# New SExI tools to evaluate the evolution and anthropic disturbance in geothermal fields: The case of Los Azufres geothermal field, México

**Hipólita Ramajo[1], Jordi Tritlla[1,4], Gilles Levresse[1,*], Enrique Tello-Hinojosa[2], Germán Ramírez[3], and Héctor Pérez[3]**

*[1] Universidad Nacional Autónoma de México, Centro de Geociencias, Campus Juriquilla, Blvd. Juriquilla 3001, 76230 Santiago de Querétaro, Querátaro, México.*
*[2] Melecio Aguilar Nº 186, Col. Dr. Miguel Silva, 58186 Morelia, Michoacán, México.*
*[3]Gerencia de Estudios Geotermoeléctricos, Comisión Federal de Electricidad, Alejandro Volta Nº 655, Col. Electricistas, 58290 Morelia, Michoacán, México.*
*[4] Present address: Grupo de Disciplinas Geológicas, Executive Managing Direction of Upstream, REPSOL Exploración, Paseo de la Castellana 280, 28046, Madrid, Spain.*
** glevresse@geociencias.unam.mx*

**ABSTRACT**

*Lee's classification (Lee, K.C., 1996, Proceedings, Twenty-First Workshop SGP-TR-151 on Geothermal Reservoir Engineering: Stanford, California, Stanford University, 85-92; Lee, K.C., 2001, Geothermics, 30(4), 431-442), based on the specific exergetic index (SExI) has been sparsely used in geological sciences as a way to classify a natural energetic resource. Although useful, it does not take into account the modifications induced to a geothermal field by human exploitation, where exergy is not controlled anymore by natural-driven variables but by the anthropic ones.*

*In this paper we propose a new way to evaluate the energy-exergy dichotomy, taking into account both geochemical (chlorinity) and anthropic (water flow rate, effective well radius) variables applied to a geothermal field (Los Azufres) where intensive data has been gathered during the past three decades. This original approach will allow to understand the past and present, as well as to evaluate the future behavior of a geothermal well and to plan a better exploitation strategy that prevents geothermal fluid exhaustion.*

*Key words: geothermal fields, classification, exergy, flow rate, chlorinity, anthropic effects, Los Azufres, Mexico.*

**RESUMEN**

*La clasificación basada en el índice de exergía específica (SExI) propuesta por Lee (Lee, K.C., 1996, Proceedings, Twenty-First Workshop SGP-TR-151 on Geothermal Reservoir Engineering: Stanford, California, Stanford University, 85-92; Lee, K.C., 2001, Geothermics, 30(4), 431-442) ha sido escasamente utilizada en las ciencias geológicas como una manera de clasificar un recurso energético natural. Aunque útil, no toma en cuenta las modificaciones inducidas a un campo geotérmico por la explotación humana, donde ya no se controla la exergía por variables naturales, sino por variables introducidas por procesos antrópicos.*

*En este artículo se propone una nueva manera de evaluar la dicotomía de energía-exergía, teniendo en cuenta variables tanto geoquímicas (clorinidad) como antrópicas (caudal de agua, variables eficaces y radio) aplicadas a un campo geotérmico (Los Azufres) usando datos que han sido recopilados durante las últimas tres décadas. Este enfoque original permite entender el pasado y el presente, así como evaluar*

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*el comportamiento futuro de un pozo geotérmico y planificar una mejor estrategia de explotación que impida el agotamiento de fluidos geotermales.*

*Palabras clave: campos geotérmicos, clasificación, exergía, caudal, clorinidad, efectos antrópicos, Los Azufres, México.*

## INTRODUCTION

Due to the so-called "oil crisis" that showed up at the beginning of the 2000's, caused by several natural (exhaustion of main oil reservoirs worldwide, scarcity of new oil field discoveries, etc.) and anthropogenic causes ("hunger" for energetic sources from development countries, western countries oil-based societies, international markets speculation, etc.), coupled with the "global warming" discovery effect, provoked that energy-related disciplines received direct pressure from society to develop new sources of energy.

Renewable and non-renewable, geology-related sources of energy received new attention from the scientific and industrial world. Among these, geothermal energy is considered one of the most viable, "quasi-renewable" energetic resources in countries with high geothermal gradients, like Mexico.

Exergy is a tricky term that has been sparsely used in geothermics. As expressed in the second law of thermodynamics, all activity in the universe derives from matter and energy becoming more disorganized. This law can be used to quantify the degree of disorder and defines the work potential of a substance relative to a reference state (Hermann, 2006). When the substance is allowed to interact only with a reservoir in the reference state, this work potential is the exergy of the substance (Keenan, 1951). Then, exergy describes the quality and quantity of energy, *i.e.*, the useful portion of energy. To obtain that exergy for mankind purposes, our reference system must be out of equilibrium with the environment.

Following Hermann (2006), exergy exists in many different types of energy reservoirs, from the chemical potential stored in hydrocarbon bonds to the kinetic energy of the wind, tides or even the rotation of the Earth. Humankind access and extracts exergy from these reservoirs in order to obtain energy services. This term is not in relationship with the ability to exploit a resource, but is a path-independent property, serving as a model for the theoretically extractable work contained in a resource regardless of geometry, technology and economics.

Then, exergy is an independent instrument to ascertain the efficiency of the energy conversion and, used in geological sciences, a way to classify a natural energetic resource.

### Energy and exergy use in geothermal systems

Lindal (1973) was the first to categorize the geothermal fluid according to its temperature range, suggesting their application in every case. Lately, Armstead (1983) proposed that a geothermal field can be considered as a thermal area (temperature gradient greater than 40 ºC/km depth) with subsurface permeability which allows the containment of a fluid that can carry deep-seated heat to the surface. Also, he firstly proposed a classification of the geothermal systems using an energetic approach into three categories: (1) semi-thermal fields, producing hot water up to 100 ºC at the surface; (2) hyper-thermal wet fields, producing hot water and steam at the surface; and (3) hyper-thermal dry fields, producing dry saturated or superheated steam at the surface.

Other authors (Muffler and Cataldi, 1978; Haenel *et al.*, 1988; Benderitter and Cormy, 1990; Hochstein, 1990) classified geothermal systems into low, intermediate and high enthalpy resources using their reservoir temperatures.

Lee (1996, 2001) proposed a modification of these temperature-enthalpy classifications, including the pure exergetic concept as previously suggested by Bodvarsson and Eggers (1972). The latter considered exergy as the theoretical amount of mechanical work that can be derived from the heat content of a substance at given initial and end conditions.

Lee (1996, 2001) proposed the calculation of the specific exergy of a geothermal fluid as follows:

$$e = (h - h_0) - T_0(s - s_0) \quad (1)$$

where $e$ represents the specific exergy; $h$ is the specific enthalpy of the fluid in kJ/kg; $s$ is the specific entropy of the fluid in kJ/kg×K; $T$ is the absolute temperature expressed in Kelvin degrees; and the 0 subscript accounts for the reference condition (triple point of pure water).

Lee (1996) defined an specific exergetic index that he called SExI, to account for the quality of the geothermal resources. The SExI parameter relates the exergy of a particular fluid and the exergy of a saturated steam at 90 bar, with the following equation:

$$SExI = \frac{(h_{fluid} - 273.16 s_{fluid})}{1192} \quad (2)$$

where $h_{fluid}$ is the specific enthalpy of the fluid in kJ/kg; $s_{fluid}$ is the specific entropy of the fluid in kJ/kg×K obtained using a linear regression from the empirical tables presented in Lee (1996); and 1192 is the enthalpy value for pure water saturated with steam at 90 bar (9 Mpa) of pressure at 303 ºC. According to Lee (1996), the maximum exergy of a saturated steam pulled out from several geothermal systems throughout the world occurs between 90 and 100 bars of pressure. Although higher exergy values are possible for a superheated steam, it is rarely seen. Hence, the exergy values can be normalized by using the corresponding maximum exergy found (Lee,1996).

Lee (1996, 2001) also proposed an arbitrary criteria to evaluate the capacity of a geothermal fluid to do work, based on the Lindal (1973) diagram. Lee (1996, 2001) proposed as the lower SExI limit the value of a high performance well at Wairakei (New Zealand) that generates electricity at atmospheric pressure, with a corresponding SExI value of 0.5. Therefore, high exergy resources were proposed by Lee (1996, 2001) to have SExI values higher or equal to 0.5, similarly to the "hyperthermal dry field" established by minimum exergy acceptable for direct uses, *i.e.*, the equivalent of a saturated water at atmospheric conditions, with a corresponding SExI value of 0.05, in analogy with the "semithermal field" proposed by Armstead (1983). Hence, medium performance resources have SExI values between 0.05 and 0.5, corresponding to the Armstead (1983) "hyperthermal wet field". Finally, Lee (1996) represented these SExI boundaries as straight lines located at 0.05 and 0.5 (Equation 2) within the Mollier's Diagram (*h-s* plot) and used the resulting plot as a graphical way to classify geothermal fields (Figure 1).

## SExI application

Lee (1996, 2001) applied his plot (Figure 1) to classify dry geothermal steam fields, as Larderello (Italy) and the Geysers (USA), as high exergy resources with SExI values greater than 0.5. Similarly, two-phase geothermal fluids with enthalpies above 1600 kJ/kg, as in Ohaaki (New Zealand) and Cerro Prieto (Mexico) geothermal fields, are likely to be high exergy resources. Those fields with enthalpies between 1600 and 1000 kJ/kg were considered to be of medium exergy, as Wairakei (New Zealand) and Otake (Japan). Finally, those geothermal fields with enthalpies below 1000 kJ/kg must be classified as low exergy resources, such as in Fuzhou (China).

Lately, different authors used the SExI index in an effort to classify other geothermal fields as Ahuachapán and Berlin geothermal fields (El Salvador; Quijano, 2000) and the Tuzla geothermal field (Turkey; Baba and Ozgener, 2006).

Quijano (2000) applied the methodology proposed by Lee (1996) to calculate the SExI values at well-head conditions. He used both, the SExI values and the output characteristic curves of the production wells to estimate the efficiency of the geothermal power plants and the extracted thermal energy.

In this paper, we propose a new way to classify and evaluate the energy-exergy dichotomy, using as an example the historical data gathered at the Los Azufres geothermal field (LAGF), in Michoacán State (Mexico). In order to do so, we used the calculated reservoir conditions of the geothermal fluid obtained from three representative wells, to gain a clear insight within both the "original" (pristine) and the anthropically disturbed (present day) conditions of the geothermal field. The new diagrams we propose in this paper can be used to improve the energy recovery as well as to avoid both the over-exploitation and the reinjection effects of this natural, quasi-renewable resource.

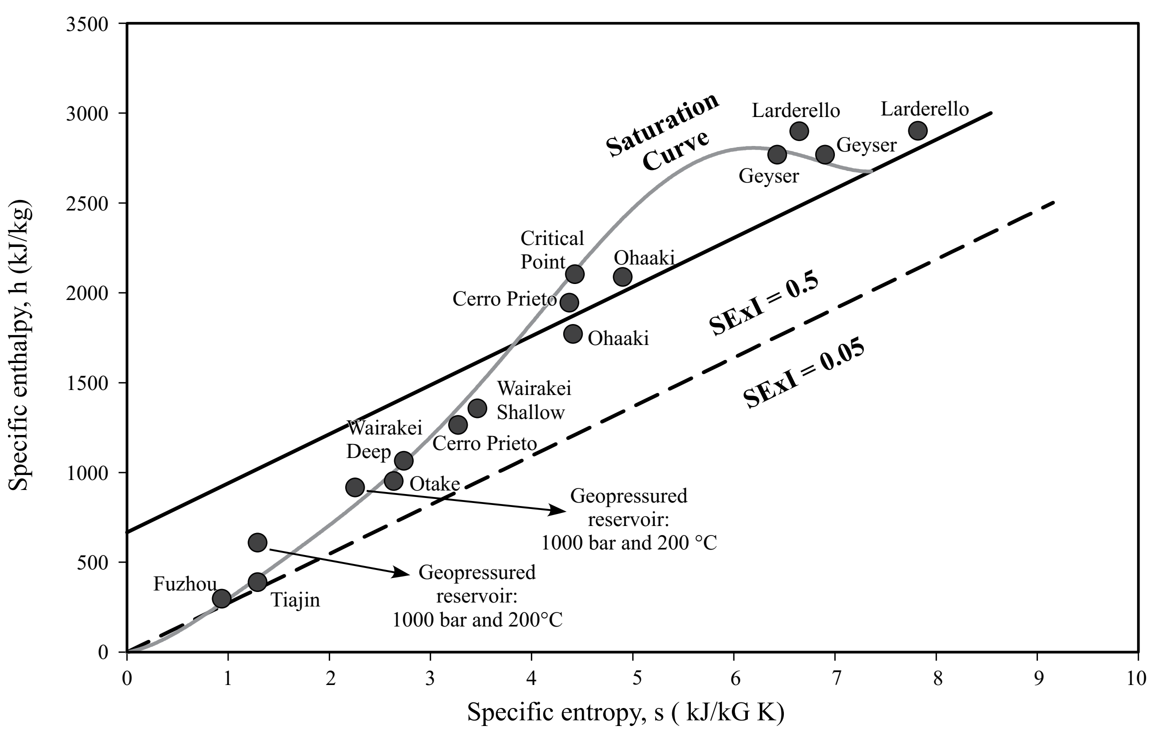


Figure 1. Lee's SExI plot with some important worldwide geothermal fields (modified from Lee, 1996, 2001).

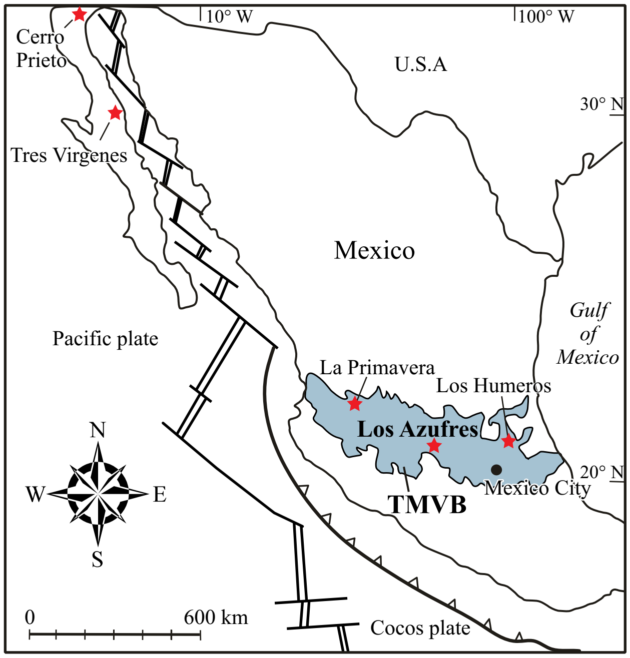


Figure 2. Location map of the Los Azufres geothermal field (modified from Montiel *et al.*, 1998). Red stars: localization of active geothermal fields; TMVB: Trans-Mexican Volcanic Belt.

## GEOLOGICAL SETTINGS AT LOS AZUFRES GEOTHERMAL FIELD

Los Azufres geothermal field (LAGF) is located at the Chapala-Cuitzeo central depression (Garduño and Mahood, 1987). More specifically, this geothermal field is placed within the Sierra San Andrés, in the intersection of two main depressions, the Valle Juarez to the north and La Venta depression to the south (Ferrari *et al.*, 1991), covering an area of about 42 km$^2$ (Figure 2 and 3).

The Los Azufres geothermal field is located at around 200 km northwest of Mexico City and 80 km to the east of the city of Morelia (Michoacán, Mexico; Figure 2 and 3). Geologically, it is placed at the centre of the Trans-Mexican Volcanic Belt (TMVB; Demant and Robin, 1975), a Neogene volcanic arc built on the southern edge of the North American plate (Ferrari *et al.*, 1991). It is characterized by the presence of abundant volcanism with a wide range of chemical compositions, from intermediate to silicic rocks with ages spanning from 17 Ma (late Oligocene) to the present. Although the TMVB trend is not parallel to the Middle American Trench, the origin of this volcanic province has been linked to the subduction of the Cocos plate beneath the North American plate (Demant and Robin, 1975) at the rate of approximately 6 cm/y (DeMets *et al.*, 1990). An exhaustive description of the local geology can be found in the following papers: Aumento and Gutiérrez, 1980, Gutiérrez and Aumento, 1982, Dobson and Mahood, 1995, Garduño, 1988.

Comisión Federal de Electricidad (Garduño, 1984) based upon surface geology, alteration distribution and structural controls, proposed that LAGF can be divided into the Northern (NZ) and Southern (SZ) Zones, with a central, non productive zone, accepting "implicitly" a two-reservoir field compartmentalization. Other studies (López, 1991; Ramajo *et al.*, 2007) supported a single reservoir field configuration.

The LAGF central area, in between the North and South Zones, is characterized by an intense hydrothermal alteration (kaolinitzation and silicification) affecting the outcropping volcanic series, forming a blanket several meters thick and suggesting the former existence of a surficial hydrothermal discharge zone. Alteration minerals throughout the field include microcrystalline silica, kaolinite, chlorite, zeolites (chabazite and wairakite), calcite and pyrite, most of them only distinguished by means of XRD methods (Pandarinath *et al.*, 2006). This alteration assemblage display a vertical arrangement, roughly correlated with increasing temperatures, with argillitization/silicification at shallow levels, zeolite/calcite formation and sericitization/chloritization at medium depths and chloritization/epidotization at deeper levels.

The present day active geothermal field is closely related to systems of faults and fractures oriented N-S, NNW-SSE, NE-SW and E-W directions (Garduño, 1988; López, 1991).

The geothermal fluid in Los Azufres is represented

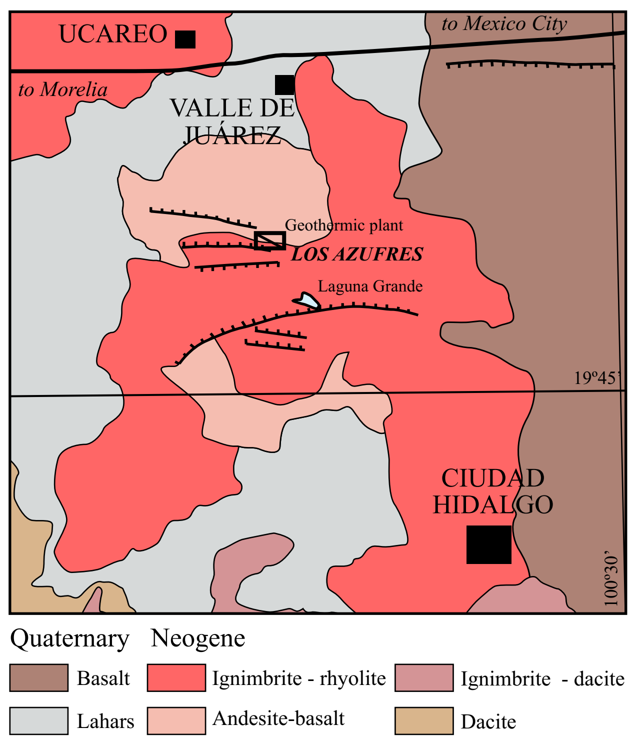


Figure 3. General geology of Los Azufres geothermal field area (modified from Montiel *et al.*, 1998).

by a low salinity, NaCl-dominant brine (~0.8 wt. %) and a non-condensable gas fraction, composed mainly by $CO_2$ (between 70 and 99 %) with minor quantities of $H_2S$, $N_2$, $H_2$ and $CH_4$ (Verma and Santoyo, 1997). Fluid temperatures at equilibrium, estimated using the Na-K fluid geothermometer, range from 230 to 340 ºC (Verma and Santoyo, 1997). Head pressures span between 6 to 41 MPa.

Three types of natural springs can be found at LAGF (Verma and Santoyo, 1997):

1) Sodium-bicarbonated springs of clear surficial origin, from the percolation of meteoric waters.

2) Sodium-chloride-dominated hot springs of deep origin, intimately related with the present-day geothermal fluids.

3) Steam-heated, acid-sulphate spring waters, after the interaction of deep, NaCl-hot, boiling water with perched, surficial waters.

## GEOTHERMICS AT LOS AZUFRES

Los Azufres is the second most important geothermal field in Mexico in terms of electricity generation, after the Cerro Prieto geothermal field in Northern Baja California peninsula (Figure 2). LAGF was firstly studied during the 50's decade of the last century (Maldonado, 1956). In 1972 interest in LAGF resumed, culminating in 1977 with the completion of the first producer well (Az-001). Between 1979 and 2004, a total of 85 production wells and six injection wells were drilled, while commercial electricity generation began in August 1982. At present, the installed capacity is 188 MW.

### SExI revisited at LAGF

The SExI concept is a very useful parameter to apply to pristine geothermal systems. Despite that, under dynamic conditions, geothermal fields react changing their thermodynamic and geochemical properties. Usually, these forceful conditions provoke the over-exploitation of the resource and, when the system is re-injected, the geothermal fluid behavior modify the natural state of the geothermal system. Consequently, we decided to apply the SExI index/classification with some modifications in order to look for a way to properly evaluate the anthropic disruption on this geothermal resource. The present work is based on the diary production and geochemical data gathered throughout the period comprised from 1980 until 2004. These data were filtered so as to remove the systematic errors that appeared as cero values in the production variables, for their no physical meaning, and those in the geochemical parameters with an error higher than 10 % in their ionic balance. Once these data were filtered, a program was generated to process monthly and annual statistics for every well involved in the power generation.

### Recalculation of the input parameters at reservoir conditions

The geochemical variable we use to evaluate the reinjection effect is the chlorine content at reservoir conditions, as this electrolyte behaves very conservatively in crustal environments even though it can be loss in small quantities through boiling as HCl. Chlorinity has been calculated using the equations of Arnorsson *et al.*, (1982) and using the temperatures calculated at reservoir conditions by means of the Na-K geothermometer (Verma and Santoyo, 1997), considering that albite and the K-feldspar assemblage are in equilibrium at a specific temperature:

$$T(\text{ºC}) = \frac{(1289\ (\pm 76))}{(\log(\frac{\text{Na}}{\text{K}}) - 1.615(\pm 0.179))} - 273.15 \quad (3)$$

The Na and K concentrations (in ppm) were obtained from the analyses performed on the recovered geothermal fluid. Hence, the Cl ($C_R$) content can be obtained applying the methodology established (Arnorsson *et al.*, 1982):

$$C_R(solute) = \frac{C_{TD}}{(1 - X_V^{RC})} \quad (4)$$

$X^{RC}{}_V$ represents the fraction of vapor at reservoir conditions and $C_{TD}$ is the concentration of the solute at discharge conditions. $X_V$ is calculated as:

$$X_V(Reservoir) = \frac{(H_0 - H_L)}{(H_L - H_V)} \quad (5)$$

$H_0$ is the enthalpy measured at separated conditions and $H_L$ and $H_V$ are the enthalpies of the liquid and vapor phase calculated at reservoir conditions assuming following (Arnorsson *et al.*, 1982):

$$H_L = 35.9+3.6053\cdot T+2.3838\times10^{-3}\cdot T^2+7.1004\cdot e^{(0.004\cdot T)} \quad (6)$$
$$L = 2384.1-0.3960\cdot T-9.1537\times10^{-3}\cdot T^2-1.9416\cdot e^{(0.004\cdot T)} \quad (7)$$

and $C_{TD}$ is obtained by the following expression:

$$C_{TD}(solute) = C_L(solute)\cdot(1-X^{DC}{}_V)+CV(solute)\cdot X^{DC}{}_V \quad (8)$$

where $C_L$ and $C_V$ are the concentration of the solute dissolved in the liquid and vapor phase measured and $X^{DC}{}_V$ is the fraction of vapor at discharge conditions; that is:

$$X_V(Total\ discharge) = \frac{H_0 - H_L}{L} \quad (9)$$

being $H_0$ the enthalpy measured, $H_L$ the enthalpy calculated at total discharge conditions and $L$ the latent heat.

The production variables considered in this paper are the water flow rate ($Q_L$), the effective well radius (D) and the specific enthalpy (h). The LAGF dataset provided by Comisión Federal de Electricidad (1980-2004) presents some gaps in the register (Tables 1, 2 and 3) due to exploitation problems.

Table 1. Processed data from Az-062 geothermal well. ** No data available.

| Year | s (kJ/kg K) | h (kJ/kg) | SExI (%) | $D/D_{max}$ (%) | $SExI/Q_L$ (%) | $Cl_L/Cl_{Lmax}$ (%) | SExI/Cl (%) | $Q_L/Q_{Lmax}$ (%) |
|---|---|---|---|---|---|---|---|---|
| 1995 | 4.2 | 1881.0 | 60.9 | 21.2 | 2.2 | 27.0 | 0.4 | 17.1 |
| 1996 | 4.1 | 1837.1 | 59.1 | 26.7 | 1.1 | 26.8 | 0.3 | 34.1 |
| 1997 | 4.2 | 1874.4 | 60.7 | 27.2 | 1.0 | 28.2 | 0.3 | 35.9 |
| 1998 | 4.2 | 1872.7 | 60.6 | 31.8 | 1.1 | 29.7 | 0.3 | 34.8 |
| 1999 | 4.2 | 1853.3 | 59.8 | 29.3 | 0.9 | 29.2 | 0.3 | 41.2 |
| 2000 | 4.1 | 1822.0 | 58.4 | 29.3 | 0.8 | 29.7 | 0.3 | 43.0 |
| 2001 | 4.1 | 1826.6 | 58.6 | 28.5 | 2.0 | 29.6 | 0.3 | 18.1 |
| 2002 | ** | ** | ** | ** | ** | ** | ** | ** |
| 2003 | 4.1 | 1817.7 | 58.2 | 46.5 | 0.7 | 28.5 | 0.3 | 47.3 |
| 2004 | 4.1 | 1787.2 | 56.9 | 58.6 | 0.6 | 31.3 | 0.3 | 59.0 |

Besides this irregular register, the amount of data available is enormous, so we decided to use annual average values. Moreover, we normalized the gathered data taking into account the maximum and minimum values registered at LAGF for every variable, considering the following relationship:

$$X\,(Normalized) = \frac{X_0 - X_{min}}{X_{max} - X_{min}} \qquad (10)$$

where $X_0$, $X_{max}$ and $X_{min}$ are the different measured, maximum and minimum values of each of the parameters.

## Plot construction and evaluation

According to the criteria exposed by Lee (1996, 2001), the geothermal fluids have been classified within high (H.E.F.), medium (M.E.F) and low (L.E.F.) exergy values. This classification is not very accurate under dynamic conditions, because it makes no difference between natural vapor-producing and over-exploited wells. To evaluate the anthropic disturbance caused by geothermal resource human exploitation, we propose to correlate the SExI parameter with the production ($Q_L$, D) and geochemical (chlorinity) parameters.

Then, we propose the use of three different graphic representations:

a) *Outlet effect (OE) plot:* representing the normalized effective well radius ($D/D_{max}$) versus the SExI evolution (Figures 4b, 5b and 6b). This plot gives an insight into the exergy behavior of the well during the manipulation of the diameter of the well.

b) *Chlorinity effect (CE) plot:* representing the normalized chlorine content ($Cl_L/Cl_{Lmax}$) versus the $SExI/Q_L$ ratio

Table 2. Processed data from Az-013 geothermal well. ** No data available.

| Year | s (kJ/kg K) | h (kJ/kg) | SExI (%) | $D/D_{max}$ (%) | $SExI/Q_L$ (%) | $Cl_L/Cl_{Lmax}$ (%) | SExI/Cl (%) | $Q_L/Q_{Lmax}$ (%) |
|---|---|---|---|---|---|---|---|---|
| 1980 | 4.4 | 1950.8 | 63.9 | 25.7 | 3.6 | 22.8 | 0.4 | 10.9 |
| 1981 | 3.7 | 1586.4 | 48.4 | 16.1 | 1.8 | 24.1 | 0.3 | 15.9 |
| 1982 | 3.8 | 1642.9 | 50.8 | 20.2 | 1.2 | 25.3 | 0.3 | 25.1 |
| 1983 | 4.2 | 1866.9 | 60.3 | 38.1 | 1.2 | 24.5 | 0.4 | 29.3 |
| 1984 | 4.1 | 1784.7 | 56.8 | ** | 0.9 | 22.1 | 0.4 | 37.7 |
| 1985 | 4.2 | 1859.0 | 60.0 | 34.2 | 1.2 | 23.6 | 0.4 | 29.5 |
| 1986 | 3.9 | 1710.4 | 53.7 | 29.3 | 0.9 | 24.1 | 0.3 | 36.3 |
| 1987 | 3.8 | 1624.6 | 50.0 | ** | 0.7 | 25.0 | 0.3 | 45.2 |
| 1988 | 3.7 | 1606.8 | 49.3 | ** | 0.7 | 25.7 | 0.3 | 44.7 |
| 1989 | 5.6 | 2661.4 | 94.2 | 6.6 | 2.5 | 0.2 | 81.6 | 23.1 |
| 1990 | 5.0 | 2321.2 | 79.7 | 2.5 | 9.7 | 19.4 | 0.6 | 5.0 |
| 1991 | 5.1 | 2351.9 | 81.0 | 20.9 | 5.0 | 18.9 | 0.7 | 9.8 |
| 1992 | 5.2 | 2448.9 | 85.2 | 94.1 | 5.6 | 16.0 | 0.8 | 9.3 |
| 1993 | 3.7 | 1573.1 | 47.8 | 97.7 | 3.4 | 5.2 | 1.4 | 8.5 |
| 1994 | 5.6 | 2638.0 | 93.2 | 97.7 | 7.9 | 1.6 | 17.5 | 7.1 |
| 1995 | 5.3 | 2479.2 | 86.5 | 91.2 | 7.9 | 7.3 | 1.8 | 6.6 |
| 1996 | 5.7 | 2699.9 | 95.9 | 60.2 | ** | ** | ** | 3.1 |
| 1997 | 5.6 | 2655.8 | 94.0 | 58.6 | 18.2 | 0.2 | 91.3 | 3.1 |

Table 3. Processed data from Az-002 geothermal well. ** No data available (well closed for recovery).

| Year | s (kJ/kg K) | h (kJ/kg) | SExI (%) | $D/D_{max}$ (%) | $SExI/Q_L$ (%) | $Cl_L/Cl_{Lmax}$ (%) | SExI/Cl (%) | $Q_L/Q_{Lmax}$ (%) |
|---|---|---|---|---|---|---|---|---|
| 1980 | 3.6 | 1520.8 | 45.6 | 9.7 | 1.6 | 25.1 | 0.3 | 17.1 |
| 1981 | 3.5 | 1458.4 | 42.9 | 12.8 | 1.8 | 26.6 | 0.2 | 14.2 |
| 1982 | 3.3 | 1357.6 | 38.6 | 16.3 | 1.8 | 28.3 | 0.2 | 12.7 |
| 1983 | 3.7 | 1561.1 | 47.3 | 5.8 | 1.5 | 27.4 | 0.3 | 19.7 |
| 1984 | ** | ** | ** | ** | ** | ** | ** | ** |
| 1985 | ** | ** | ** | ** | ** | ** | ** | ** |
| 1986 | 3.0 | 1222.0 | 32.8 | 2.4 | - | 24.0 | 0.2 | - |
| 1987 | ** | ** | ** | ** | ** | ** | ** | ** |
| 1988 | 3.7 | 1615.5 | 49.6 | 18.5 | 0.9 | 31.9 | 0.2 | 33.0 |
| 1989 | ** | ** | ** | ** | ** | ** | ** | ** |
| 1990 | 3.1 | 1230.1 | 33.2 | 19.5 | 1.0 | 40.0 | 0.1 | 19.5 |
| 1991 | ** | ** | ** | ** | ** | ** | ** | ** |
| 1992 | ** | ** | ** | ** | ** | ** | ** | ** |
| 1993 | 3.1 | 1271.7 | 35.0 | 30.4 | 0.3 | 50.9 | 0.1 | 64.6 |
| 1994 | ** | ** | ** | ** | ** | ** | ** | ** |
| 1995 | 3.2 | 1327.0 | 37.3 | 28.3 | 0.4 | 59.3 | 0.1 | 54.9 |
| 1996 | 3.2 | 1288.3 | 35.7 | 36.7 | 0.3 | 66.1 | 0.1 | 84.7 |
| 1997 | 3.1 | 1253.1 | 34.2 | 28.4 | 0.4 | 70.0 | 0.1 | 54.5 |
| 1998 | ** | ** | ** | ** | ** | ** | ** | ** |
| 1999 | ** | ** | ** | ** | ** | ** | ** | ** |
| 2000 | 3.1 | 1231.9 | 33.3 | 27.8 | 0.5 | 68.4 | 0.1 | 41.1 |
| 2001 | 3.3 | 1353.1 | 38.4 | 20.4 | 1.9 | 68.9 | 0.1 | 12.3 |
| 2002 | ** | ** | ** | ** | ** | ** | ** | ** |
| 2003 | 3.0 | 1199.8 | 31.9 | 7.9 | 3.3 | 61.9 | 0.1 | 5.8 |

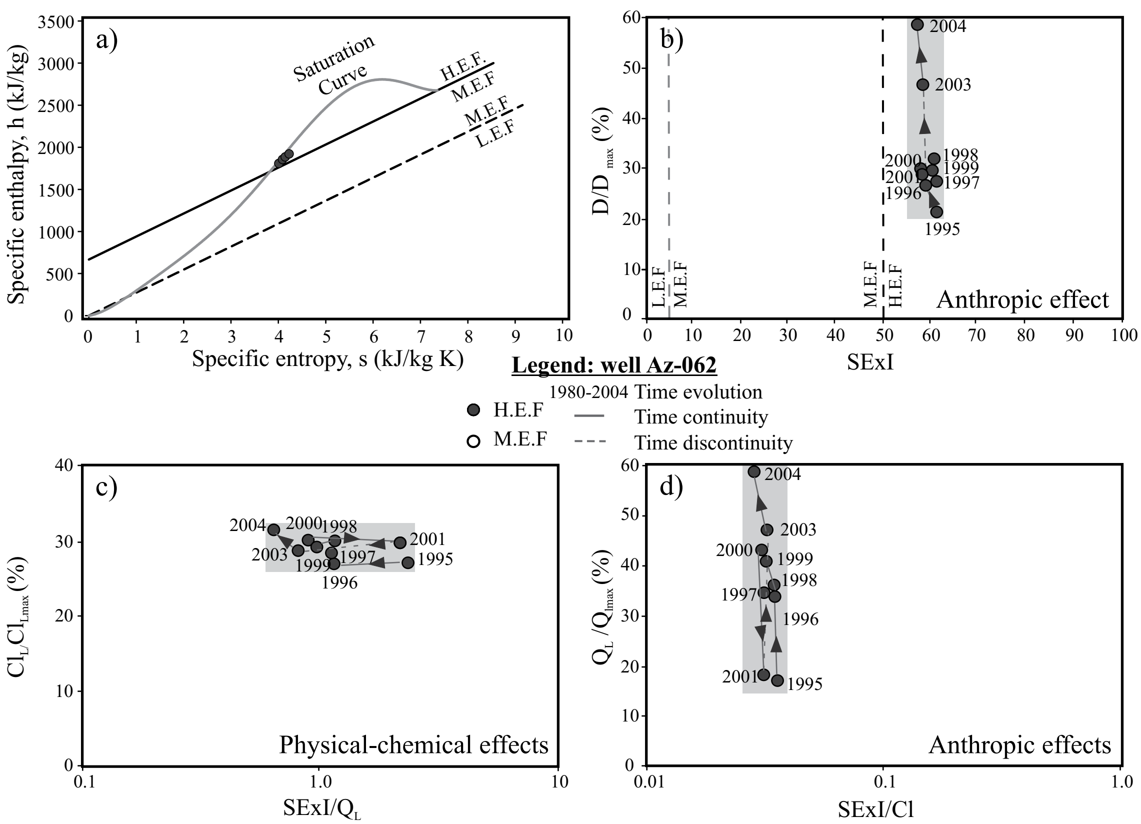


Figure 4. Az-062 well plots. a) Lee's SExI plot; b) OE plot: $D/D_{max}$ *vs*. SExI; c) CE plot: $Cl_L/Cl_{Lmax}$ *vs*. $SExI/Q_L$; d) the normalized $Q_L$ ($Q_L/Q_{Lmax}$) versus SExI/Cl plot ($Q_L$ effect, QE). The thick solid and the dotted lines indicate the position of the low (L.E.F.), medium (M.E.F.) and high (H.E.F.) exergy fields, following the criteria of Lee (2001). See text for discussion.

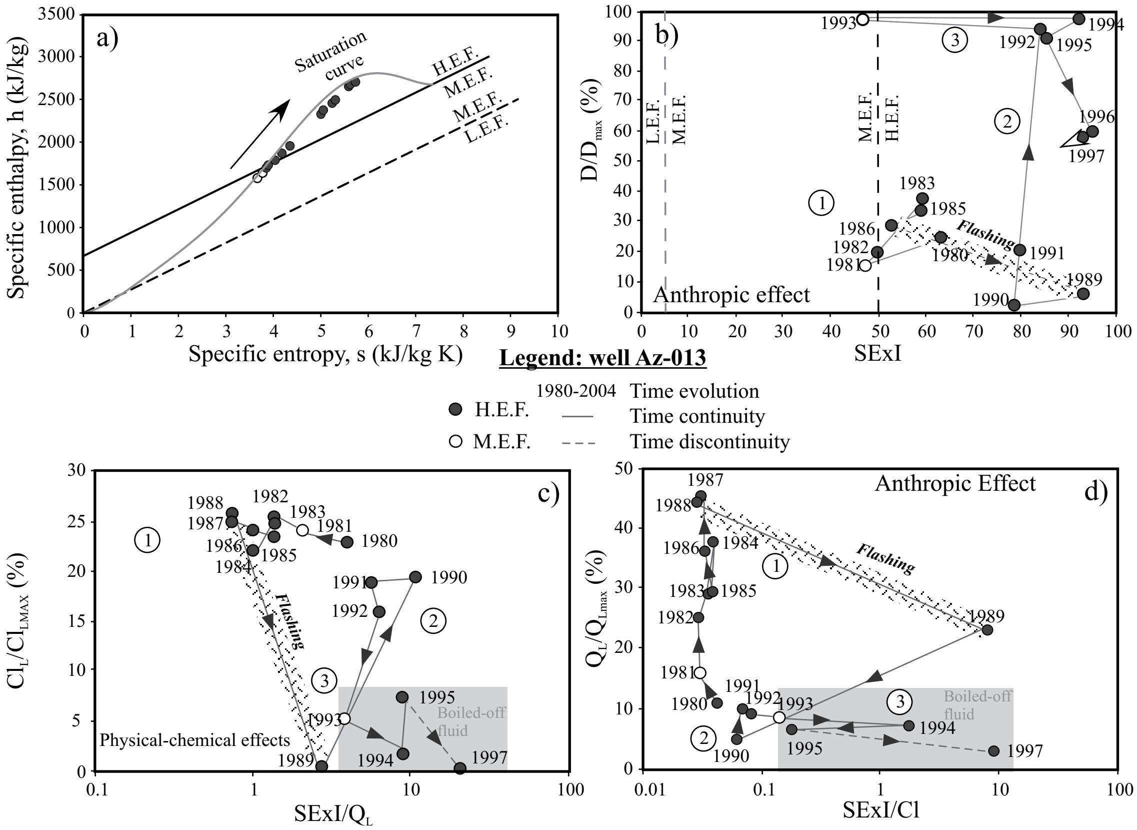


Figure 5. Az-013 well plots. a) Lee's SExI plot; b) OE plot: $D/D_{max}$ *vs.* SExI; c) CE plot: $Cl_L/Cl_{Lmax}$ *vs.* SExI/$Q_L$; d) the normalized $Q_L$ ($Q_L/Q_{Lmax}$) versus SExI/Cl plot ($Q_L$ effect, QE). The thick solid and the dotted lines indicate the position of the low (L.E.F.), medium (M.E.F.) and high (H.E.F.) exergy fields, following the criteria of Lee (2001). See text for discussion.

(Figures 3c, 4c and 5c), constructed to evaluate the effects of both, over-exploitation and fluid re-injection.

c) *$Q_L$ effect (QE) plot:* representing the normalized $Q_L$ ($Q_L/Q_{Lmax}$) versus the SExI/Cl ratio (Figures 4d, 5d and 6d), constructed to depict the evolution of over-exploitation and re-injection effects.

We checked the use of our plots using three carefully characterized set of well data series at LAGF:

1) The Az-062 well, located at South of LAGF that represents a sustainable behavior at LAGF (Figure 4, Table 1).

2) The Az-013, at the North of LAGF, that represents a well clearly over-exploited (Figure 5, Table 2).

3) The Az-002, well at South of LAGF, which is affected by re-injection of the residual geothermal fluid (Figure 6, Table 3).

In order to have a sound set of data to work with, several thousand individual daily measurements, spanning between 1980 and 2004, have been checked, filtered and evaluated (Ramajo *et al.*, 2007).

## DISCUSSION

Geothermal data (Figures 4a, 5a and 6a) on Mollier's classic plot (Lee, 1996, 2001) for Az-013 and Az-062 wells fall within the high exergy field (H.E.F.), whereas the fluid extracted from well Az-002 displays a medium exergy pattern (M.E.F.).

The Az-062 well represents a high exergetic fluid that it is not affected by exploitation, with a SExI value of around 60% (Figure 4b), being one of the most constant geothermal wells of the area.

In contrast, the Az-013 well exhibits three different trends. The first trend occurred between 1980 until 1990, where the well-outlet was less than or equal to 40 % and SExI values fall within the range of 50 to 80 %. The middle trend, between 1990 and 1994, is characterized by a drastic increase in $D/D_{max}$ up to 100 %, to end up with a 60 % of well-outlet. In this period SExI increased from 45 up to 95% of the maximum value assumed by Lee (1996, 2001). Therefore, the fluid produced at Az-013 is, almost all the time, a H.E.F., turning it into a profitable geothermal fluid. Yet, when we use the other (CE and QE) plots (Figures 5c and 5d), the anthropically induced over-exploitation effect becomes evident from 1991 until 1997, where the drastic increase of the outlet provoked on one hand an exergy growth and, on the other hand the sudden drop of the Cl content and $Q_L$ that gave rise to a boiled-off fluid. So, an exergetically useful fluid in Lee's plot depicts a depletion trend towards the complete exhaustion

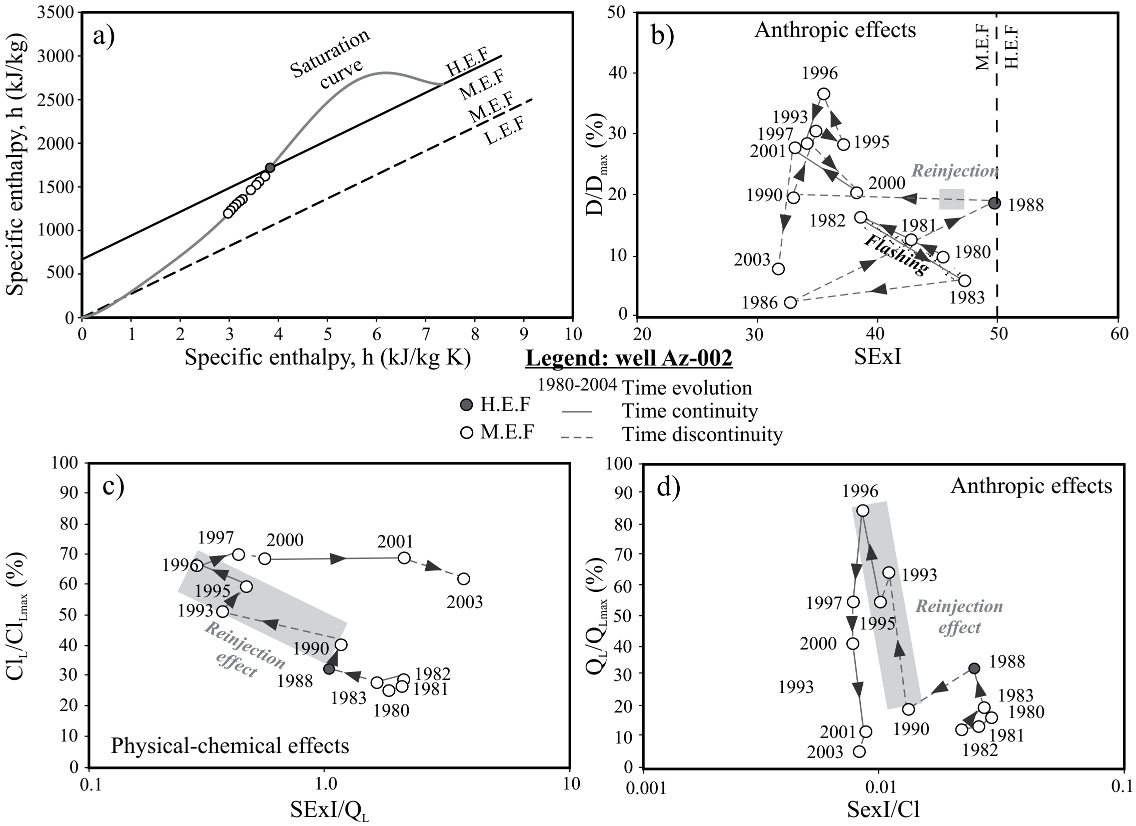


Figure 6. Az-002 well plots. a) Lee's SExI plot; b) OE plot: D/$D_{max}$ *vs.* SExI; c) CE plot: $Cl_L/Cl_{Lmax}$ *vs.* SExI/$Q_L$; d) the normalized $Q_L$ ($Q_L/Q_{Lmax}$) versus SExI/Cl plot ($Q_L$ effect, QE). The thick solid and the dotted lines indicate the position of the low (L.E.F.), medium (M.E.F.) and high (H.E.F.) exergy fields, following the criteria of Lee (1996). See text for discussion.

of the geothermal resource.

Az-002 represents a well affected by re-injection in neighboring Az-007 and Az-008 wells. Following Lee, this well produces a medium exergetic fluid (Figure 6a). Figure 6b indicates a well complex manipulation and subsequent behavior, never reaching the high exergetic fluid field which was the main purpose of such manipulation. As can be seen in the same Figure, trials were made to increment the productivity of the well by first opening (1980-1982) the main valve, resulting in a SExI decrease, and then strangling the well outlet (1982-1986) to recover the initial state. The coupling of opening and reinjection led to a SExI decrease as well as an increase in salinity of the fluid; one can argue that both effects make no sense, as salinity increase can be produced by boiling that triggered the system towards higher SExI values; in this case, this apparent contradiction is due to the reinjection of a boiled-off, higher salinity remnant fluid, recovered at surface from other producing wells. From 1996, re-injected fluid become dominant explaining the constant Cl contents. From 2001, the slight drop in chlorinity is coupled with a dramatic increase in mineral precipitation (in situ observation by Ramajo) and the exhaustion of the geothermal fluid (Figure 6d), leading to the subsequent abandon of the well. In order to recover steam production, another well was drilled nearby Az-002, avoiding the already-sealed preferential paths.

As can be seen, from Lee's SExI classification both Az-062 and Az-013 wells should produce a high exergetic fluid (Figures 4a and 5a) and no differences can be drawn between them, even though their exploitation regime and, consequently, their fluid behavior is clearly different (Figures 4b and 5b). Az-062 geothermal fluid displays a regular behavior regardless any anthropic manipulation, as compared with the whole LAGF wells, showing null to slight Cl concentration increase (Figure 4b), while flow rate increased (Figure 4d) due to the opening of the well-outlet (Figure 4d). Contrastingly, the Az-013 well never reached a close-to-equilibrium exploitation state as the fluid boils resulting in an anthropic-triggered, unstable H.E.F., as can be seen in Figures 5c and 5d, leading to a complete loss of control of the well. This over-exploitation is confirmed by the sudden drop on Cl concentration (Figure 5c) linked to the exhaustion of the liquid phase (Figure 5d). In this case, over-exploitation is associated to a huge opening of the well-outlet that took place in 1993 (Figure 5b), however, there are some cases when the well outlet is not completely opened but the well still experiments over-exploitation as in a memory effect. A probable cause for this is low rock permeability in the vicinity of the well.

## CONCLUSIONS

Lee's exergy classification (Lee, 1996, 2001), although useful, does not provide a deep insight into the geothermal fluid itself.

The exergy of a fluid in a mature geothermal field, as LAGF, is not controlled anymore by natural-driven variables but by the anthropic ones. Then, the new discriminating plots we propose in this paper concerning high enthalpy geothermal fields (>100ºC) can be applied to: (1) understand the natural behavior of a newly drilled well after production tests, regardless their exergetic characteristics; (2) to understand and characterize the anthropic disturbance originated by continuos exploitation; and (3) to predict the future behavior of a geothermal resource, regardless its history. Thus, this new approach allows us to discriminate among several relevant effects, and to plan a better exploitation strategy that prevents geothermal fluid exhaustion.

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