Production forecast and estimation of the recovery factor of the Los Humeros geothermal field, Mexico.

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Abstract

Production data from the Los Humeros geothermal field in Mexico are used to develop a forecast method for operation of the field in the future. This method supports understanding the limitations of sustainably exploiting a geothermal reservoir. Using such forecasts, fluid extraction could be scheduled in order to fulfill the steam demand of the installed capacity. Moreover, the forecast of the extraction can diminish the commercial risk involved and therefore clear the way for new investments. Herein, we determined the total extracted heat from the Los Humeros geothermal system, with the aim to forecast the next phase of fluid extraction. We took the information from 29 producing wells to analyze their historic geothermal fluid production. From their statistical distribution of data, we estimated the amount of extracted fluids for a future phase. The size of the heat reserve previous to exploitation was calculated from the forecasted and the extracted heat. Thus, the recovery factor of the system was calculated as the ratio of the accumulated production of heat and the initial heat content. The general recovery factor for 60 years of production was calculated as 37...44 %. Due to the heterogeneity of the system, we conducted individual assessments. The forecasted heat extraction for the next thirty years of production, amounts to 580 PJ assuming a constant extraction rate between 6 and 56 ton·[hr]⁻¹. The results of this study potentially complement the existing models of the geothermal exploitation and offers an estimation of the future production of the Los Humeros, which could be a good basis for decision-making and management of the site.
High temperature fluid bearing reservoirs have been found and exploited all over the world and also in Los Humeros in Mexico. The question is how sustainable their exploitation is. Therefore, continuous monitoring of a geothermal system is required. This is a key prerequisite to control a successful exploitation (Armstead 1973; Axelsson 2008). This measure not only increases the knowledge and understanding of the system, it also is the base for future development in a sustainable manner (Axelsson et al., 2004; Stefansson and Axelsson 2005).

In Los Humeros, Mexico, a conventional geothermal system has been exploited since the early 1980s. During thirty years of continuous production, several surveys have been conducted about the response and evolution of the geothermal system as a consequence of fluid extraction (Aragon-Aguilar et al. 2017; García-Gutiérrez et al. 2002; Arellano-Gómez et al, 2008; Aragon-Aguilar et al. 2019). Moreover, as Los Humeros is considered to be a potential superhot geothermal system, it is one of the study sites of the Mexican-European collaborative project GEMex (Jolie et al. 2018). The objective of GEMex was the use of the superhot geothermal resource. Although the use and development of a superhot geothermal system could happen in the near future, the assessment and monitoring of the conventional geothermal system of the Los Humeros, is needed in order to extend and preserve its use for future generations.

Previous studies about the evolution of the system to exploitation show changes on temperature, pressure and thus enthalpy at the reservoir depth. In general, these changes do not seem to affect the performance of the wells (Aragon-Aguilar et al. 2005; Arellano-Gómez et al. 2008). The analysis of productivity data suggests the existence of two reservoirs separated by a tuff layer (Arellano Gómez et al. 2003). The performance of the wells could be linked with both the grade of their connection with the deepest and hotter reservoir and with the physicochemical parameters of the extracted brine (Aragon-Aguilar A., Moya, and zquierdo 2005; Arellano-Gómez et al. 2008). In this context, the evaluation of the size of the reserve based
on the production, which is the focus of this paper, substantially complements the
coloration of the system.

The main goals of this work are 1. to estimate the original amount of heat in the currently
exploited reservoir of Los Humeros and 2. to forecast the mass extraction for the next thirty
years. The extrapolation time is taken from the time frame suggested by development banks to
this type of energy projects. The results of the goals allow us to calculate the heat recovery factor
of the system for sixty years of continuous production. We assume the forecasted production
as economically exploitable, as the necessary technology is already installed. Hence, we consider
this quantity to be the heat reserve of the Los Humeros (P. Muffler and Cataldi 1978; L. Rybach
2015).

The Los Humeros production history

The Los Humeros caldera system is located in the central part of Mexico (Figure 1). The drilling
campaign started in 1986. After four years of exploration, drilling, well testing and construction
infrastructure and facilities, the power plant began operation in 1990 (Ordaz Méndez, Flores
Armenta, and Ramírez Silva 2011). The power plant started with 5 MW of installed capacity and
the reinjection of brine commenced in 1992 (Ascencio Cendejas, 1992). Today, the total capacity
has increased to 95 MW, distributed in three main production clusters: north, center and south.
Each one with different production units (Garcia-Gutierrez, et al. 2015; Gutiérrez-Negrín, 2019).
The injected mass amounts to 16 % of the extracted mass (Arellano-Gómez et al. 2008), and the
reinjected temperature is 40 °C on average according to the available operation data provided
by the Federal Commission of Electricity (CFE), the proprietor company. Nowadays, there are
five injection wells operating inside the production zone. In spite of a temperature drop between
production and reinjection of more than 100 K, the reinjection does not seem to affect the
production of the hot brine (Ascencio Cendejas 1992; Iglesias et al. 2012).
Production wells use a pump to extract the fluids from the reservoir. Then, the brine is conducted through a separator unit, splitting the flow into liquid and steam. Resulting brine is reinjected, while the steam flows to the turbines by different pipe arrangements (Rosales López 2006). Available monitoring data, collected on site since the beginning of operation, include the well head pressure, the extracted mass as a sum of brine and steam; and steam enthalpy. Our objective is to, based on this data, estimate the amount of heat that has been produced from the system, what is the prospect for future production and what are the implications for the sustainability of extraction.

Figure 1 Location of the Los Humeros, Puebla.

Production forecast and estimation of geothermal heat reserve

The production forecast using historical production data includes three main categories: decline analysis, lumped parameter and numerical simulations. Some authors have applied this procedure analyzing the productivity data for different geothermal. Decline analysis takes a time series of one variable and look for trends to adjust it and forecast the behavior systems (Atkinson et al. 1978; Manuel Nathenson 1975). This procedure helps to identify signs of depletion and future production by a trend analysis. The lumped parameter is a tool that consider the reservoir as a closed tank. It takes the average properties of the reservoir in order to find a declining trend
Each approach depends on the quality of the data and the goal of the estimation. For our case, the available data was not sufficient to carry out these approaches. The time series of extraction rates used in this study do not show any kind of trend (Figure 2).

The estimation using a volumetric heat in place model for the Los Humeros has already been made. In this study, the authors performed a numerical simulation including the heat flow and fluid motion equations (Bonté et al., 2020). From the geological model of the Los Humeros, they consider all the layers of rock with the same heat potential and with their respective physical characteristics. Their result offers an estimation of the energy content of the whole caldera. Our estimation of the size of the Los Humeros reserve is limited to the productivity zone and it is based on the production data, moreover it considers the layer of rocks along the feed zones reported on the well logs by the CFE.

Arellano Gómez et al. (2003) suggested a pressure model to estimate the undisturbed distribution of pressure along the reservoir; later, Arellano-Gómez et al. (2008) reported a decline pressure rate with values between 0.9 to 1.03 bar/year. The use of lumped parameter demands direct measurements of pressure (Brigham and Neri 1979). Unfortunately, the Los Humeros lacks an observation well and therefore direct records of pressure changes. Although the use of Arellano’s approach might lead to a pressure distribution during exploitation, this estimation must be validated against direct measurements. Moreover, extraction data do not show a clear declining rate for the majority of the wells (Figure 2), making the decline analysis difficult to perform.

In this sense, our forecast method of heat recovery is based on the statistical description of the data. We calculate two quartiles of the heat production history of each well. The first quartile represents a pessimistic scenario, while the third quartile stands for an optimistic scenario of production. This approach considers the variability of production (as a range between those two quartiles) while ignoring irrelevant outliers that determine the absolute minimum and the
maximum, the obvious characterizing the range of values. Assuming a similar extraction for the
next thirty years without any recharge by conduction or convection from below, we forecast the
production. Furthermore, we estimate the initial amount of heat with a sum of the reserve plus
the accumulated production of heat. These two quantities allow the calculation of the heat
recovery factor.

Figure 2 Extraction history of the most productive wells of the system.

Methodology

This study involves the productivity analysis of 29 wells with the aim to estimate the heat reserve
and the heat recovery factor of the Los Humeros productive geothermal system. The data was
collected during thirty years of continuous production and provided by CFE. The cumulated
extracted heat was calculated from the fluid and enthalpy reported per month per well. The
production of the next thirty years was forecasted from the statistical analysis of the data as
described above. The recovery factor is the ratio of the extracted quantity and the initial amount
of heat. Heat loss through the pipe wall and heat flow from the reservoir to the fluids were neglected. Furthermore, the possible interference of the injection wells was not considered.

**Extraction of heat**

The productivity data provided by the CFE includes mass extraction rate ($\dot{m}$), enthalpy ($h$), and well pressure. The data shows two frequencies: from 1986 till 2000 it was recorded daily, but from 2000 till 2017 it changed into a monthly record. In order to have the same frequency we calculated a monthly average of the daily data. Then, we described the data distribution to make the extraction forecast. The estimation of the total available heat at the surface began with the calculation of the heat flow ($\dot{Q}$), multiplying the mass flow rate ($\dot{m}$) and the enthalpy ($\Delta h$). The mass flow rate was reported as a sum of steam ($\dot{m}''$) and brine ($\dot{m}'$). However, the provided enthalpy describes to the vapor phase ($h''$). Without pressure data to calculate the corresponding enthalpy of the liquid phase, the model only considered the steam fraction, which represents more than 95% of the total mass flow for the majority of the wells. The last member in the model to get the available heat at the surface per well ($Q_e$) was the time difference between data points ($\Delta t$):

$$Q_e = \sum (\dot{m}'' \Delta h'') \Delta t \quad (1)$$

where $\Delta h'' = h'' - h_0$, and $h_0$ is the value of enthalpy of water at Los Humeros average annual temperature, i.e. 21 °C (Vidal-Zepeda R. 1990).

Then, we estimated the area of the reservoir affected by the fluid extraction. Since we neglect heat loss, the available heat at the surface equals the same quantity in the reservoir ($Q_R$); i.e. $Q_R = Q_e$. To estimate the energy stored, the volumetric heat in place consider an effective thickness times an area, i.e. an effective volume (Limberger et al. 2018). In our case, we are assuming that this area is the affection of each well in the reservoir. Hence, this calculation was carried out by the combination of the volumetric heat in place and the eq. (1):
\[ A = \frac{Q_e}{\varrho c_p \Delta T_{fz} \Delta \xi} \quad (2) \]

where \( \Delta T_{fz} \) is the temperature difference between the feed zone and the injected brine; \( \Delta \xi \) is the effective thickness of the feed zone. In this model \( \varrho c_p \) is the weighted average of the volumetric heat capacity of the rocks. This includes the isobaric heat capacity \( (c_p) \), the density \( (\varrho) \) and the porosity \( (\phi) \) for each different rock type \( (r) \) along the feed zone of the well:

\[ \varrho c_p = \frac{\sum_{n=1}^{N} \omega_n [\varrho_{rn} c_{pr} (1 - \phi_n)]}{\sum_{n=1}^{N} \omega_n} + \frac{\sum_{n=1}^{N} \omega_n [\varrho_{wn} c_{pw} \phi_n]}{\sum_{n=1}^{N} \omega_n}, \quad (3) \]

where \( w \) is water; \( (N, n) \) are the number of different rock types along the feed zone, and the weight \( \omega \) is the depth percentage of the respective rock type around the corresponding well. \( (\sum_{n=1}^{N} \omega_n = 1) \) Therefore, the weighted average is:

\[ \varrho c_p = \sum_{n=1}^{N} \omega_n [\varrho_{rn} c_{pr} (1 - \phi_n)] + \sum_{n=1}^{N} \omega_n [\varrho_{wn} c_{pw} \phi_n]. \quad (4) \]

We calculated the depth percentage of rocks from the bore hole reports of the CFE. The values to feed each member of \( \varrho c_p \) are shown in table 1, it also includes the porosity of the rocks \( (\phi) \).

As previously mentioned, the difference \( \Delta T_{fz} = T_{fz} - T_{inj} \), takes the temperature at the feed zone depth \( (fz) \) and the plant’s brine reinjection \( (inj) \). Finally, the term \( \Delta \xi \) is the effective thickness of the aquifer. In this particular case, the effective thickness was considered identical to the permeable zone per well. We took the location and thickness of the permeable zones from injection test reports of the CFE. According to the reports, the majority of the wells have more than one permeable zone, although it is not clear which ones are the actual feed zones.

Lacking this information, we assume a sum of the thicknesses of the permeable zones as well as an average of \( T_{fz} \) (Error! Reference source not found.).

\[ Table \ 1 \ Physical \ parameters \ of \ rocks, \ \sigma \ is \ the \ standard \ deviation \ (Weydt \ et \ al. \ 2020). \]
|                  | [kg m⁻³] | z | [-] | [-] | [J kg⁻¹ K⁻¹] |
|------------------|----------|---|-----|-----|--------------|
| Basalt lava      | 1,920    | - | 0.32| 0.01| 761          |
| Andesite         | 2,150    | - | 0.22| 0.04| 784          |
| Limestone        | 2,320    | 0.01| 0.14| 0.06| 793          |
| Ash fall deposits| 1170     | - | 0.51| -   | 861          |

**Forecast of production and estimation of the original reserve of heat**

The following forecast was based on the productivity rate of each well. The equation that was applied is:

\[
Q_{\text{ex}}(t_{\text{ex}}) = \begin{cases} 
Q_{\text{opt}} = \dot{m}''_{C3} \Delta h''_{C3} \Delta t_{\text{ex}} \\
Q_{\text{pes}} = \dot{m}''_{C1} \Delta h''_{C1} \Delta t_{\text{ex}} 
\end{cases}
\]  

(5)

where, the subscripts C1, C3 are first and third quartile of the production flow rate, which define the optimistic (opt) and pessimistic (pes) scenario. \(\Delta t_{\text{ex}}\) is the extrapolation time, in this case thirty years. \(Q_{\text{ex}}\) is the production forecast for the next period. In our case we are considering thirty years as the duration of a production period, therefore \(Q_{\text{ex}} \rightarrow Q_{30}\), and \(\Delta t_{\text{ex}} = 30\) years.

The theoretical used area was also calculated with eq. (2) Error! Reference source not found.

The initial reserve of heat (\(Q_0\)) was calculated with the sum of the extracted (\(Q_e\)) plus the forecasted heat (\(Q_{30}\)):

\[
Q_0 = Q_e + Q_{30}.
\]

(6)
To validate eq. (6), we performed a test using the known production data. We applied this methodology to the first twenty years of production to forecast the last ten. After results we compared the forecast with the monitoring data.

Figure 3 Sketch showing the assumption of merging of the feed zones. The outer cylinder is the resulting volume of the forecast.

Theoretical heat content

The theoretical heat content was calculated by combining the results obtained by Bonté et al. (2020) and the accumulated heat production ($Q_{30}$). From $Q_{30}$ the used area was calculated with eq. (2). Then, this area was multiplied by the middle heat density value reported in the map from Bonté et al. (2020). This result was considered as the theoretical heat content.

Recovery factor of the Los Humeros

The last parameter estimated was the recovery factor ($R_f$). The $R_f$ is defined as the ratio between the available heat produced at the wellhead ($Q_{wh}$) and the theoretical heat potential ($Q_R$) (Gringarten, 1978; Muffler & Cataldi, 1978; Williams, 2007; Garg, 2010; Grant, 2014):
In this research, we did not focus on the theoretical potential of the system. Instead, $R_f$ was calculated as the ratio of the actual extracted heat ($Q_e$) and the original reserve of heat ($Q_0$):

$$R_f = \frac{Q_{wh}}{Q_R} \quad (7)$$

$$R_{60} = \frac{Q_e}{Q_0} \quad (8)$$

The $R_{60}$ is an estimation of how much heat can be extracted from the system under the particular circumstances of 60 years of production, 29 wells and holding a certain rate of extraction.

Results

The statistical description of the data is shown in Figure 4B. The violin charts show the distribution of the data including the first and the third quartile, as well as the median of the data, being the second quartile. The productivity ranges from 6 to 56 ton·hr$^{-1}$. The first and third quartiles of each well were used in the pessimistic and optimistic scenarios. Individual assessment of the extracted heat and the forecast is shown in table 2. Results displayed in table 2 show a huge heterogeneity among the wells. The validation of the forecast model shows that 75% of the production lies within the forecasted value (shown in Figure 5).

After thirty years of continuous production, the extracted heat from the system is calculated as approximately 340 PJ. The forecasted heat production is between 430 (pessimistic) and 580 PJ (optimistic). Therefore, the total reserve size amounts to 770...920 PJ. These are the resulting sums of the individual assessments for each well. The corresponding recovery factor in 2017 is 37...44%.

The area calculated with eq. (2) was plotted in the map of Figure 6B. This allows us to appraise the extension of the area of the reservoir that each well has affected. For this estimation, no recharge was considered.
The map on Figure 6B includes the volumetric heat in place calculated during the GEMex project by Bonté et al. (2020). The accumulated production of heat ($Q_{30}$) until 2017 is 340 PJ. The equivalent area is 4.1 km$^2$, calculated with eq. (2). The middle value of the heat in place is 1750 PJ·km$^2$. Therefore, the resulting $Q_R$ is 7,175 PJ and the $R_f$ is 4.75%.
Figure 4 A) Well depths and feed zones visualized as colored squares. On the top of each well is the year of the first productivity record. B) Violin chart showing the distribution of the production rates. The widths are proportional to the number of data points with the given flowrate. The median, Q1 and Q3 are presented by white lines. The gray block shows the range of the whole production. The bottom of the square is set by the Q1 of the less productive well. The top is set by the Q3 of the most productive well.
Figure 5 Validation of the model given by eq. (6). The observed value for the extraction is shown in blue. Forecast using our model with 80% of the data for training are shown as purple and green colors. The model is considered to be appropriate when the observed value is between the pessimistic and the optimistic values. Wells enclosed in parenthesis operated for 22 years and they are not considered into the validation as they do not have enough data.
Table 2 Estimation of the extracted heat, forecast of production and recovery factor per well
| Well | Date of first record | UTM (14N) | Extracted heat (2017) | Forecasted initial heat reserve | Radius (forecast) | Thickness | $R_{50}$ |
|------|---------------------|-----------|-----------------------|-------------------------------|------------------|-----------|---------|
|      |                     |           | PJ                    | PJ                            | PJ               | m        | m       | m       |
| m-yy | X       | Y       | Q1 | Q2 | Q3 | Q1 | Q3 | Q1 | Q2 |
| H1   | 6-82         | 661906   | 2175064 | 8.2 | 6.6 | 13.9 | 14.8 | 22.1 | 185 | 248 | 303 | 160 | 55% | 37% |
| H7   | 7-84         | 661838   | 2175871 | 34.4 | 27.5 | 34.3 | 61.9 | 68.7 | 332 | 445 | 469 | 250 | 56% | 50% |
| (H8) | 8-85         | 661582   | 2176392 | 7.3 | 5.6 | 13.5 | 12.9 | 20.8 | 228 | 304 | 386 | 100 | 56% | 35% |
| (H16) | 12-85        | 661557   | 2178250 | 8.2 | 9.1 | 21.3 | 17.4 | 29.6 | 173 | 251 | 328 | 250 | 47% | 28% |
| H11  | 1-86         | 662574   | 2177436 | 8.9 | 5.8 | 8.0 | 14.7 | 16.9 | 218 | 280 | 301 | 170 | 60% | 52% |
| H17  | 7-86         | 662298   | 2178606 | 13.3 | 14.4 | 17.0 | 27.7 | 30.3 | 150 | 216 | 226 | 350 | 48% | 44% |
| H6   | 7-86         | 663508   | 2173545 | 22.1 | 17.6 | 33.8 | 39.7 | 55.9 | 225 | 302 | 358 | 250 | 56% | 40% |
| H12  | 7-86         | 663830   | 2173053 | 34.5 | 30.8 | 42.0 | 65.4 | 76.5 | 177 | 244 | 264 | 800 | 53% | 45% |
| H9   | 8-86         | 660618   | 2178216 | 41.0 | 34.6 | 45.2 | 75.6 | 86.3 | 541 | 734 | 784 | 100 | 54% | 48% |
| H19  | 10-86        | 662881   | 2176443 | 16.4 | 15.4 | 18.3 | 31.9 | 34.8 | 116 | 162 | 169 | 600 | 52% | 47% |
| H15  | 1-88         | 661638   | 2178804 | 15.8 | 18.2 | 22.3 | 34.0 | 38.1 | 195 | 285 | 302 | 400 | 47% | 42% |
| H20  | 1-88         | 663330   | 2177486 | 25.0 | 24.2 | 28.8 | 49.2 | 53.9 | 233 | 327 | 342 | 300 | 51% | 46% |
| H30  | 10-88        | 661488   | 2178547 | 14.3 | 14.3 | 18.1 | 28.6 | 32.4 | 173 | 244 | 260 | 400 | 50% | 44% |
| H31  | 3-89         | 661832   | 2179041 | 24.5 | 24.7 | 28.0 | 49.2 | 52.6 | 375 | 531 | 549 | 150 | 50% | 47% |
| H32  | 4-89         | 662631   | 2178043 | 18.3 | 23.4 | 25.6 | 41.7 | 43.9 | 205 | 309 | 317 | 400 | 44% | 42% |
| H33  | 5-89         | 661534   | 2177986 | 5.7 | 4.7 | 8.5 | 10.5 | 14.2 | 189 | 256 | 299 | 100 | 55% | 40% |
| H3   | 10-94        | 660622   | 2177903 | 3.5 | 4.6 | 5.5 | 8.1 | 9.0 | 111 | 169 | 178 | 175 | 43% | 39% |
| H34  | 10-94        | 662965   | 2177207 | 3.6 | 4.4 | 5.6 | 8.0 | 9.2 | 126 | 186 | 200 | 130 | 45% | 39% |
| H37  | 2-96         | 661074   | 2178346 | 9.4 | 15.5 | 19.1 | 25.0 | 28.6 | 271 | 441 | 471 | 70 | 38% | 33% |
| (H36) | 2-96        | 662564   | 2177396 | 0.5 | 4.1 | 5.3 | 4.7 | 5.9 | 39 | 114 | 128 | - | 12% | 9% |
| H39  | 4-98         | 663365   | 2173291 | 10.3 | 14.6 | 25.8 | 24.9 | 36.1 | 76 | 118 | 142 | 920 | 41% | 29% |
| H42  | 7-10         | 663320   | 2173500 | 1.5 | 6.1 | 6.8 | 7.6 | 8.4 | 55 | 124 | 130 | 300 | 20% | 18% |
**Figure 6 A)** Full extension of the Los Humeros caldera color indicating the density of the heat in place (Bonté et al., 2020). **B)** Resulting area affected by the production. **C)** Sketch showing the virtual merging of the feed zones and the assumed cylindric shape of the reservoir volume affected by the extraction.

**Discussion**

The exploitation of the Los Humeros geothermal reservoir has been the subject of several studies (Aragon-Aguilar A., Moya, and Izquierdo 2005; Arellano Gómez et al. 2003; Arellano-Gómez et al. 2008; García-Gutiérrez et al. 2002). While these reports have focused on the...
characterization of the system and its response to the exploitation, none of them have appraised
the size of the heat reserve of the Los Humeros nor the extraction of heat in the future. In this
work, we addressed these topics. We forecasted the extraction of energy, based on the history
of production and we estimated the size of the original reserve of heat. The forecast for energy
was 430...580 PJ with a model accuracy of 75 %. The original reserve is 770 and 920 PJ for the
pessimistic and optimistic scenario, respectively. Assuming no recharge, the recovery factor for
60 years and 28 wells, under an extraction rate of 6 to 56 ton·hr⁻¹, suggests that less than 45 %
of the system’s heat can be harvested.

Past and future of production

Past

The violin charts in Figure 4 show the historical distribution of the production data. There is high
variability in the extraction range of the wells. The highest value which is an outlier, belongs to
well H31. But the highest median belongs to well H12. The violin chart of the well H12 presents
two peaks which could be related with two different regimes of production, just like its
neighboring wells (H6 and H39). The extraction history for the well H12 (Figure 2), shows a lot
of variation for older records than the year 2000. Although, we made both plots after the
frequency reduction, if this bimodality were a consequence of this data treatment, all the wells
would present this distribution. Moreover, the well H39 still present this bimodality and this well
did not suffer a frequency reduction. This bimodality might be related with local changes in this
cluster or to their geographical position.

One example of geographical influence is the faulting. These three wells (H6, H12, H39) are in
the south, they are close to each other, and, they are next to Maztaloya fault. Therefore, the
permeability at this zone caused by the fault might have a seasonal effect linked with the rainfall
recharge in the aquifer. Although, the bimodality could be also a consequence of different
surface processes, as different pumping rates for example, if this was the consequence of the
bimodality, the three wells should experience similar changes on their surface processes. But, Aragon-Aguilar et al. (2005) suggested a geographical classification of the wells, according to them those wells close to the faults have a similar productivity index and extraction rate. Following this idea, those wells with a bimodal distribution (H1, H8, H16, H6, H12, H9, H39) are at the left of the Maztaloya fault. Yet, this feature is not conclusive as more wells are at the left of this fault and they do not present a bimodality. Maybe the bimodal wells not only are to the left of Maztaloya, but also, their feed zone are within the same rocks.

The extraction rate of the wells is quite different. The three most productive wells have one feed zone below 800 m (a.s.l.). According to Arellano Gómez et al. (2003) below this level, a second and hotter aquifer is found. Moreover, the only feed zone of the well H9 is below this level and it is the most productive well in the field. Thus, the high productivity rates could be a consequence of the location of this feed zone, or the deepest reservoir is more productive. This observation agrees with Arellano-Gómez et al. (2008). In their work, they showed a change in the physical parameters of the fluids. They linked negative changes to a bad connection with the deeper aquifer. Nevertheless, a feed zone located below the 850 m (a.s.l) is not the only requirement to have a high productivity rate as the wells H16, H11, and H17 also have a feed zone located below the 850 m, but their production is much lower than well H7 for example.

**Future**

From the different extraction quartiles, we applied eq. (5) to forecast the production. The model used to forecast the production of the data is very simple. We assumed the two quartiles as the constant future extraction rate. Despite its simplicity, the validation of the model shows that 75% of the forecasted heat production values are within the quartile range (Figure 5). Nevertheless, when comparing this result with the forecast calculated with the decline analysis and lumped parameter method, our approach looks bad. Both procedures were applied in the geothermal field Cerro Prieto, having an accurate prediction of the future values and a good
match between the production and the trend line proposed (Hector and Campbell 1990; Westwood and Castanier 1981). However, there are some remarks to be made about our model.

Since our model is based on the mass flow rate, the forecast shows the quantity of heat available at the surface if the extraction rate remains constant. For example, the well H7 has an accumulated heat production of 34.4 PJ and the forecast for the optimistic scenario is 34.3 PJ. Both numbers after 30 years of continuous extraction. This result might offer a clue about the extraction rate needed to produce a similar amount of heat. The assumption of a constant rate of extraction is a bit naïve, especially after the violin charts show a huge heterogeneity in the data, but it offers a coarse perspective about where the limits of the production could take place in the future. Still, this forecast is not entirely meaningless. It helped us to estimate the reserve of the heat of the Los Humeros.

The reserve that we calculated for the Los Humeros is the size of the system’s technical potential as defined by Rybach (2015), i.e. it is an exploitable amount of heat under the actual legal frame and using the installed technology. The cumulative heat production per well tells us how much heat has been already taken (assuming no heat loss). By the premise of a constant rate, the forecast tells us how much heat can be produced. The sum of these quantities offers an approximate insight of the original heat in place assuming a “closed tank”, i.e. without recharge. Nevertheless, the limits of the production are not considered at all. Since the mass extraction has a close relationship with the system pressure, this assumption is far from reality. More extraction could reduce reservoir pressure. In this sense, a better approximation needs precise pressure monitoring.

Influence of the wells in the reservoir

To estimate the extension of the reservoir, we applied eq. (2). This expression calculates the equivalent heat area, i.e., the area needed to have equality between the cumulative heat production ($Q_{30}$) and the stored heat in place ($Q_0$). This area is presented as a circle, which in
The 2D surface projection of a 3D subsurface cylinder (Error! Reference source not found.). The circles traced per well show the resulting area calculated with eq. (2) assuming a radial and steady flow (Figure 6). Eq. (2) describes the growing area as a function of extracted heat ($Q_e$). These circles will grow until production is stopped. Thus, the circle’s area might show the limit of the maximum level of extracted heat for the accumulated time of production.

When two cylinders’ outer boundary meet, the heat production of the implicated wells could be affected. If two cylinders meet, their shapes merge, decreasing the heat flow rate in the overlapping zone to the wells. To compensate for this reduction in the flow, the other parts of both cylinders will to grow faster:

Figure 7 Sketch of the circles deformation when to wells share the same aquifer. The size of the arrows is proportional to the heat flow into the well. In the central sketch, these arrows are larger. The right sketch represents the circles deformation as a consequence of a higher extraction rate. The name tag makes a reference to any couple of wells, sharing the same aquifer and whose circles meet.

The wells h15, h30, and h31 might represent this effect. These wells are sharing the same aquifer. The deformation of the cylinder is a much more complicated case since the feed zones are not at the same depth nor the same thickness. The cylindric deformation could include a stretching or shortening of the feed zone. This effect is beyond our considerations.

As previously stated, we are not considering any recharge. However, when the recharge of fluid is included, this effect might be different. The encounter of cylinders might derivate into a decrease of the water level in the effective thickness, i.e. a drop of pressure. In response to this pressure drop, a higher rate of the aquifer fluid might enter into the cylinder. Thus, the deformation of the shape could be slower or it could go to one well. For example, if the pumping
rate increase in well Hy (Figure 7) this increment on fluid demand could take fluid supply from the well Hx, diminishing the whole performance of Hx.

In any case, this encounter effect derivates in a demand increment. Here is another consideration. Although, the injection wells do not seem to affect the temperature of fluid (Ascencio Cendejas 1992; Iglesias et al. 2012), to satisfy this demand the cold front of injection could move faster towards this wells. If this new fluid is colder, then the temperature might be decreased affecting the performance of the implicated wells. Although any decrease in heat production has been recorded yet, it could happen within the next thirty years of production. The CFE reports do not mention from which feed zone the fluid is coming into the well and there are no pressure measurements regarding the flow. Therefore, we assumed that the geothermal brine flows into the well in all the feed zones. This model is extremely simple but it might offer a very coarse visualization of the possibility of wells interruption. However, there is no clear evidence of this effect on the surface, the performance of the wells has not decreased. Thus, if the interruption on the extraction between wells is happening, no evidence at the surface could mean that the recharge of hot fluid is very effective.

**Technical potential extension**

The size of the circles represents the used area, it also could be seen as the affected area of the system. The affected area is the portion of the reservoir that actually contains the hot fluid that was extracted by the wells. So, the area of eq. (6) is the Los Humeros reserve extension \( A(Q_0) \).

The difference between \( A(Q_0) \) and \( A(Q_{30}) \) is the potential area to be used with the installed equipment. In other words, it is the extension of the technical potential area of the Los Humeros. The theoretical potential is 20 times bigger than the technical one. Bonté et al. (2020) consider a much larger thickness (ca. 5 km). In their work, each layer of rock has the same potential to be a reservoir of heat. In this study, it is not the case. We are only considering the effective thickness of the aquifer, and our thickest value is less than 1 km (H12). In any case, this comparison just reflects the general idea about the technical potential of a geothermal resource, from which the
entire potential cannot be extracted (Nathenson & Muffler, 1975; Muffler & Cataldi, 1978; Rybach, 2015).

Technical recovery factor

The recovery factor based on sixty years of continuous production gives an insight into the maximum producible heat under these particular conditions (29 wells, extraction rate, etc.). This amount of heat is expressed in the technical potential of the system. In Los Humeros, all the technology needed to harvest the heat is already installed. Thus, this reserve is the technical portion of the system heat. Ergo, the $R_{60}$ delimitates the maximum level of heat that can be harvested from the technical potential stored.

The heat recovery factor ($R_f$) is closer to the relation of what is theoretically contained in the reserve vs. what can be extracted from it (Gringarten 1978; L. J. P. Muffler 1979; Williams 2007; Garg and Combs 2015; Grant 2014). In this sense, $R_f$ can help to delimitate the technical potential from the theoretical potential of the Los Humeros. It could define the maximum amount of heat attainable from the theoretical potential reserve.

The individual results show that the older wells have a similar $R_{60}$. Although each well is unique, this parameter can be found within a range imposed by their technical boundaries. Therefore, it gives an idea of the production limits. The $R_f$, calculated with the accumulated production and the theoretical heat in place, is similar to the value reported in the literature. The $R_{60}$ shows how much energy can be extracted under a given time frame. Eq (6) implies that the size of the reserve is defined by the extraction rate and the production time. In this sense, when this production phase ends in thirty years, another recovery factor could be defined (in that case $R_{90}$).

Sustainability of the system

Our approach assumes a tank of energy as the reserve. The analysis presented here is a vision of the actual state of the reservoir. Since we are considering neither heat nor fluid recharge, the
production cannot be sustainable in the actual sense of the word. Nevertheless, the geothermal system probably experiences recharge. This hint is shown by the wells H15, H30, and H31. If this recharge were in equilibrium with the extraction, the Los Humeros would be a fully renewable system, as described by Stefansson (2000). In contrast, O’Sullivan and Mannington (2010) argue that full renewability is rarely reached. Yet the production of wells H15, H30, and H31 is prominent, this could be related to other reasons. For example, the original reserve of energy is bigger than the actual calculation (i.e., a larger tank). In this case, a colder body of water has not been reached by the cylinders.

In this work, we assumed thirty years as the duration time per production phase. The forecast of energy offers a rough evaluation of the productivity of the system during this time frame. Based on these results, the system can sustain another period of production under comprehensive management of the site (reasonable extraction rates, enough injection, etc.). Based on the volcanic nature of the Los Humeros, the availability of enough heat to ensure the longevity of the exploitation is very likely, thus the main challenge is keeping the balance between extraction of fluids and the natural recharge of hot fluids, including injection. Although the injection of colder water does not seem to affect the whole production, precise pressure monitoring is needed, even the use of observation wells, to enhance the monitoring of the aquifer. Axelsson et al. (2004) presented a maximum level of production, which defines the limit of sustainable production. According to them, this limit is reached when the water level is stable under its actual exploitation regime and, below this limit the production can be sustained for 100 years or more. Besides, Rybach (2003) argues a long productivity period is the main characteristic of geothermal sustainability. Both papers emphasize the need for constant monitoring of the aquifer.

In this sense, at this stage is difficult to define the sustainable limit of production of the Los Humeros. In our estimation, the future production is achieved. Furthermore, the visualization of
the use of the reservoir by the wells is a useful tool to enhance the management of the site and ensures the future production.

Profitability and environmental affectation

A full insight of the sustainability of the heat extraction includes an economic assessment plus an evaluation of the environmental impact. Based on the fluid extraction and the energy production, a profitability assessment can be carried out which could help with the management of the system. Finally, a life cycle assessment could close an integrated evaluation of the Los Humeros exploitation.

Conclusions

We presented a forecasting method of the feasible heat extraction of the Los Humeros and the estimation of the heat recovery factor. Our findings define a limit of the future heat production levels (assuming a constant extraction rate). Based on this limit, the definition of the original reserve of the system delimitates the extension of the technical potential of the Los Humeros. In this sense, the technical recovery factor states the maximum level of heat production attained for thirty-year-old wells under a defined extraction rate. This information can be used by stakeholders to clarify the limitations of the production and therefore meet the risk associated with new investment in the system. Although these results are not enough to claim something about the sustainability of the system, they open important topics to put the focus on. For example, the overlapping of circles of the resulting used area. The exploitation of the same aquifer by near wells could be an aggressive strategy, which might increase the pressure drop and compromising the heat production.

List of symbols and abbreviations

\[ A \] Area \([m^2]\) \[ R_{60} \] Technical recovery factor
Availability of the data
The productivity data in which we based our investigation belongs to a private-state company and we do not have the permission to make it public. Although it is presented here in the violin charts, they are shown for analysis purposes.

Declaration of competing interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
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Authors Contribution

Hector Gonzalez-Garcia: Writing original draft, Conceptualization, Visualization, Methodology, validation, Formal Analysis and Project administration. Henning Francke: Conceptualization, Visualization, Methodology, Formal Analysis. Ingo Sass: Project administrator, Methodology. Ernst Huenges: data acquisition, Conceptualization, project administrator.

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