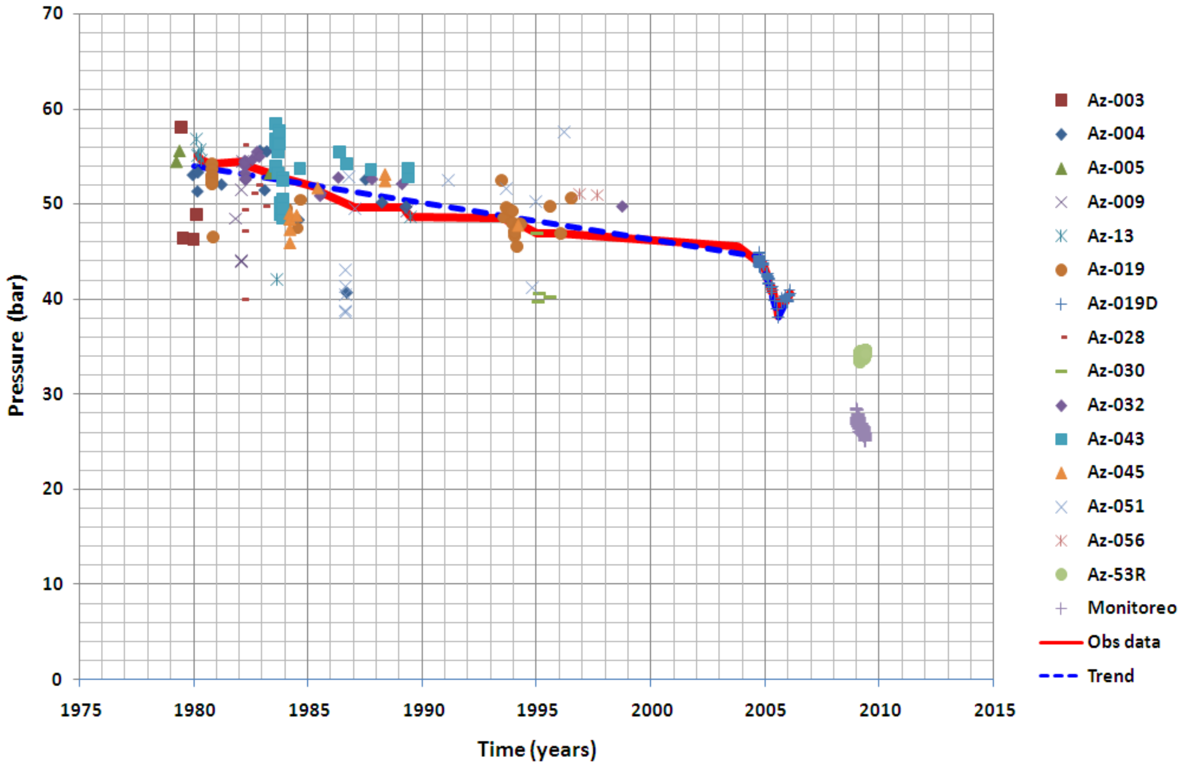

FIGURE 9: Pressure history measurements in wells

3.4 Production and injection

The production and injection data were acquired from a database of the Los Azufres. The production information was obtained from January 1980 to May 2009, and basically the total production was calculated by adding the amount of steam and brine that each of the wells produced. This information was obtained with a monthly frequency. The unit of the data were in tons/h and was converted to kg/s.

The injection data were also acquired from a database of the Los Azufres and obtained from September 1982 to May 2009. In this case the information came in days, hence it was converted to information per month to match with the production. The unit of the data is in tons/h and these were also converted to kg/s units. Figure 10 shows the total production of the North Los Azufres, the injection, the pressure and the estimated production. The estimated production was obtained through multiplying the total production with the percentage of tracer recovery in the zone, taken to represent the amount of water that recharges the production area from injection.

3.5 Results of tracer test

On September of 2005, two types of tracers were injected into well Az-15 in the western part of the north zone of Los Azufres, one for the liquid phase (1,3,6 tsn – trisulfonat of naphthalene) and one for the vapour phase (sulphur hexafluoride - SF_6). Previous studies indicated that the fluid injected into the well Az-15 would move to the west of it. But as producing wells are located to the east of the Az-15, it was thought that, after two decades of production, the current pressure gradient might favour the recharge of the producers mentioned. The tracer test was carried out to study this.

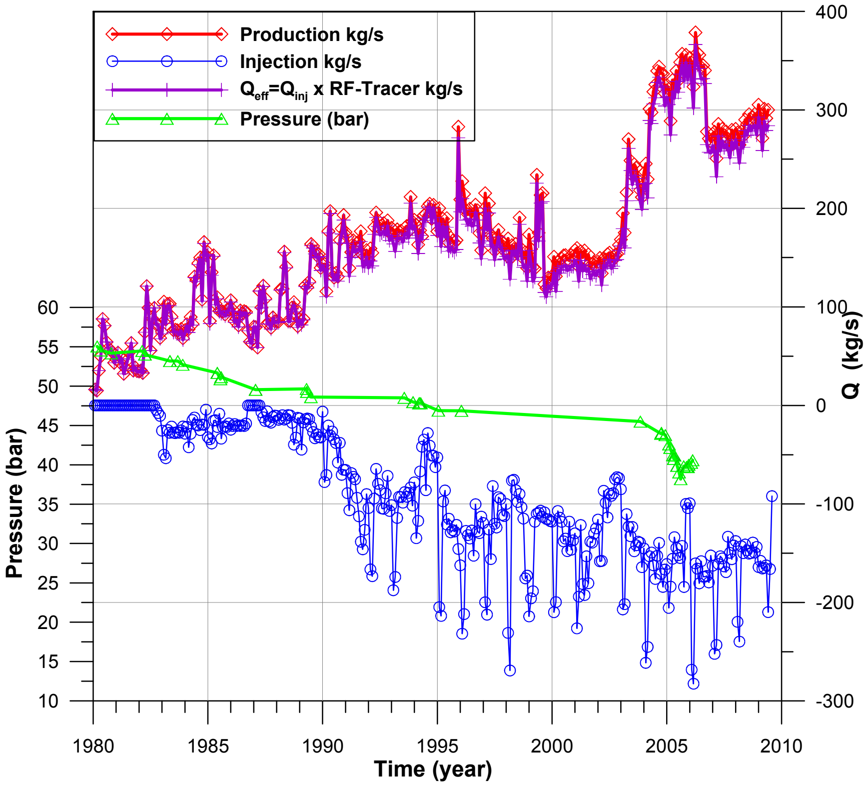

FIGURE 10: Production and injection in the North Los Azufres field; production is given with a red line and diamonds, the injection with a blue line and circles, the pressure with a green line and triangles, and finally, the purple line and crosses show the production after the estimated reinjection returns have been subtracted

The monitored wells were Az-65D, Az-04, Az-41, Az-30, Az-28 and Az-66D, in order of increasing distance to the injection well. The sampling period was 279 days from the day of injection. In the wells that produce water-vapour, i.e. Az-66D, Az-04, and Az-28, both tracers were, but in the rest of the wells only the vapour-phase tracer was detected. It is might be mentioned here that after the sample input of the tracers had been stopped, significant amounts continued to be recovered, both in the liquid and vapour phases.

The total tracer amounts recovered through the liquid phase (1,3,6 tsn – trisulfonat of naphthalene) in wells Az-65D, Az-04 and Az-28 up to 279 days after the injection were, respectively, 6.1, 0.90 and 0.16% for a total recovery of 7.61% while the total amounts of tracer recovered in the vapour phase (sulphur hexafluoride - SF_6) in wells Az-65D, Az-04, Az-41, Az-30, Az-28 and Az-66D were, respectively, 0.0482%, 1.37×10^{-3}%, 1.48×10^{-3}%, 6.38×10^{-4}%, 1.38×10^{-3}% and 4.31×10^{-4}% for a total recovery of 5.35×10^{-2}%. The study demonstrated that injection of waste brine in well Az-15 is effective in recharging the production area, even though the amounts seen are at the lower boundary for the magnitude of expected recovery in each of the wells and the total amount recovered (Iglesias et al., 2006).

The results of the tracer test will be used to obtain the amount of production in the geothermal field without influence from the injection. Later, the information will be also be used as starting values for the lumped parameter model. In other words, the production data is corrected through subtracting from the production flow rates, the percentage received from the recovery of the tracer multiplied by the injection flow rate. This is assumed to be the flow back to the feed-zones of production wells.

3.6 Lumpfit modelling

By using the Lumpfit parameters (Table 3), the main reservoir properties of the Los Azufres geothermal system can be estimated (Table 4). Like mentioned before, the storage in a liquid-dominated geothermal system can be affected of two types of storage mechanisms. If the reservoir is confined, the storage may be controlled by both liquid and formation compressibility, see Equation 11, in the other case, the storage may be controlled by the mobility of a free surface of the reservoir, see Equation 12. In our case the reservoir is confined. The water compressibility C_w is estimated to be 5×10^{-10} (Pa^{-1}) and the compressibility of the rock matrix C_r, is approximately 2×10^{-11} Pa^{-1}. The total compressibility is C_t=6.8×10^{-11} Pa^{-1}. The values for density, 826 km/m^3, and the viscosity, 1.4×10^{-7}, m^2/s are taken from the program TAFLA (also included in the *ICEBOX* package, see Arason and Björnsson, 1994) at thermodynamic conditions of 235°C and 8.9 MPa, temperature and pressure respectively. Porosity is assumed to be 10% which was the most likely value used for the Monte Carlo assessment.

TABLE 3: Lumpfit parameters for the North Los Azufres field

Number of tanks	**1 tank**	**2 tanks**
Model type / **Parameters**	**Open**	**Closed**
A_1	0.00134394	0.00231939
L_1	0.0142857	0.0447012
B		0.120832×10^{-3}
κ_1 (ms^2)	19286.6	10622
κ_2 (ms^2)		203891
σ_1 (ms)	0.000106298	0.174115×10^{-3}
Root mean square (RMS)	1.19890	0.941071
Coefficient of determination	94.769%	96.777%

TABLE 4: The North Los Azufres properties estimated by the Lumpfit models

Model	**Properties**		**First tank**	**Second tank**	**Total**
1-tank open	Reservoir volume V (m^3)	Confined	3.43373×10^{-11}		3.43373×10^{-11}
	Area A (km^2)	Confined	171.68		171.68
	Permeability k (m^2)	Confined			
2-tanks closed	Reservoir volume V (m^3)	Confined	1.89111×10^{-11}	3.63002×10^{-12}	3.81913×10^{-12}
	Area A (km^2)	Confined	94.55	1815.01	1909.56
	Permeability k (m^2)	Confined	3.30638×10^{-15}		

The volume of the reservoir for 2D flows can be calculated by Equation 15 and the area and the permeability for the two-tanks closed model can be calculated with Equations 16 and 17, respectively:

$$\kappa_1 = V_1 \rho C_t \; ; \; \kappa_2 = V_2 \rho C_t \tag{15}$$

$$R_1 = \sqrt{\frac{V_1}{\pi H}} \; ; \; R_2 = \sqrt{\frac{V_1 + V_2}{\pi H}} \tag{16}$$

$$r_1 = R_1/2 \; ; \;\; r_2 = R_1 + (R_2 - R_1)/2 \tag{17}$$

3.7 Predictions for different production scenarios

Based on the calibration of the model it is used to make predictions of the pressure response of different production scenarios in order to assess the reservoir and its production in different ways and compare the results with those obtained in the volumetric analysis with Monte Carlo. Four scenarios of production were calculated, all for 30 years:

- Production of 200 kg/s;
- Production of 300 kg/s;
- Production of 400 kg/s;
- Production of 500 kg/s.

Figure 11 shows two models, the upper graph is for the 1-tank open model which fits the observed data with the calculated data with a coefficient of determination of 94.77%. This model represents the optimistic scenarios for the four rates of production during the 30 years of prediction time. The second graph shows the 2-tanks closed model that fits the observed data with a coefficient of determination of 96.78%. This model represents pessimistic scenarios for the four rates of productions during the 30 years of prediction time.

As mentioned before the likely response of the reservoir pressure is in between the two models, the optimistic and pessimistic one. The results from the two models indicate that the responses of the pressure for each of the four different rates of production (200, 300, 400 and 500 kg/s) show an average difference of 6.5 bars after 30 years between the two models.

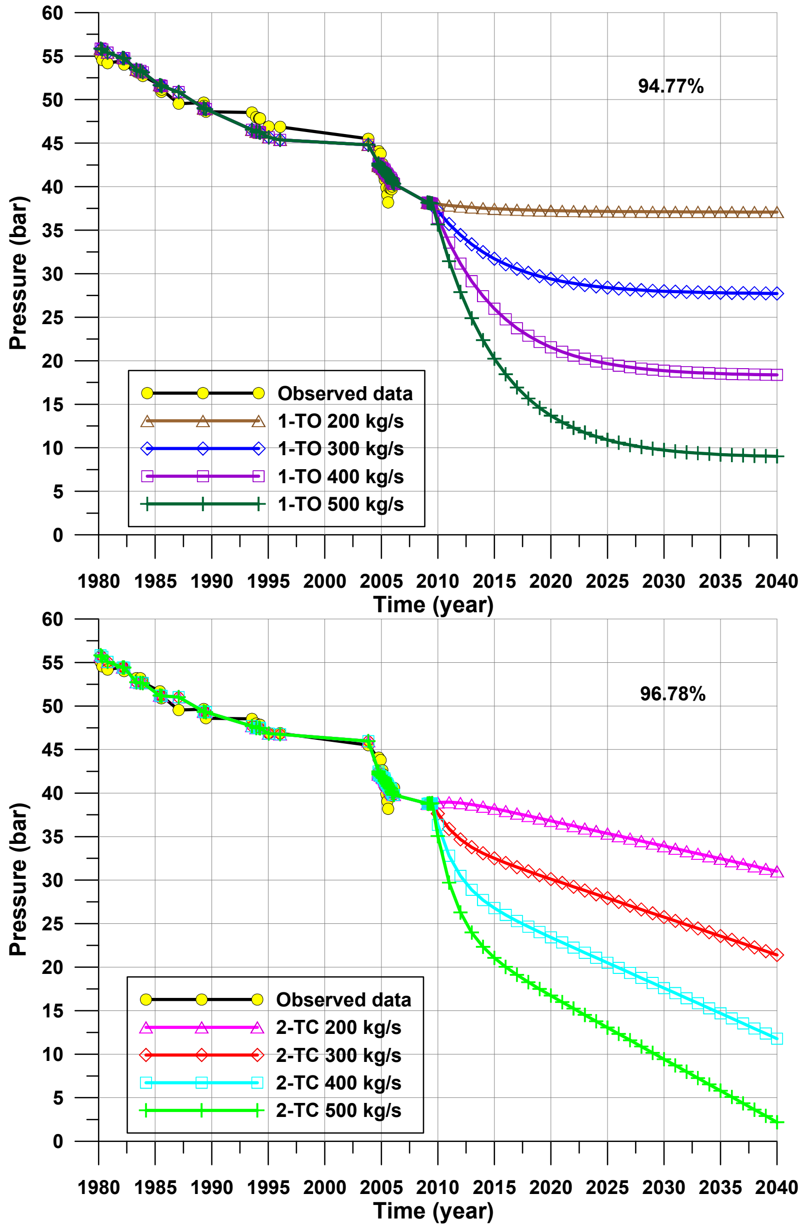

FIGURE 11: Predicted behaviour for the reservoir based on the 1-tank open model (upper graph) and the 2-tanks closed model (lower graph)

Moreover, it can be seen that for the scenario of 400 kg/s and 2-tank model, the pressure has dropped to 10 bar after a period of 30 years and for the scenario of 500 kg/s it has dropped to 10 bar after a period of 20 years. This indicates that these two scenarios would be difficult to sustain in the long term. Table 5 shows the results of the changes in pressure of the four production scenarios in the three different times predictions.

TABLE 5: Result for the calculated pressure (bar) for the four production scenarios of the two models for the North Azufres geothermal field

Time (year)	1-T O 200 kg/s	2-T C 200 kg/s	1-T O 300 kg/s	2-T C 300 kg/s	1-T O 400 kg/s	2-T C 400 kg/s	1-T O 500 kg/s	2-T C 500 kg/s
2030	37.11	33.92	27.99	25.75	18.86	17.59	9.73	9.43
2035	37.10	32.47	27.81	23.58	18.52	14.69	9.23	5.81
2040	37.09	31.02	27.73	21.40	18.38	14.79	9.02	2.18

4. COMPARISON BETWEEN THE VOLUMETRIC ASSESSMENT AND LUMPED MODEL

From the results of the two assessments it can be seen that the volumetric assessment with the Monte Carlo method shows higher values for power potential than the Lumpfit approach. One of the reasons for this could be that different approaches are considered by each method. With the Monte Carlo method the temperature is the main parameter to estimate the potential, while for the Lumpfit method the pressure response is used as the main parameter for the assessment.

The results of the Monte Carlo simulation show that for a period of 20-30 years the field can produce at least 190-290 MWe while the Lumpfit calculations show that for a production of 500 kg/s (corresponding to 155 MWe) in a period of 30 years, the pressure at 1100 m below the surface will be somewhere between 9 and 2 bar and dropping. This pressure drop is not sustainable and can cause problems for the production. This indicates that the level of production suggested by the Monte Carlo results might not be sustained without more effective reinjection. It must be emphasized that the pressure data are not totally consistent and are separated by a long interval of no measurements which may influence the results of the Lumpfit model. New pressure logs from shut-in wells might improve the accuracy of the model considerably.

5. CONCLUDING REMARKS AND RECOMMENDATIONS

The conclusions obtained from the two different approaches used to assess the northern part of the Los Azufres geothermal field are:

- Volumetric geothermal assessment by using the Monte Carlo method shows that there is 90% probability that the electric power can be at least sustained at 290 MWe for a period of 20 years, at 230 MWe for a period of 25 years and at 190 MWe for a period of 30 years.

- Lumpfit models predict a substantial pressure drawdown, reaching almost as low as 10 bar-g at 1770 m above sea level, for the production scenario of 400 kg/s in a period of 30 years and even lower for the production scenario of 500 kg/s in a period of 30 years. These production rates will be difficult to sustain.

- Comparing the results with previous works, the obtained values here for the power capacity of the area are lower. One of the reasons could be that a smaller area was considered.

- The conservative values used to determine the effects on the production due to injection could be one of the factors causing the pessimistic results of the Lumpfit model.

- Lack of monitoring data in the last 3 years, i.e. from 2006 to 2009, could influence the accuracy of the predictions of the Lumpfit model.

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