Sustainability assessment of geothermal systems under exploitation: Los Humeros, Mexico, as a study case

Dissertation

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Declaration

I hereby declare that the presented dissertation is based on original research and is the result of my own work. I certify that this dissertation contains no material which has been accepted for the award of any other degree in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

Potsdam, August 17, 2022

A mis padres,
y a ti,
Óscar.

Abstract

Nowadays, humanity is facing a significant challenge due to climate change. Therefore, the pressure to use sustainable ways to solve the current necessities is growing. One of the primary necessities is energy supply, and geothermal resources might represent a sustainable way to solve this. However, detailed monitoring at different development phases is needed to ensure sustainable use. This work proposes a general methodology to assess the sustainable exploitation of any geothermal site in the world. This methodology is based on Los Humeros, a geothermal site in Mexico exploited for the last 30 years.

The proposed methodology is based on three basic aspects present in any producing geothermal site in the world: the stored energy, the environmental affectation, and the profitability performance of the project. Since geothermal energy is considered a renewable source and the environmental affectation is low, this work hypothesizes that exploiting the geothermal reservoir at Los Humeros is done under sustainable limits. To prove that, three main objectives were proposed:

- To estimate the stored energy in the geothermal system
- To determine the CO_2 footprint of the power station
- To assess the financial performance of the power project

Each of the objectives represents one of the three cornerstones to define the sustainability of geothermal exploitation: enough available energy, low environmental impact, and sufficient money to cover all the possible externalities.

Los Humeros is located in an active volcanic caldera. Therefore, there is a constant recharge of heat, which means enough energy to supply the demand of the power station for centuries. The first objective resulted in estimating the heat production for the next 30 years. This goal was reached by analysing production data from the wells. This data included mass extraction rate and fluid enthalpy—the analysis derived two production scenarios named pessimistic and optimistic. The optimistic one provided an estimation of 580 PJ, whereas the pessimistic predicted an energy extraction of 430 PJ. These scenarios were based on the quantiles of the historical mass extraction. Enough energy alone does, however, not fulfil the requirement for sustainability. The geothermal reservoir must be constantly monitored to manage the exploitation rate under the system's sustainability limits and thus, the next generation will be able to exploit this volcanic geothermal reservoir.

This last phrase leads to the next objective. The second objective was to determine how large is the CO_2 footprint per kWh generated by the power station in Los Humeros. In this accounting, the CO_2eq released due to the construction of the power station was included. As a result, with an emission factor of 442 to 580 $g_{CO2}eq/kWh_{el}$ Los Humeros is in the the same range as the average Mexican emission factor (480 $g_{CO2}eq/kWh_{el}$ in 2019). Finally, some options to deal with this CO_2 externality were explored. Among them, the possibility of changing the current conversion technology for a closed binary station was considered.

However, in order to make this change in technology, Los Humeros needs investment. The government and/or private investors can make this investment, or the profit of the power station can be enough, then the operator company (the *Comisión Federal de Electricidad*) can finance it in a free-debt scheme. In any case, the project needs to be profitable to solve all the possible externalities.

In this sense, this dissertation's third goal was to estimate the power station's profitability. As mentioned before, Los Humeros has been under exploitation for the last 30 years. For the next period, upgrading of the conversion technology was carried out. To do that, the power station required a considerable investment. Therefore, this dissertation's last goal was to estimate two financial metrics to know the profitability of the geothermal power station: the break-even and the net present value (NPV). The NPV was evaluated using different interest rates.

The profitability assessment was done for two scenarios. The first one considered the actual business scheme. It is called “the vesting contract”. The second scenario assumes that the power station participates in the open and regulated Mexican electricity market. The vesting contract is designed to prevent the volatility of the spot market, but it also aims to make the power station profitable. The results showed a break-even after 8 years in this scenario and after 4.5 years in the second one. However, the NPV showed only negative values for the second scenario. In principle, that outcome suggests not to invest in this project, yet this NPV evaluation was done for only five years and not for the entire 25 years of the lifetime.

After the application of this proposed methodology, the results showed that the current exploitation of Los Humeros is not sustainable. The three studies are necessary to have a wider overview of the current situation of this activity. The results showed enough available energy for the next period. Although the CO_2 footprint is comparable with the average fossil Mexican emission factor, some options to mitigate this could be applied with the earnings perceived by the sale of electricity. Thus, exploiting the geothermal reservoir is currently not sustainable, but there is a solid potential to be. The explored aspects defined three indicators: energy, CO_2 footprint, and money. Two offered positive results towards sustainability; however, the environmental affectation is a hurdle that could be overcome in the following years.

Resumen

Actualmente la humanidad se enfrenta a un gran desafío debido al cambio climático. Por lo tanto, la presión para utilizar formas sostenibles de resolver las necesidades actuales está creciendo. Una de las principales necesidades es el suministro de energía, y los recursos geotérmicos podrían representar una forma sostenible de resolver esto. Sin embargo, se necesita un seguimiento detallado en las diferentes fases de desarrollo para garantizar un uso sostenible.

Este trabajo propone una metodología general para evaluar la explotación sostenible de cualquier sitio geotérmico en el mundo. Esta metodología se basa en un sitio geotérmico en México explotado durante los últimos 30 años. Los Humeros es el sitio elegido para este estudio. La metodología propuesta se basa en tres aspectos básicos presentes en todo sistema geotérmico bajo explotación: la energía almacenada, la afectación ambiental y el rendimiento de rentabilidad del proyecto.

Dado que la energía geotérmica se considera una fuente renovable y la afectación ambiental es normalmente baja, este trabajo plantea la hipótesis de que la explotación del yacimiento geotérmico en Los Humeros se realiza bajo límites sostenibles. Para demostrarlo, se propusieron tres objetivos principales:

- Estimar la energía almacenada en el sistema geotérmico.
- Determinar qué tan grande es la huella de CO_2 de la central eléctrica.
- Evaluar el desempeño financiero del proyecto de energía.

El objetivo de estas metas es dar una comprensión de tres piedras angulares necesarias para definir la sostenibilidad de la explotación geotérmica: suficiente energía, bajo impacto ambiental y una buena rentabilidad para cubrir todas las posibles externalidades. Los Humeros se encuentra en una caldera volcánica activa. Por lo tanto, hay suficiente energía para abastecer la demanda de la central eléctrica durante siglos.

El primer objetivo fue en la estimación de la producción de energía para los próximos 30 años. Esta estimación se hizo mediante el análisis de los datos de producción de los pozos. Estos datos incluyeron la tasa de extracción masiva y la entalpía de fluidos: el análisis derivó dos escenarios de producción. Estos han sido llamados pesimista y optimista. El optimista ofrecía una estimación de 580 PJ, mientras que el pesimista da una extracción de energía de 430 PJ. Estos escenarios se basaron en los cuartiles de la extracción histórica de masa. Suficiente energía no cumple con el requisito de sostenibilidad. El sistema geotérmico debe ser monitoreado constantemente para garantizar que la próxima generación utilice este yacimiento geotérmico volcánico.

Esta última frase da la introducción al siguiente objetivo. Las emisiones de CO_2 asociadas a la actividad volcánica son bien conocidas. Por lo tanto, el segundo objetivo fue determinar qué tan grande es la huella de CO_2 por kWh generada por la central eléctrica de Los Humeros. Para esta contabilidad, se incluyó el CO_2eq causado por la construcción de la central eléctrica. Como resultado, con un factor de emisión de 442 a 580 $g_{CO2}eq/kWh_{el}$ Los Humeros se encuentra bajo los mismos niveles que el factor de emisión promedio mexicano (480 $g_{CO2}eq/kWh_{el}$ en 2019). Finalmente, se exploraron algunas opciones para hacer frente a esta externalidad de CO_2. Entre ellos, se incluyó la posibilidad de cambiar la tecnología de conversión.

Sin embargo, para tener una oportunidad real de instalar una nueva central eléctrica, Los Humeros necesita inversión. El gobierno y los inversores privados pueden hacer esta

inversión, o la central eléctrica puede resolverla. En cualquier caso, el proyecto debe ser rentable para resolver todas las externalidades posibles de forma saludable. En este sentido, el tercer objetivo de esta tesis doctoral era estimar la rentabilidad de la central.

Como se mencionó anteriormente, Los Humeros ha estado bajo explotación durante los últimos 30 años. Durante este tiempo, Los Humeros cambió la tecnología de generación. Para ello, la central eléctrica requirió una inversión considerable. Por ello, el último objetivo de esta tesis doctoral es estimar dos métricas financieras para conocer la rentabilidad del proyecto eléctrico: el Periodo de retorno y el valor presente neto (VAN).

El VAN se evaluó utilizando diferentes tasas de interés. La evaluación de la rentabilidad se realizó para dos escenarios. El primero consideró el esquema de negocios real. Se llama "el contrato legado", el segundo escenario supone que la central eléctrica participa en el mercado eléctrico mexicano abierto y regulado. El contrato legado está diseñado para evitar la volatilidad del mercado spot, pero también tiene como objetivo hacer que la central eléctrica sea rentable. Los resultados mostraron equilibrio financiero luego de 8 años en este escenario y 4.5 años para el segundo. Sin embargo, el VAN mostró valores negativos para el segundo escenario. En principio, ese resultado sugiere que no se debe invertir en este proyecto, sin embargo, esta evaluación del VAN se realizó durante solo cinco años y no durante los 25 años completos de la vida útil.

Tras la aplicación de esta metodología, se puede derivar la afectación a los diferentes indicadores de sostenibilidad. En las circunstancias dadas la explotación del recurso geotérmico no es sostenible. Los resultados mostraron suficiente energía almacenada para el próximo período. Aunque hay una huella de CO_2 sustancial, algunas opciones para mitigar esto se pueden aplicar con las ganancias percibidas por la venta de electricidad. Por lo tanto, explotar el reservorio geotérmico no es sostenible, pero existe un sólido potencial para serlo. Los aspectos explorados definieron tres indicadores: energía, huella de CO_2 y dinero. Dos ofrecieron resultados positivos hacia la sostenibilidad; sin embargo, el impacto ambiental es un obstáculo que podría resolverse en los próximos años.

Kurzfassung

Heutzutage steht die Menschheit aufgrund des Klimawandels vor einer großen Herausforderung. Daher wächst der Druck, nachhaltige Wege zur Lösung der aktuellen Probleme zu finden. Eins der Hauptbedürfnisse ist die Energieversorgung, und geothermische Ressourcen können eine nachhaltigen Beitrag zu dessen Erfüllung leisten. Allerdings ist eine detaillierte Überwachung in den verschiedenen Entwicklungsphasen erforderlich, um eine nachhaltige Nutzung zu gewährleisten. In dieser Arbeit wird eine allgemeine Methodik zur Bewertung der nachhaltigen Nutzung eines beliebigen geothermischen Standorts irgendwo in der Welt vorgeschlagen Als Beispiel für diese Studie und als Basis für diese Methode wurde der geothermischen Standort Los Humeros in Mexiko gewählt, wo seit 30 Jahren produziert wird.

Die vorgeschlagene Methode basiert auf drei grundlegenden Aspekten, die an jedem aktiven geothermischen Standort auf der Welt vorhanden sind: die gespeicherte Energie, die Umweltauswirkungen und die Rentabilität des Projekts. Da die geothermische Energie als erneuerbare Quelle gilt und die Umweltauswirkungen gering sind, wird in dieser Arbeit die Hypothese aufgestellt, dass die Nutzung des geothermischen Reservoirs in Los Humeros innerhalb nachhaltiger Grenzen erfolgt. Um dies zu beweisen, wurden entsprechend den genannten Aspekten drei Hauptziele aufgestellt:

- Abschätzung der gespeicherten Energie im geothermischen System

- Bestimmung des CO_2-Fußabdrucks des Kraftwerks

- Bewertung der Profitabilität des Kraftwerksprojekts

Jedes der Ziele steht für einen der drei Pfeiler der Nachhaltigkeit der Nutzung geothermischer Reservoire: ausreichend nutzbare Energie, geringe Umweltauswirkungen und genügend Geld, um alle möglichen externen Effekte zu decken. Los Humeros liegt in einer aktiven Vulkancaldera. Daher kann davon ausgegangen werden, dass genügend thermische Energie vorhanden ist, um den Bedarf des Kraftwerks für Jahrhunderte zu decken. Das erste Ziel bestand darin, die Wärmebereitstellung für die nächsten 30 Jahre abzuschätzen. Dieses Ziel wurde durch die Analyse der Förderdaten aus den Bohrlöchern erreicht. Diese Daten umfassten die Förderrate und die Fluidenthalpie. Aus der Analyse wurden zwei Szenarien abgeleitet, ein pessimistisches und ein optimistisches. Das optimistische Szenario liefert eine Schätzung von 580 PJ, während das pessimistische Szenario eine Energiegewinnung von 430 PJ ergibt. Diese Szenarien basierten auf den Quantilen der historischen Massenentnahme. Eine ausreichende Energiemenge genügt aber nicht, um die Anforderungen der Nachhaltigkeit zu erfüllen. Das geothermische Reservoir muss feinmaschig überwacht werden, um die Förderrate innerhalb der Nachhaltigkeitsgrenzen des Systems zu steuern, damit auch nachfolgende Generationen dieses vulkanische geothermische Reservoir noch nutzen können.

Dieser letzte Satz führt zum nächsten Ziel. Die mit der vulkanischen Aktivität verbundenen CO_2-Emissionen sind allgemein bekannt. Daher bestand das zweite Ziel darin, den CO_2-Fußabdruck pro erzeugter kWh im Kraftwerk Los Humeros zu bestimmen. Für diese Bilanzierung wurden die Emissionen von Treibhausgasen (CO_2eq) durch den Kraftwerksbau berücksichtigt. Das Ergebnis: Mit einem Emissionsfaktor von 442 bis 580 $g_{CO2}eq/kWh_{el}$ liegt Los Humeros unter dem Niveau des durchschnittlichen

mexikanischen Emissionsfaktors. Abschließend wurden einige Optionen für die Senkung dieses Emissionsfaktors untersucht. Eine Möglichkeit wäre, die Umwandlungstechnologie zu ändern.

Um das umzusetzen, braucht Los Humeros Investitionen. Die Regierung und/oder private Investoren können diese Investitionen tätigen oder das Kraftwerk kann diese Aufgabe übernehmen. In jedem Fall muss das Projekt rentabel sein, um alle möglichen externen Effekte auf gesunde Weise zu lösen.

In diesem Sinne bestand das dritte Ziel dieser Arbeit darin, die Rentabilität des Kraftwerks abzuschätzen. Wie bereits erwähnt, wurde das Kraftwerk Los Humeros in den letzten 30 Jahren genutzt. Für den nächsten Zeitraum wurde eine Modernisierung der Umwandlungstechnologie durchgeführt. Dazu war eine erhebliche Investition in das Kraftwerk erforderlich. Daher bestand das letzte Ziel dieser Dissertation letztendlich darin, zwei Finanzkennzahlen zu ermitteln, aus denen sich die Rentabilität des Projekts ergibt: den Break-even und den Kapitalwert (NPV). Sie wurden unter Verwendung verschiedener Zinssätze bewertet.

Die Rentabilitätsbewertung wurde für zwei Szenarien durchgeführt. Im ersten Szenario wurde das tatsächliche Geschäftsmodell betrachtet. Dabei handelt sich um einen sogenannten Freizügigkeitsvertrag (vesting contract). Das zweite Szenario geht davon aus, dass das Kraftwerk am offenen und regulierten mexikanischen Strommarkt teilnimmt. Der Freizügigkeitsvertrag soll die Volatilität des Spotmarktes verhindern, zielt aber auch darauf ab, das Kraftwerk rentabel zu machen. Die Ergebnisse zeigen, dass die Gewinnschwelle im ersten Szenario nach 8 Jahren und im zweiten Szenario nach 4,5 Jahren erreicht wird. Der Kapitalwert (NPV) wies jedoch für das zweite Szenario negative Werte auf. Im Prinzip spricht dieses Ergebnis dafür, nicht in dieses Projekt zu investieren, doch wurde diese NPV-Bewertung nur für fünf Jahre und nicht für die gesamten 25 Jahre der Lebensdauer durchgeführt.

Nach der Anwendung dieser Methode kann die Auswirkung auf die verschiedenen Nachhaltigkeitsindikatoren abgeleitet werden. Unter den gegebenen Umständen ist die Ausbeutung der geothermischen Ressource nicht nachhaltig.

Die Ergebnisse zeigen, dass genügend Energie für den nächsten Zeitraum zur Verfügung steht. Obwohl es einen erheblichen CO_2-Fußabdruck gibt, könnten einige Optionen zur Abschwächung dieses Effekts mit den Einnahmen aus dem Verkauf von Strom finanziert werden. Die Ausbeutung des geothermischen Reservoirs ist also momentan nicht nachhaltig, könnte es aber sein. Für die untersuchten Aspekte wurden drei Indikatoren definiert: Energie, CO_2-Fußabdruck und Geld. Zwei davon zeigen positive Ergebnisse im Hinblick auf die Nachhaltigkeit; die Umweltauswirkungen stellen jedoch ein Hindernis dar, das allerdings in den nächsten Jahren überwunden werden könnte.

Preface

This cumulative dissertation presents a methodology to estimate the sustainable exploitation of a geothermal site. The idea came from the three-pillar conception of what sustainability must include: social, environment and economics. However, to adapt that concept for the geothermal applications required a different conception. Although, economic and environment is included, the social impact regarding the use of geothermal can be derivate from these two.

This work was developed with the entire help and supervision of Dr.-Ing. Henning Francke, who put an idea on my mind regarding sustainability, he told me “it means forever” and my mind just exploded. After that, the question regarding what does this mean for geothermal came and the answer was the proposal I am offering here.

Although much work is still needed, I strongly believe that the agreement regarding this concept in the geothermal industry is vital to have not only better management of the sites but also stronger laws regarding the use of geothermal.

I hope this work open the dialog to reach an agreement about the requirements needed to make a full disclosure of sustainable geothermal energy. Attend the necessities of our industry will help to cover the energy demand under acceptable development limits.

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Potsdam, 2022

Héctor Michán

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Abreviations

atm	atmosphere
ºC	Celsius
CENACE	*Centro Nacional de Control de Energía*
CEL	*Certificado de Energía Límpia*
CFE	*Comisión Federal de Electricidad*
BEP	Break-even point
EF	Emission Factor
EGS	Enhanced geothermal systems
FU	Functional Unit
g-G	Geothermal gradient
GHG	Greenhouse gases
GTPS	*G*eothermal Power Station
GP	Geothermal Project
GS	Geothermal System
INAI	*Instituto Nacional de Acceso a la Información*
IPCC	Intergovernmental panel of climate change
LC	Levelized cost
LCA	Life cycle analysis
LCOE	Levelized Cost of Energy
LCI	Life cycle inventory
MBP	*Mercado de Balance de Potencia*
MECP	*Mercado eléctrico a corto plazo*
MEM	*Mercado Eléctrico Mayorista*
MMXN	Millions of Mexican Peso
MIA	*Manifestación de Impacto Ambiental*
NCG	Non-condensable gases
Q_E	Extracted heat
Q_F	Forecasted heat
NPV	Net present value
nCO_2	Non-condensable CO_2
nCO_2eq	Equivalent non-condensable CO_2
SENER	*Secretaría de Energía*
Re	Recovery factor
O&M	Operation and Maintenance
ORC	Organic rankine cycle
SF	Single flash
TMVB	Transmexic Volcanic Field
UN	United Nations
UP	Unit-Process

Formula Symbols

A	Area
Cf	Cashflow
c_p	Heat capacity factor
C(K)	Cost function
e	Electricity
eP	Electricity Price
h''	Steam enthalpy
i	Interest
I	investment
Ic	Installed Capacity
$\dot{m}$	Mass flow
Oc	Operational Cost
Q	Heat (formula)
Q_0	Initial heat

Subindices

T	time
R_{60}	Recovery 60 years
V	Volume

Greek

K	Quantity
ϱ	Density
Δ	Difference
ξ	Temperature
ω	Weight
ϕ	Porosity

Units

$g_{CO2}eq$	Grams of equivalent CO_2
GW	Gigawatt
kt	Kilotons
kW	Kilowatt
MW	Megawatt
PJ	Peta Joules
T	Thickness

el	Electric
f	Fluids
F	Forecast
fz	Feed zone
h	Hour
R	Reservoir
r	Rock
WH	Well head

Cumulative dissertation

This cumulative dissertation comprises three journal publications and one data base, which are included in the manuscript.

Appendix A: **González-García, H.**, Francke, H., Sass, I. *et al.* Production forecast and estimation of the recovery factor of the Los Humeros geothermal field, Mexico. *Geothermal Energy* **9,** 13 (2021). https://doi.org/10.1186/s40517-021-00194-z

Appendix B: **González-García, H.,** H. Francke, L. Göllner-Völker, B. Welsch, S. Kranz, E. Huenges, L Schebeck, and I Sass. 2022. "CO_2 Emission Assessment of the Geothermal Power Station Los Humeros, Mexico." *Geothermics* 104 (February): 102471. https://doi.org/10.1016/j.geothermics.2022.102471.

Appendix C: **González García, H.** and Francke, Henning and Huenges, E. and Sass, I., Financial Performance Analysis of the Geothermal Power Station of Los Humeros, Mexico.Available at SSRN: https://ssrn.com/abstract=4160005 or http://dx.doi.org/10.2139/ssrn.4160005

1. Sustainability, Mexico and the use of geothermal

The energy transition decarbonizes the electric grid (Solomon & Krishna, 2011). This strategy is one of the measures applied to mitigate climate change by reducing the CO_2 footprint associated with electricity generation. This process is being applied in many countries. Germany is the leading nation in Europe on this topic, and it has put much effort into designing a feasible electric matrix using only renewable sources. Among all the States, the speed and the effort in this task differ. However, this is a topic of constant discussion. In America, the situation is different. On one side, many Countries have adopted international agreements to reduce their carbon footprint, but the process has been slow due to the continent's economic situation (International Renewable Energy Agency, 2022).

Mexico aims to produce more than 50 % of its electricity by 2050 (SENER, 2017a). Therefore, a low-carbon electricity matrix design should include all the available renewable resources. In all the Mexican territories, vast potential for each one of the renewable sources of primary energy can be found (Pérez-Denicia et al., 2017). The *Secretaría de Energía* (SENER), the Mexican energy authority, has claimed that the decarbonization of the energy matrix will be done by installing many variable technologies. Their forecast states that in 2030, 22 % of renewables will be shared by wind, whereas the growth of geothermal is expected to reach 1 % (Figure 1). The emission factor for the current status of the electricity matrix is in Table 1.

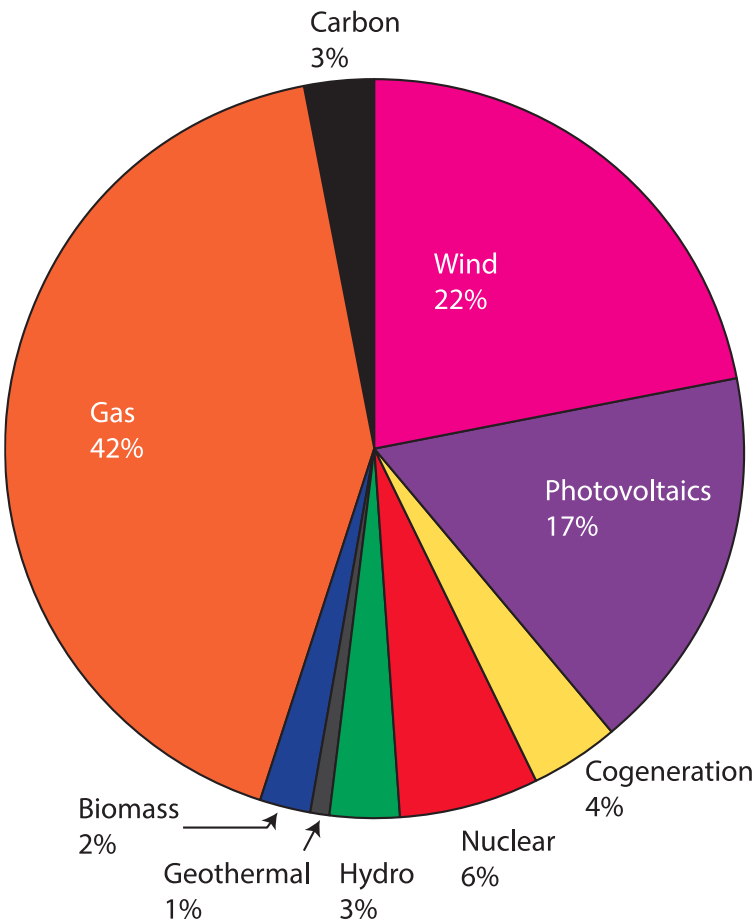

Figure 1 Mexican electric matrix. Share per type of resource/technology for 2030 (SENER, 2017b).

This low growth projected for geothermal energy does not reflect the Country's current potential for this resource. Mexico is a country rich in geothermal resources (Prol-

Ledesma & Morán-Zenteno, 2018). This energy source has been used since pre-Columbian times (Hodgson, 2018). The industrial exploitation of geothermal resources began with the installation of the binary power station in the town of Pathé, Hidalgo (DiPippo, 2022). From this point, extensive exploitation of this kind of energy followed, with the installation of 6 different geothermal power stations (GTPS) along the entire Country. Currently, Mexico has nearly 1 GW_{el} of installed capacity (Gutiérrez-Negrín, 2020). Although most of the power stations are located in the Trans Mexican Volcanic Belt, a couple is outside this region (Figure 2).

Table 1 Average emission factor for the Mexican Electricity Matrix (SEMARNAT, 2022).

Year	$g_{CO_2}eq/kWh_{el}$
2014	454
2015	458
2016	458
2017	582
2018	527
2019	505
2020	494
2021	423

Mexico is a developing country. This implies that energy demand is expected to grow in the following years (SENER, 2017b). Due to climate change, the United Nations demands that the development of the countries should be done under sustainable terms. In that sense, Mexico is tasked with designing a decarbonization scheme for its electricity matrix ((GOB), 2015). For this task, geothermal energy can be used. However, to ensure that their exploitation would help this, a sustainable assessment of the usage of these resources must be carried out.

The motivation of this work was to explore the sustainability potential of the exploitation of geothermal resources under the hypothesis:

"A geothermal resource under exploitation can meet the necessities of the actual generation without compromising the future necessities of the coming one."

More concrete, those necessities are the energy demand. This hypothesis is a rephrase of the World Commission on Environment and Development's definition of sustainability (UN, 1987). Los Humeros was the chosen site to prove this statement. This decision was made due to the availability of the data. Currently, the geothermal resource of Los Humeros is under exploitation. Therefore, the necessities of the actual generation are met. To meet these necessities, energy is extracted from the reservoir. This energy is converted into electricity; this electricity is delivered to the Mexican grid and generates income for the power station. These activities incur monetary expenses (i.e., operational costs) and affect the environment. This thesis aims to explore each mentioned topic to determine if a future generation will be capable of using this same resource.

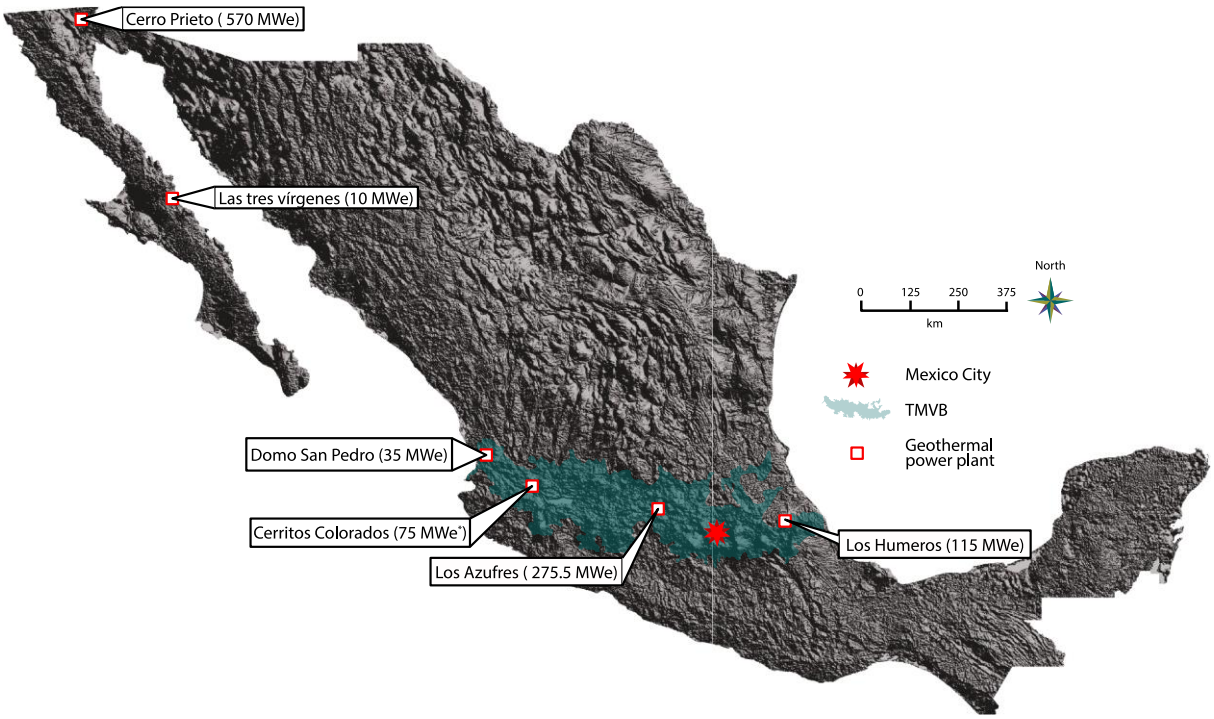

Figure 2 Distribution of geothermal power stations in Mexico (L. C. A. Gutiérrez-Negrín, 2020) DEM by INGEGI (2022). TMVB: Trans Mexican Volcanic Belt (Map taken from González-García, et al. (2021))

1.1. State of the art: what does sustainability mean in geothermal?

Geothermal energy is the heat that the earth irradiates from its depth to the surface. Not so long ago, this phenomenon was seen as a touristic attraction in the forms of geysers, hot pools, etcetera. However, this changed when the first gas turbine was driven with geothermal steam in the Italian town of Larderello to generate electricity (Minissale, 1991). This event marked the beginning of the use of geothermal for industrial porpoises. Nowadays, installed capacity in geothermal reached 15 GW_{el} ((IEA), 2020).

As already mentioned, Mexico has a long history with the use of geothermal, during which several hurdles have appeared. To mention one example, one of the largest geothermal power stations in the world was located in Cerro Prieto in the northern part of Mexico (Figure 2). This facility could run almost 1 GW_{el} of installed capacity. However, the pressure dropped due to overexploitation; nowadays, this power station can only operate below the 600 MW_{el} (L. C. A. Gutiérrez-Negrín, 2020).

This context and climate change due to global warming pushed to use of geothermal resources under sustainable limits. As a result, geothermal energy is considered a renewable energy source with a low environmental affectation (Goldstain et al., 2011). However, there is a substantial difference between renewability and sustainability. Both terms are defined from a human-scale perspective. However, renewability refers only to the reservoir: it is renewable if it can be replenished on a human scale. Sustainability, however, includes many other societal factors, like health and economics.

In that sense, sustainable development requires an evaluation of several indicators to declare that the use of any resource is, in fact, sustainable (Shortall, Davidsdottir, & Axelsson, 2015; UN, 2022). These indicators comprise many categories regarding human health, environmental affectation, the economy of the project, and the long-term preservation of the resource (Table 2). Geothermal systems are unique due to their intrinsic geological context. This variety makes a sustainable evaluation not so straightforward. However, the UN demands evaluating each of the sustainable indicators

to declare weather or not a project is sustainable. Nevertheless, those might not apply to all the geothermal systems in the world nor during all the phases of development.

In this sense, the evaluation of all the indicators might represent a waste of resources. For example, an affectation on human health may be neglectable when the particular resource is far away from any town. It does not mean that human health is not being affected but the vulnerability is low and thus the affectation to this indicator is low (yet, no zero). To mention another example regarding the education, not all systems have an impact on it. However, Groß Schönebeck is a remarkable example of an in situ geothermal lab in which much scientific research has been done (Huenges & Hurter, 2002).

This argument might explain the lack of a consensus regarding the categories that must be included to assess the sustainable use of geothermal resources (Shortall et al., 2015). Sustainability assessment help to make decisions and design policies to make society more sustainable (UN, 2022). A few frameworks help assess projects using all the indicators (Shortall et al., 2015). These procedures suggest to include all the indicators to understand their interaction and make better decisions. Table 2 shows the long list of sustainable indicators. They can be merged into three big and general categories: environment, economy, and society.

Table 2 Sustainable indicators and how they are affected by geothermal exploitation. This table is a summary of Shortall et al. (2015).

Category	Indicator	Effect of geothermal
Economic	Poverty	Increase employment. It might give economic benefit to the owners of the land (e.g., Philipines (Anave & Cala, 2005)) Access to clean energy. (e.g. Pathé, Hidalgo (DiPippo, 2022))
Society	Health	Replacement of primary energy sources might reduce the emission of harmful gases (e.g., Kenya (Ogola, Davidsdottir, & Fridleifsson, 2011)). Therapeutic uses of geothermal (e.g., Iceland and the blue lagoon)
Society-economic	Education	Access to electricity in rural areas. In-situ geothermal lab (e.g. Groß Schönebeck)
Society-economic	Natural Hazards	Increase the incidence of earthquakes as a response to exploitation.
Society	Demographics	Affectation to local communities due to construction and further operation of the GTPS (e.g., USA (Farhar & Dunlevy, 2003))
Environment-society	Atmosphere	Emission of greenhouse gases (e.g., Italy (Bravi & Basosi, 2014))
Environment	Land	Alteration of the Land for the construction of the power station (e. g., Costa Rica (DiPippo & Moya, 2013))
Environment-society	Freshwater	Use of possible freshwater resources for operation and drilling.
Environment	Biodiversity	Alteration of the local flora and fauna (e.g., New Zealand (Boothroyd, 2009))
Economic	Economic development	Improves energy security. Reduction in fuel consumption.
Economic	Consumption patterns	Cheaper energy modifies its consumption and waste patterns.

Some proposals of what sustainability means for geothermal have been published. None of them includes the UN indicators for sustainability (Table 3). They all suggest continuous monitoring of the physical indicators involved with the brine production to elongate the use of the reservoir as much as possible. In addition, some authors relate the production rate with the project's economic performance, arguing that exploitation should be done above economic limits.

Table 3 Approaches regarding the sustainable conceptualization of geothermal exploitation.

Indicator	Affectation due to exploitation	Reference
Energy	Heat swept due to brine extraction. Replenishment depends on the rocks' heat capacity and the thermal equilibrium rate.	(Axelsson, el al., 2004)
Energy and economic	Heat swept; generation capacity linked to economic scope. Step-wise development to set the reservoir's capacity.	(Axelsson, 2010; Stefansson & Axelsson, 2005)
Energy, economic, and environment	Reservoir nature and exploitation technology. Sustainability-based on limits of production.	(Rybach and Mongillo, 2006)
Production rate	Production rate under rechargeable limits and above economic feasibility. Fluid extraction might trigger seismicity.	(Ladislaus Rybach, 2003)
Economic	Production should meet economic levels.	(S. K. Sanyal, 2004b)
Production rate	Physical indicators related to production in order to keep them under economic levels.	(Axelsson, 2008)
Production rate, economics	Production rate capable of covering investment and maintenance	(Lovekin, 2000)

However, this economic level can be above renewability and produce a drop in production and, therefore, a disaster. The best example are the Geysers in California and Cerro Prieto in Baja California (Hector & Campbell, 1990; Sanyal et al., 2000). For both cases, the exploitation rate was much above the reservoirs' limits. In both cases there were a serious drop of pressure which generates a decline in production. Then, the economics of both stations (several companies for the case of the Geysers) were affected.

From these examples exploitation rate was the main affected indicator. Economics was another affected indicator (Table 2). The cases explored from other authors argue that sustainability for geothermal is a combination of sustainability with the renewability of the geothermal system (GS) (Table 3). While heat content is the primary indicator that defines geothermal, several others surge once the system goes into exploitation.

Moreover, though all the phases of geothermal projects, those indicators might not apply. Furthermore, due to the wide variety of geothermal resources, the technology to exploit them also varies and therefore the level of affectation changes. Thus, all the indicators might not be applicable.

As stated before, all the indicators can be included in three big branches (Table 2). Nevertheless, strictly how are they related to geothermal? Extensive research on these three topics has been done. The first idea that emerges from this research is that the three big categories in geothermal could be:

- Environment: related with the environment pillar of sustainability

- Economics: related with the economic pillar of sustainability
- Resource renewability: related with the environment pillar of sustainability

The social pillar of sustainability is not included in the fundamental pillars of sustainability for geothermal. Due to the nature of these projects, the society affectation is derived from the basic pillars. In the following sections, they will be addressed. First, a short explanation regarding the exploitation of a geothermal system is provided.

1.2. The exploitation of geothermal resources

A diagram of a completed geothermal power station is shown in Figure 3. The average time to reach this point is eight years (Sanyal & Morrow, 2010; Sanyal et al., 2016). The development of geothermal projects began with site identification and later exploration. The exploration is usually made through multidisciplinary approaches in which the main result is the first assessment of the heat stored in the area. Ideally, the proposal of drilling sites is a goal included in this early phase of development. Although, that depends on the type of the system.

The extensive classification effort is derived from the nature of geothermal systems (Armstead, 1973; I. Moeck, 2013; I. S. Moeck, 2014; L. Rybach, 2015; Sass 2016). Some authors claim that classification must be done according to the energy content (Armstead, 1973; L. Rybach, 2015). At the same time, others argue that classification includes not only the energy but also the geological context (I. S. Moeck, 2014; R. M. Prol-Ledesma & Morán-Zenteno, 2019). Geothermal systems can be broadly divided into two categories: those with water and those without it. The conventional geothermal resources include a source of heat and water. Therefore, a well must be drilled to mine the heat stored in the earth. On the other hand, dry systems only have a heat source. For those systems, a permeable path is needed to inject and heat water (or other fluid) to mine the energy (Huenges, 2010).

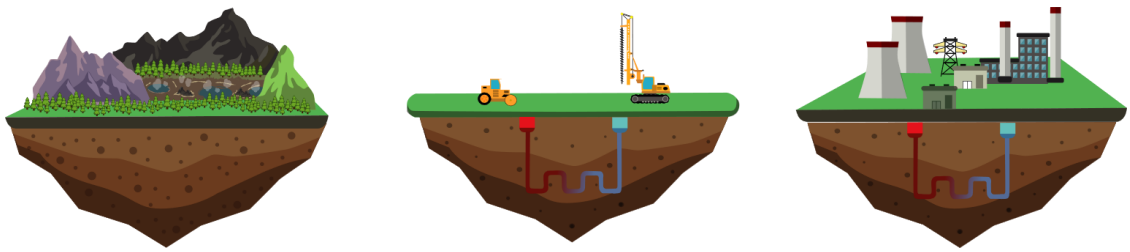

Figure 3 Development phases of a geothermal power station.

Despite this extensive categorization work, there is no doubt that heat is the only feature shared by all geothermal systems. Heat content defines its use (Sass 2016), and it is reasonable to point to heat content as the primary indicator of sustainability. The possible applications that can be developed according to the heat content are summarized in the Lindal Diagram (Figure 4). First proposed in 1992 (Líndal, 1992), this diagram has suffered several modifications, and it is constantly updated according to the new adds of recent research on geothermal applications. Besides the heat content, the effective extraction of heat depends on many other factors (Garg & Combs, 2015). However, all these parameters are met after drilling and years of monitoring and observation.

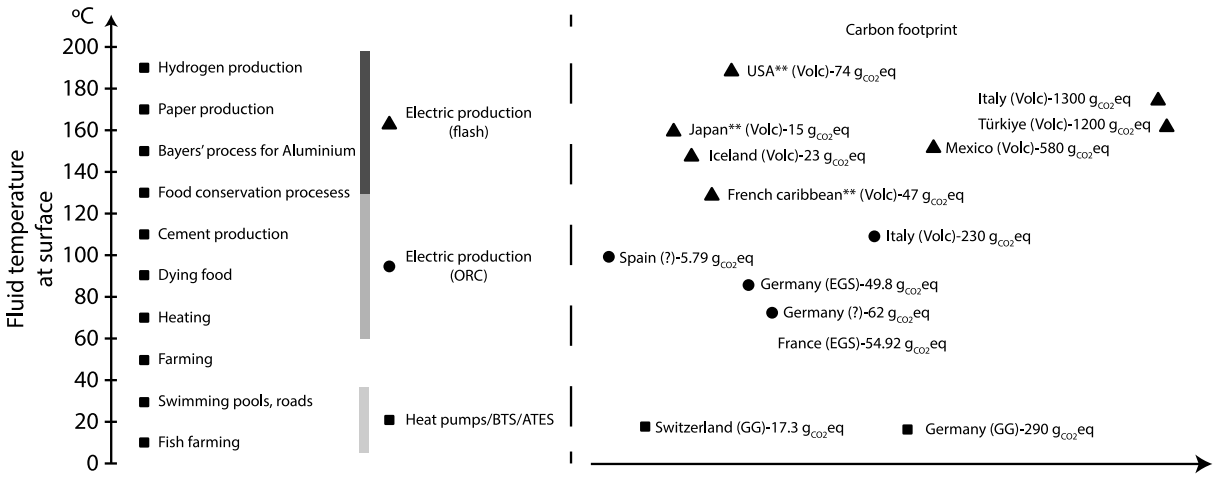

Figure 4 Lindal diagram. Carbon footprint of different applications is included. Flash refers to single or double flash units. ORC is organic rankine cycle. BTS is Bottom Thermal Storage, ATES is Aquifer Thermal Energy Storage. Volc refers to volcanic environment. EGS is the abbreviation for Enhanced Geothermal System. GG refers to geothermal-gradient. ** Do not include non-condensable gases contained in the geothermal steam. For the full reference list see Table 6.

Right after the first approach to the reservoir limitations, a second aspect appears: the cost-effectiveness of the future project. Private investors and any entity interested in developing a geothermal project will require an approximation of how much it will cost. Geothermal projects are money intensive, requiring a large amount of investment to be developed (Moore, 2016; S. K. Sanyal, 2004a; Stefánsson, 2002). The cost of exploiting a geothermal system is usually governed by the cost of drilling (S. K. Sanyal, 2004a; Sass et al., 2016). These costs vary according to many factors, for example, the target depth and the type of rocks (Augustine, Tester, Anderson, & Petty, 2006; Lukawski et al., 2014; Sass et al., 2016). A well (or several) might not be expensive to drill and complete. However, the chosen area is based on surface observations. No matter how accurate those observations and interpretations are, there always be a large amount of uncertainty (Witter, Trainor-Guitton, & Siler, 2019), which is translated into high chances of failure and, therefore, a larger final cost. Although, a common practice to reduce this uncertainty is to drill a test well, which is usually cheaper than a production one (Augustine et al., 2006; S. K. Sanyal & Morrow, 2010; Sass et al., 2016). Despite this, many things can still go wrong when drilling, but once a well is a success, the previous heat content estimations are confirmed or adjusted, and the exploitation begins.

Environmental damage also starts from the very moment the site's exploration begins. With the project's development progress, the affectation on the land also increases. Although these are renewable resources of energy, these do not exempt them from causing damage to the environment (Atilgan & Azapagic, 2016; Bravi & Basosi, 2014; Paulillo, Striolo, & Lettieri, 2019; A. S. Pratiwi & Trutnevyte, 2021; Sullivan, Clark, Han, & Wang, 2010). Of course, a minimal impact is sought. However, the damage to the environment causes an effect on several sustainable indicators, like global warming or human health, to mention a couple of examples.

So, the use of geothermal systems affects several indicators. Nevertheless, as it has been explained, not all the indicators are affected with the same intensity. Exploitation generates at least three effects: **heat extraction, environmental affectation, and financial debt**. The following sections address a brief state of the art of each topic, including how are affected by the exploitation of geothermal resources.

1.2.1. Economics of geothermal exploitation

This topic is addressed from two perspectives of time. First, the long-run evaluations of geothermal projects (GP) are based on the Levelized Cost of Energy (LCOE). This metric is helpful at the early stages of development when decisions regarding the available options are taken. The LCOE allows the comparison of technologies according to their lifetime costs and electricity production (Ueckerdt et al., 2013). The LCOE of geothermal is usually low due to the cheap maintenance of these power stations (Clauser & Ewert, 2018). However, it is well known that GP are costly, and finance can be challenging to get (Moore, 2016). Besides, the risk of losing money at the early stages of development is very high, complicating this procedure a bit more.

Although GTPS are business, there are few studies regarding profitability behaviour. The reason for this is the private status of the great majority of GTPS worldwide. The authors that address this topic focus on feasibility options, especially for a combination of projects or cascade schemes (Rubio-Maya et al., 2016). At the same time, other authors made an effort to define what defines the cost of geothermal (Clauser & Ewert, 2018; Ueckerdt et al., 2013). In the case of Mexico, there is only one report that states the cost of producing electricity by GTPS (Hiriart & Andaluz, 2000).

The conclusion on many of them is that geothermal is cost-intensive at the beginning of the project, it is a cheap-maintenance power project, and when a cascade scheme is used, the profitability increases significatively. Besides, profitability conclusions (i.e., if the GP is profitable or not) and estimations of time needed to cover the debt are missing.

1.2.2. Environmental affectation due to geothermal exploitation

Geothermal is a renewable source of energy (Armstead, 1973; Axelsson, 2010). Moreover, the environmental effect is usually low, and nowadays, the best tool to assess it is through a Life cycle analysis (LCA). The main goal of an LCA is to determine the environmental affectation associated with all the stages of any product during its lifetime (ISO, 2016). The studies addressing this geothermal topic explore all the affectation caused by a GTPS.

As said, geothermal systems are unique, so the environmental affectation also is. The main conclusion of all studies is that the highest affectation is due to the CO_2 contained in the geothermal steam. This problem has been identified in at least three countries in the world. Those are Italy, Türkiye and Mexico. Although different, the three systems in which the CO_2 footprint was measured are located in active volcanic areas, and they use single flash units to convert the electricity (Atilgan & Azapagic, 2016; Bravi & Basosi, 2014; H. González-García, Francke, Göllner-Völker, et al., 2022a).

However, the environmental affectation changes with the intended application for the geothermal system. Heating porpoises have low CO_2 emissions and better environmental performance than other options (Saner et al., 2010 and references therein). Moreover, heat pumps can "save" CO_2 by avoiding fossil fuel usage (Welsch et al., 2018). This difference can result from arrangements made to use geothermal for heating buildings. Land affectation is inevitable. However, sustainable exploitation demands a low land affectation and no threat to human health. Besides, a GP with a high CO_2 footprint cannot be considered sustainable.

1.2.3. Physical parameters affectation due to geothermal exploitation

A geothermal resource is first identified by surface activity like geysers, hot water and mud pools, mineral deposits, etcetera. These phenomena are a consequence of the

physical parameters of the reservoir. They can either disappear or change in response to the system's exploitation (Gupta & Roy, 2007; Kristmannsdóttir & Ármannsson, 2003).

Right after the first well is drilled, there is a change in the system's pressure. Although this affectation might not reach the whole system, after certain time, the original pressure conditions will finally change (M. Grant & Bixley, 2011). This parameter is not the only one affected due to the exploitation. The rock-fluids interaction is also affected (Lippmann et al., 1991); a process of heat sweeping starts (Krugert, Lam, Molinar, & Aragon-Aguilar, 1987), and many other parameters are modified (Arellano, Torres, & Barragán, 2005).

As any other thermodynamical system, when the original state is perturbed, the system will try to correct it until a new equilibrium is reached. The re-equilibrium of geothermal systems is also called renewability, and the system can regenerate almost to its original state (O'Sullivan, Yeh, & Mannington, 2010). One of the strategies to keep the exploitation under renewable limits is the constant monitoring of the system's pressure (Rivera R, Samaniego V., & Schroeder, 1980). Before, the Geysers and Cerro Prieto were mentioned. Both are examples of what can happen when the monitoring is ignored. Both systems experienced a substantial decline in fluid production due to overexploitation. The first failed due to the lack of communication within companies (S. K. Sanyal et al., 2000). The second failed due to an entry of a cold water front (Lippmann et al., 2004).

Although the steam extraction for both cases did not cease, it was diminished. Cerro Prieto had almost 1 GW_{el} of installed capacity, and nowadays it runs above 600 MW_{el}. (L. C. A. Gutiérrez-Negrín, 2007, 2020). This pressure drop did not implicate the system's abandonment; however, the drawn on the steam extraction is lower and therefore the economic levels are directly affected.

1.2.4. Motivation

The hypothesis of this work states that the exploitation of a geothermal system is sustainable if a future generation can exploit it. Besides, a discussion regarding what sustainability means for geothermal was provided. Although most proposals argue that the heat stored is the primary precursor for sustainability, some other aspects were also highlighted. Under this context, the motivation of this research was to define an applicable methodology to assess the sustainable exploitation of all geothermal systems. From the three different topics discussed before, three basic pillars are proposed: heat content, carbon footprint and profitability of the GTPS. Nevertheless, how are they related with the sustainable indicators?

To answer this question, three more were formulated:

- How large is the heat reserve?
- How good is profitability of the geothermal project?
- How bad is the environmental affectation of the power station?

This is a cumulative dissertation, in which each one of the mentioned questions was addressed by different publications.

1.2.5. Objective/Method

This work aims to evaluate the performance of three different aspects of a geothermal system under exploitation. After the evaluation, the interaction of these so-called basic pillars is analysed in order to define how they impact on the sustainability and if the proposed indicators are enough to claim the sustainable use of the system. This

information will help with the accomplishment of the goals set by the Mexican government in terms of sustainable development.

This dissertation is addressed from three different perspectives: a technical evaluation of the production of the heat, a life-cycle analysis of the CO_2 footprint per each kWh of electricity generated by the power station; and, the last parameter is the profitability performance of the electric business. The description of the methodology of each part of this topics is addressed within the following chapters.

The system that was the subject of application of this methodology is Los Humeros and the power station installed there. It is located in Mexico, at the western part of the Country. Before the explanation of how the mentioned sustainable topics were addressed in the particular power station, a brief history of Los Humeros is provided. Then, the next chapter explains how the future production was forecasted. This is followed by the estimation of the CO_2 footprint. Chapter 5 explores the profitability of the power station. The next chapter 6 combines each one of the results to define how sustainable is the exploitation of the geothermal resource. Last chapter summarizes the dissertation and present some weakness of this current investigation with the aim to also provide future work opportunities.

2. A short history of the geothermal power station of Los Humeros

Los Humeros is located at the western part of Mexico. It belongs to the state of Puebla and it is an active volcanic caldera (Arzate, Corbo-Camargo, Carrasco-Núñez, Hernández, & Yutsis, 2018). From the extensive exploration campaign carried out by the *Comisión Federal de Electricidad* (CFE), Los Humeros was a main target for developing a power station due to the early estimations of the heat potential ((SEMARNAT, 2006a)). From there, a lot of geological research were done in the site with the aim to describe as best as possible the physical context of this geothermal system.

The site is described as an active silicic caldera complex. The types of rocks are crystalline-volcanic in its majority, however, some sedimentary and metamorphic rocks were identified in the system's basement and, during the violent history of vulcanism some volcano-sedimentary rocks were formed (Campos-Enriquez & Garduño-Monroy, 1987; Ferriz & Mahood, 1984). As the stratigraphy is mainly formed by crystalline rocks, the porosity of Los Humeros is a consequence of faults. The master fault of the system is the NNW Los Humeros, in which several production wells are placed (Carrasco-Núñez, López-Martínez, Hernández, & Vargas, 2017).

The exploration of this site began in the late 60's, and the development of the geothermal project started in the 80's (H. González-García, Francke, Göllner-Völker, et al., 2022b). This site has suffered several stages of development (Table 4). To date, more than 50 wells have been drilled, 22 km of pipes were placed on the grounds and 11 conversion units have been used to generate electricity by the geothermal brine.

Table 4 Los Humeros' development history (H. González-García, Francke, Göllner-Völker, et al., 2022b).

	Years	Construction
1st phase	1984 - 1991	Wells drilled: H-(1, 2, 4, 5, 7, 9, 12, 8, 6, 10, 11, 16, 17, 14, 18, 19, 20, 21, 22, 13, 15, 23, 24, 25, 26, 27, 28, 29 ,30, 31, 32, 33). Conversion units: U-(1, 2 ,3, 4). Pipes installed (cumulative): 3,134 m
2nd phase	1993 - 1998	Wells drilled: H-(3, 34, 35, 36, 37, 38, 39, 40) Conversion units: U-(5, 6, 7) Pipes installed (cumulative): 6,000 m
3rd phase	2008 - today	Wells drilled: H-(41, 42, 43, 44, 45, 46, 49, 48, 50, 55, 56, 59) Conversion units: U-(8, 9, 10, 11) Pipes installed (cumulative): 13,300 m

Along the operation history, several works regarding the response of the system due to exploitation have been done. Aragon-Aguilar, Hernandez-Ochoa, & Arriola-Medellin, (2020) made a characterization of the wells. They included an injection test for some of the wells in the system, identifying two zones were the fluid escaped from the well. They concluded that these points are the feed zones of the wells. Also, Aragon-Aguilar A., Moya, & zquierdo (2005) studied performance curves on the wells. They could not identify any sign of production depletion, but they concluded that the best production is in the surroundings of the faults. Later, Arellano-Gómez et al. (2008) analysed the thermodynamic conditions of the fluids, their conclusion was that the reservoir's pressure has declined as a consequence of the exploitation. This drop changed the boiling

conditions at the reservoir, however that did not affect the steam production. Furthermore, Arellano-Gómez et al., (2008),(2003) identified two reservoirs based on production data. According to them, a liquid-dominated reservoir is above a steam-dominated one.

Due to the nature of this geothermal system, it was a subject of the GEMex international consortium. GEMex was aimed to research the exploitability of super-hot geothermal systems (Jolie et al., 2021). The main conclusions of this collaboration were the characterization of the super-hot reservoir and an update on the Los Humeros conceptual model (GEMex, 2022).

2.1. Electric production and efficiency of the process

Along the development of this GP, the installed capacity has changed. It began with four small power plants of 5 MW_{el}. Two years later the installation of three more started (Table 4). Nowadays, the system has three units of 25 MW_{el} of capacity and 15 MW_{el} distributed in small units of 5 MW_{el} (Gutiérrez-Negrín, 2020). Besides, the electricity production rate has not been constant (Table 5). This is mainly to maintenance of some part of the entire process (see Gutierrez-Negrín references).

Table 5 Los Humeros electricity yield. The values were compiled from different works (Gutiérrez-Negrín, 2007, 2012, 2020; Gutiérrez-Negrín & Quijano-León, 2003; Gutiérrez-Negrín, et al. 2010; Gutiérrez-Negrín, 1996; Quijano-León & Gutiérrez-Negrín, 2000). The years that could not be traced were requested to the Instituto Nacional de transparencia y Acceso a la Informaciín (INAI), Mexico.

Year	Net electricity production	Year	Net electricity production	Year	Net electricity production	Year	Net electricity production
	GWh_{el}		GWh_{el}		GWh_{el}		GWh_{el}
1995	286	**2002**	146	**2010**	326	**2016**	508
1996	337	**2003**	285	**2011**	336	**2017**	416
1997	343	**2004**	295	**2012**	303	**2018**	501
1999	351	**2006**	295	**2013**	336	**2019**	574
2001	127	**2007**	278	**2014**	321	**2020**	549
		2008	313	**2015**	408		

Furthermore, the use of the wells has changed. Some of them have failed after several years of production (e.g., H16 Figure 5). While others were unsuccessful (Table 4). Nevertheless, the heat has been extracted according to the installed capacity under operation. For example, the years with the lower electric yield were 2001 and 2002 (Table 5). During those years only 9 wells were extracting geothermal fluids (Figure 5). The average number of wells under use is around 29.

Regarding the efficiency of the process, only one work addressed this topic (Garcia-Gutierrez et al., 2015). This work analysed the thermal and exergetic efficiencies for the fluid distribution network of the power station. The results were above 90 % of both values for the distribution network. However, the whole process has a thermal efficiency of 8.4 % and an exergetic efficiency of 24 %. The average thermal efficiency of the whole process is 10 %, although it has not been constant (Figure 6).

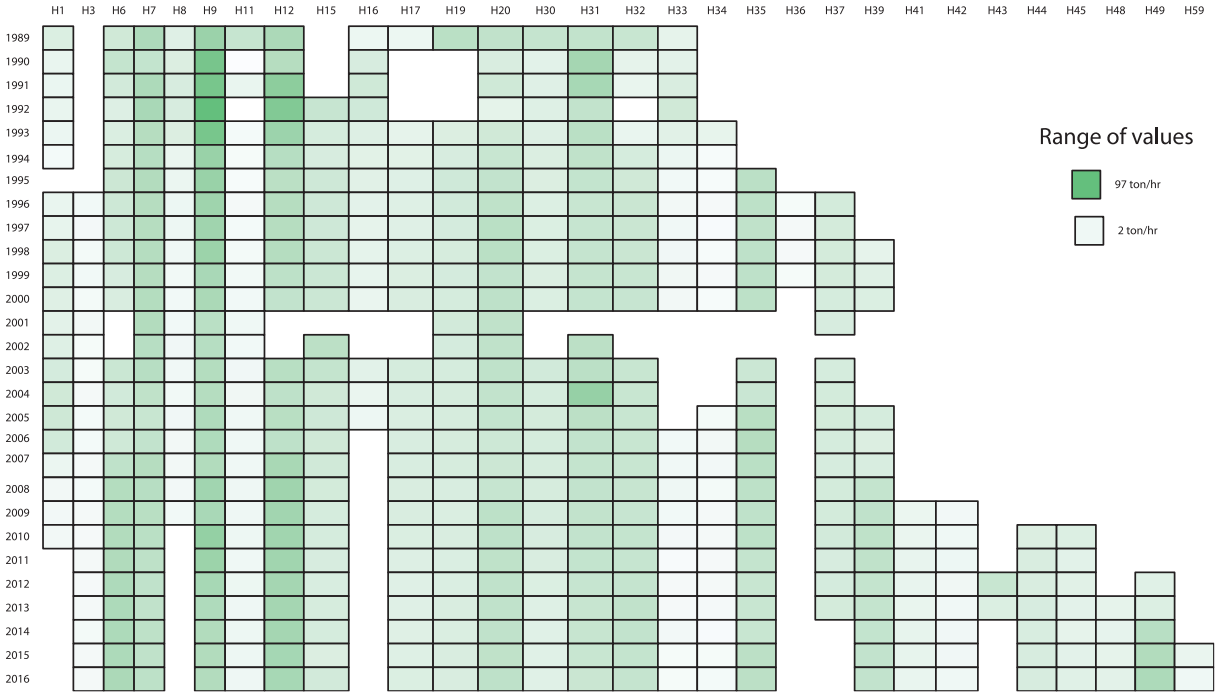

Figure 5 History production of wells (González-García et al., 2022a).

Although, this site has been the target of several scientific studies; there is no characterization or judge about the sustainable use of the geothermal reservoir. Due to the active volcanic caldera, it is assumed that the heat source of Los Humeros will last for more than one human generation (H. González-García et al., 2021). However, the exploitation might not be under sustainable terms. The following sections are intended to explore how the questions that drove this research were applied in Los Humeros, and how they tell something about the sustainability of the exploitation of this geothermal site.

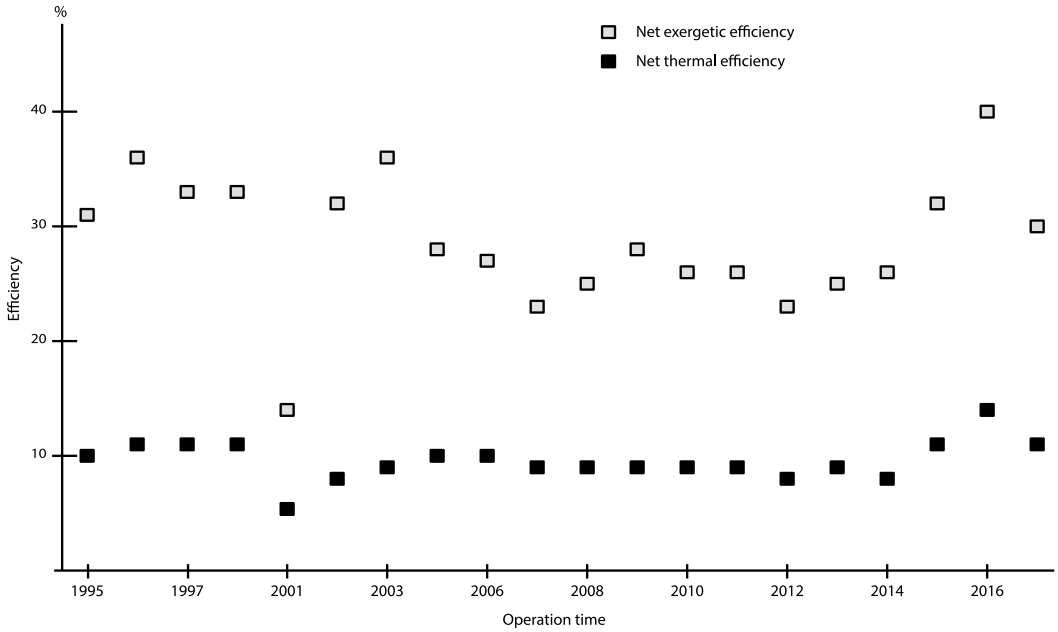

Figure 6 Variation of thermal and exergetic efficiency (H. González-García, Francke, Göllner-Völker, et al., 2022b).

3. The heat from the Earth, the engine of a geothermal power station

The introduction mentioned that heat content is the only common feature shared by all geothermal systems. There are several ways to assess the stored amount of it. Those are chosen according to the available data. The heat assessment begins with the site exploration. A common goal for explorations campaigns is to estimate the size of the reservoir (V) and its temperature (ξ_R). Besides this, the physical parameters of the rocks, like density (ϱ), heat capacity (c_p), porosity (ϕ), etc., are obtained. One model combines these results and is widely applied in the early stages of development. The volumetric heat in place is a model that requires the reservoir size (A), the temperature ($\Delta\xi$), and the physical parameters of the rocks (ϱc_p):

$$Q = \varrho c_p \, \mathrm{A} \, \Delta T_{fz} \Delta\xi \qquad (3.1)$$

This model was first proposed by Muffler & Cataldi (1978). The first attempt included the estimation of the geothermal reservoir's volume. However, since its publication, this model has suffered some modifications. Garg & Combs (2015) proposed the inclusion of the density of fluids (ϱ_f) and heat capacity (c_{pf}) to have a better representation of the heat stored in the system:

$$\varrho c_p \rightarrow \varrho_r c_{pr}(1-\phi) + \varrho_f \, c_{pf} \, \phi, \qquad (3.2)$$

where subscripts are for rock (r) and fluids (f), this part of the equation also has a new member ϕ, which describes the rock's porosity. Furthermore, they argue the inclusion of the Heat Capacity Factor, which helps to constraint the useful heat that can be mined from the system. Later, Limberger et al. (2018) constraint even the recoverable heat by the inclusion of the effective thickness of the reservoir (ΔT_{fz}), which is the high permeable zone that contains the geothermal fluids (Figure 7).

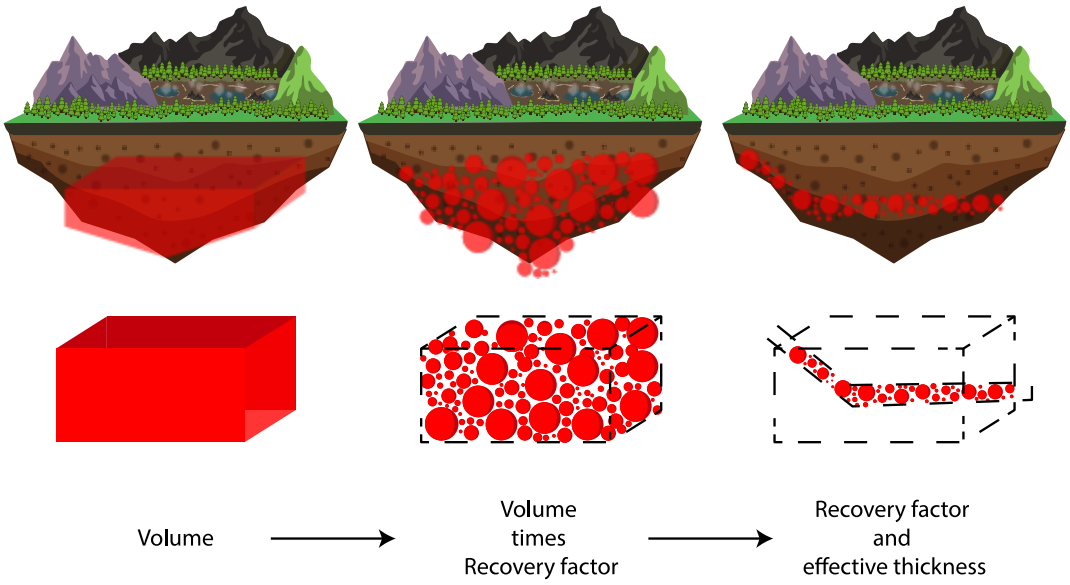

Figure 7 Evolution of the heat in place concept to evaluate the stored energy in a geothermal reservoir.

Once the results obtained by the application of this model show a good energy content, the drilling is approved (S. Sanyal et al., 2016). Exploration of underground resources is accompanied by enormous uncertainty. Within underground resources, geothermal is included (Witter et al., 2019). This uncertainty is diminished by the information obtained

by the first tasting well. A re-evaluation of the heat stored is possible once data from the reservoir is obtained. It leads to a better estimation of the capabilities of the reservoir.

However, continuous monitoring of the reservoir is needed to manage the site in a sustainable way (Axelsson, 2010). Therefore, after several years of exploitation and observation, other techniques are applied to quantify the heat stored. Those surveys are based on production data, especially the reservoir's pressure.

In the early stages, the assessment of the geothermal site aims to determine how much of this energy can be effectively extracted. This information is used to design the exploitation scheme. Later, when production data is available, i.e., pressure and geochemical changes, the scope of the assessment changes. The goal is to constrain future production and make a schedule regarding the exploitation/reinjection rate.

Like another thermodynamic system, a geothermal one can be described by its variable states. These include the pressure, temperature, enthalpy, entropy, etc. Each of these variables changes throughout the exploitation history. They are monitored to manage the operation of the wells and, thus, the extraction of the geothermal fluids (Lippmann et al., 1991). Moreover, analysing these parameters allows the identification of trends and decisions (Westwood & Castanier, 1981).

3.1. Production forecast of Los Humeros

Los Humeros has been under exploitation for the last 30 years. It means that there are loads of available production data. However, there are no pressure measurements. This data contains fluid extraction rate and steam enthalpy measured for all the wells in the site (H. González-García et al., 2021). The distribution of both parameters is shown in the violin plots in Figure 9. The forecasting procedure was based on these parameters with no more data than this. The model to calculate the heat was:

$$Q = \dot{m}\Delta h''\Delta \mathrm{t}, \qquad (3.3)$$

where heat extraction (Q) is defined by the mass extraction rate ($\dot{m}$), the enthalpy difference ($\Delta h''$) between the steam and Los Humeros environmental conditions (20ºC and 1 atm of pressure), and the last term is a timestep (Δt), which is the time lapse for the forecast.

The model was fed with the quantiles of both the mass flow and the steam enthalpy. This aimed for a broader representation of the available data. Both parameters defined two scenarios. The bottom quantile (1st quartile) was labelled as the pessimistic scenario of production, and the top quantile (3rd quartile) was the optimistic scenario of heat extraction. The idea with these scenarios was to represent a decline in heat production and its possible consequences.

The results were 430 and 580 PJ for the pessimistic and optimistic scenarios. This forecast is for the next 30 years of production. The results per well for the optimistic scenario are shown in Figure 8. The validation of the model was done with the history of production. Thirty years of data were divided to verify the model. The first 20 were taken to make a forecast of the following 10. The model was considered valid when the actual production was within the range of values defined by the scenarios proposed (Figure 10).

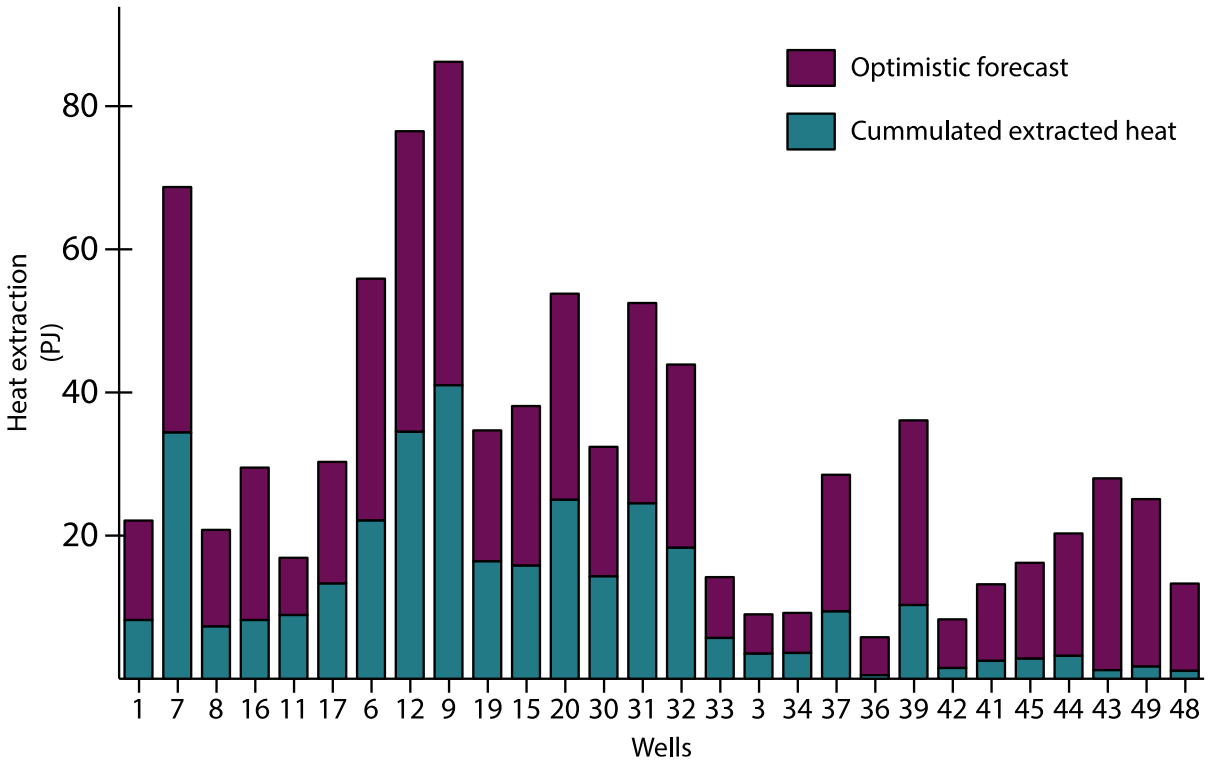

Figure 8 Heat extraction per well. The label per well includes an H, the full label is "H-1", "H-2" etc., H was removed to improve reading. The sort of the wells is according to the year they were opened.

3.2. Los Humeros' recovery factor

The heat recovery factor is defined as the ratio between the heat stored (Q_R) and the actual quantity obtained at the wellhead (Q_{WH}) (Garg & Combs, 2015; Muffler & Cataldi, 1978):

$$Re = \frac{Q_{WH}}{Q_R} \qquad (3.4)$$

Q_R is the value of the heat stored in the Caldera (ca. 8 km of radius). This estimation was a milestone from the GEMex international project. Bonté et al. (2020) generated a heat flux map for the whole area. Their results are a range of values (Figure 11-A). Using these results to feed eq. (3.4) would generate a range of values for the recovery factor since the stored heat is not homogeneous.

However, other parameters were considered for calculating the recovery factor. The recovery factor was based on the extraction conditions. This factor was the fraction between the historical extracted heat and the theoretical heat stored. The theoretical heat stored was assumed to be the sum of the cumulated extracted heat (Q_e) plus the energy forecast (Q_F):

$$Q_0 = Q_e + Q_F \qquad (3.5)$$

Then, the recovery factor (eq. (3.4)) was the fraction between the extracted heat (Q_e) and the theoretical content of heat (Q_0):

$$Re_{60} = \frac{Q_e}{Q_0} \qquad (3.6)$$

This recovery factor is not the heat recovery factor, although it is based on the same concept. The Re_{60} is the remaining heat to recover in the following 30 years. This concept assumes that the actual conditions will remain and the store heat is a finite bucket, i.e., no heat sweep.

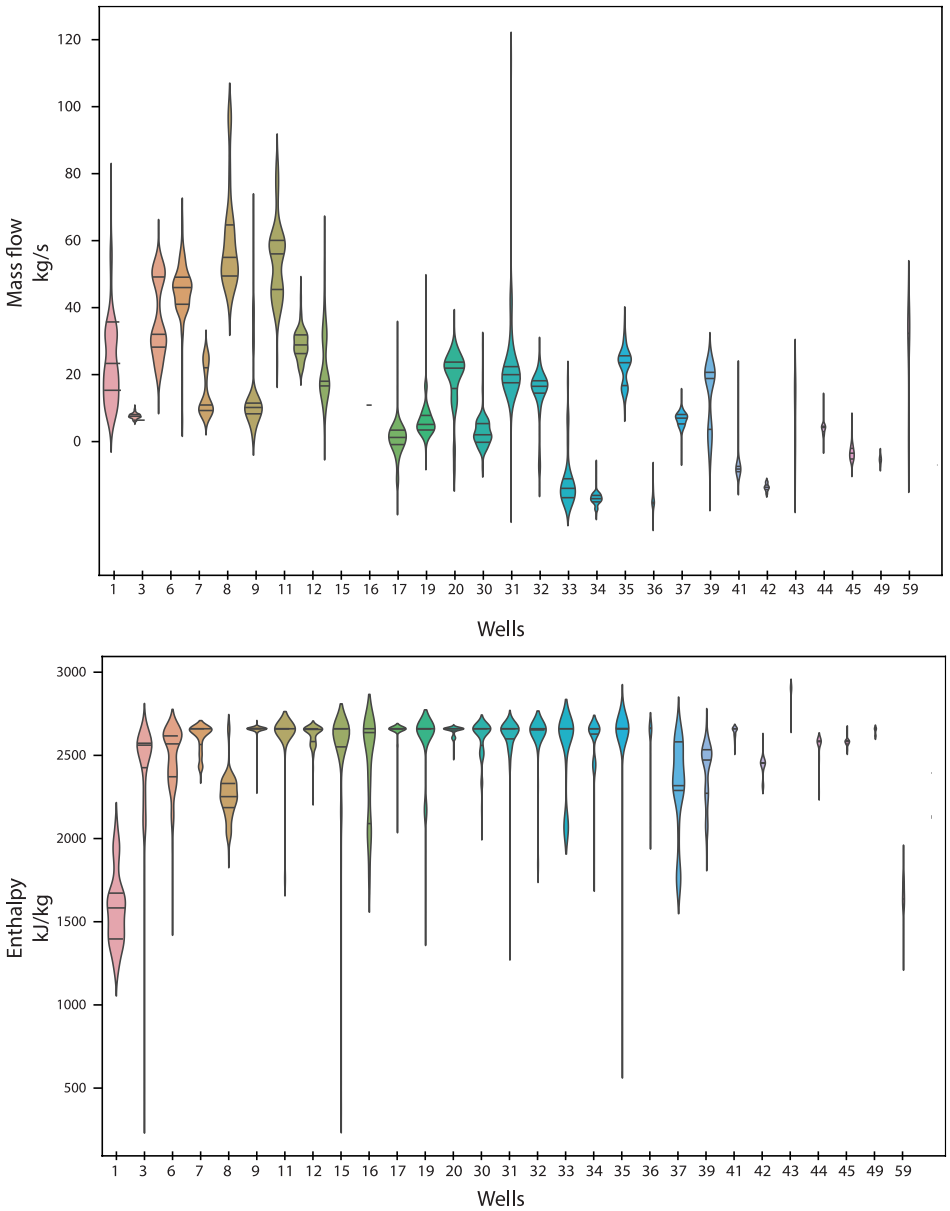

Figure 9 Violin plots for mass extraction rate and steam enthalpy. The name of the wells is H-1, H-3... etc. The H was removed to improve readability.

The stratigraphy of Los Humeros is composed of several volcanic units (Carrasco-Nuñez et al., 2017). Each one of them has its physical parameters. The boreholes go through various geological units. Therefore, the feed zones might have more than one type of rock. The concept behind the affected area is the cone of depression. The cone of depression is a geometrical shape formed in homogeneous aquifers under exploitation. However, this depression shape changes when the aquifer is not homogeneous (Singhal & Gupta, 1999). Los Humeros is a volcanic system that owes its permeability (ϕ) to faults and fractures (Aragon-Aguilar et al., 2020). Thus, it is not a homogeneous aquifer. To consider the rock variations a weighted average was taken (H. González-García et al., 2021):

$$\varrho c_{\mathrm{p}} = \frac{\sum_{\mathrm{n}=1}^{\mathrm{N}} \omega_{\mathrm{n}}\left[\varrho_{\mathrm{rn}} c_p^{\mathrm{rn}}(1-\phi_{\mathrm{n}})\right]}{\sum_{\mathrm{n}=1}^{\mathrm{N}} \omega_{\mathrm{n}}} + \frac{\sum_{\mathrm{n}=1}^{\mathrm{N}} \omega_{\mathrm{n}}\left[\varrho_{\mathrm{wn}} c_p \phi_n\right]}{\sum_{\mathrm{n}=1}^{\mathrm{N}} \omega_{\mathrm{n}}}. \qquad (3.7)$$

This equation only contains water since Los Humeros is a liquid-dominated system (Arellano Gómez et al., 2003). Superscripts are the number of different rock types along the feed zone, and the weight ω is the percentage content of the respective rock type within the corresponding borehole. ($\sum_{\mathrm{n}=1}^{\mathrm{N}} \omega_{\mathrm{n}} = 1$) thus, the weighted average is:

$$\varrho c_p = \sum_{\mathrm{n}=1}^{\mathrm{N}} \omega_{\mathrm{n}}\left[\varrho_{\mathrm{rn}} c_p^{\mathrm{rn}}(1-\phi_{\mathrm{n}})\right] + \sum_{\mathrm{n}=1}^{\mathrm{N}} \omega_{\mathrm{n}}\left[\varrho_{\mathrm{wn}} c_p \phi_{\mathrm{n}}\right]. \qquad (3.8)$$

The estimation of the theoretical affected area is shown in Figure 11-B. The circles around the wells represent the affected theoretical area by the wells' operation.

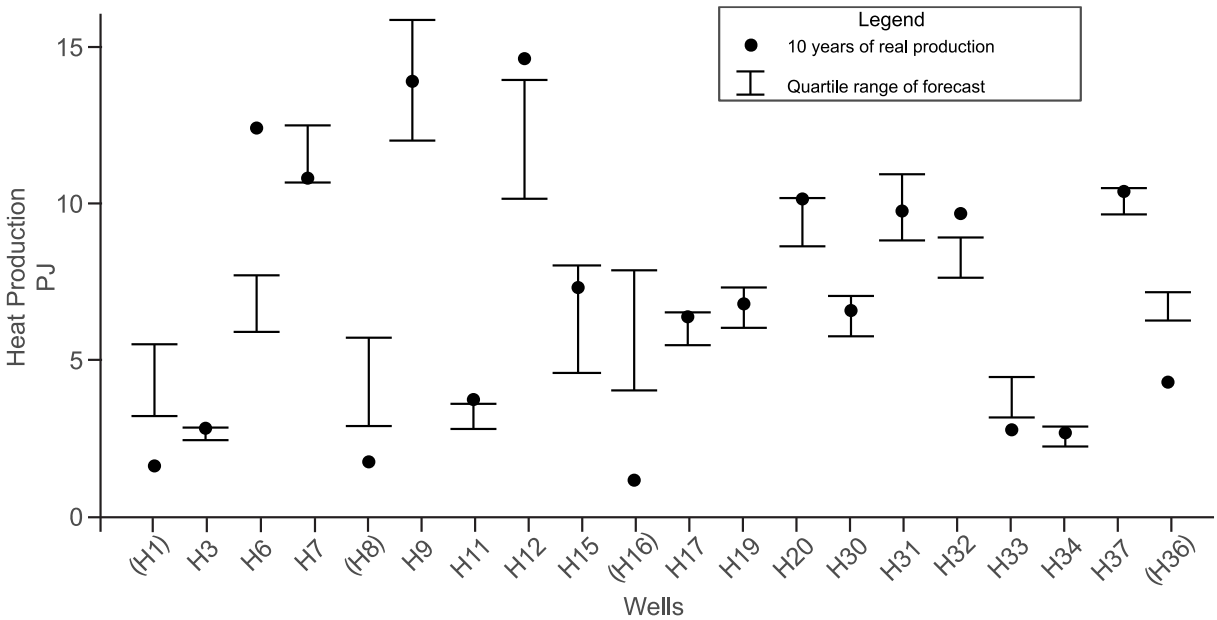

Figure 10 Forecast validation (Héctor González-García et al., 2021).

3.3. The heat content of Los Humeros and the sustainability implication of it

The current necessities are met by extracting hot fluids from the geothermal resource at Los Humeros. From the last 30 years of production, no dramatic signs of depletion have been identified. Pressure changes, but it is under acceptable limits in terms of the fluid output; i.e., those changes allow the production at a relatively constant rate.

The production forecast constraints the possible heat extraction for the next 30 years into limits shown in the power station. This calculation assumes that the conditions will continue and do not consider heat flux or water recharge rate. The system's renewability depends on two main factors: the heat flow and the water recharge rate. A drop in fluid production is a consequence of overexploitation, as seen in Cerro Prieto (M. A. Grant, Truesdell, & Mañón M., 1984).

Although no signs of such have been identified in Los Humeros, there is subsidence and earthquakes. Both are related to fluid extraction (Békési et al., 2019; Urban & Lermo, 2013). These effects are signs of aquifer overexploitation and have a solid negative

implication on environmental affectation and sustainability. Both effects increase the risk of natural hazards, which affects local towns. Moreover, these signs of overexploitation must be monitored with the system's pressure changes to avoid production depletion.

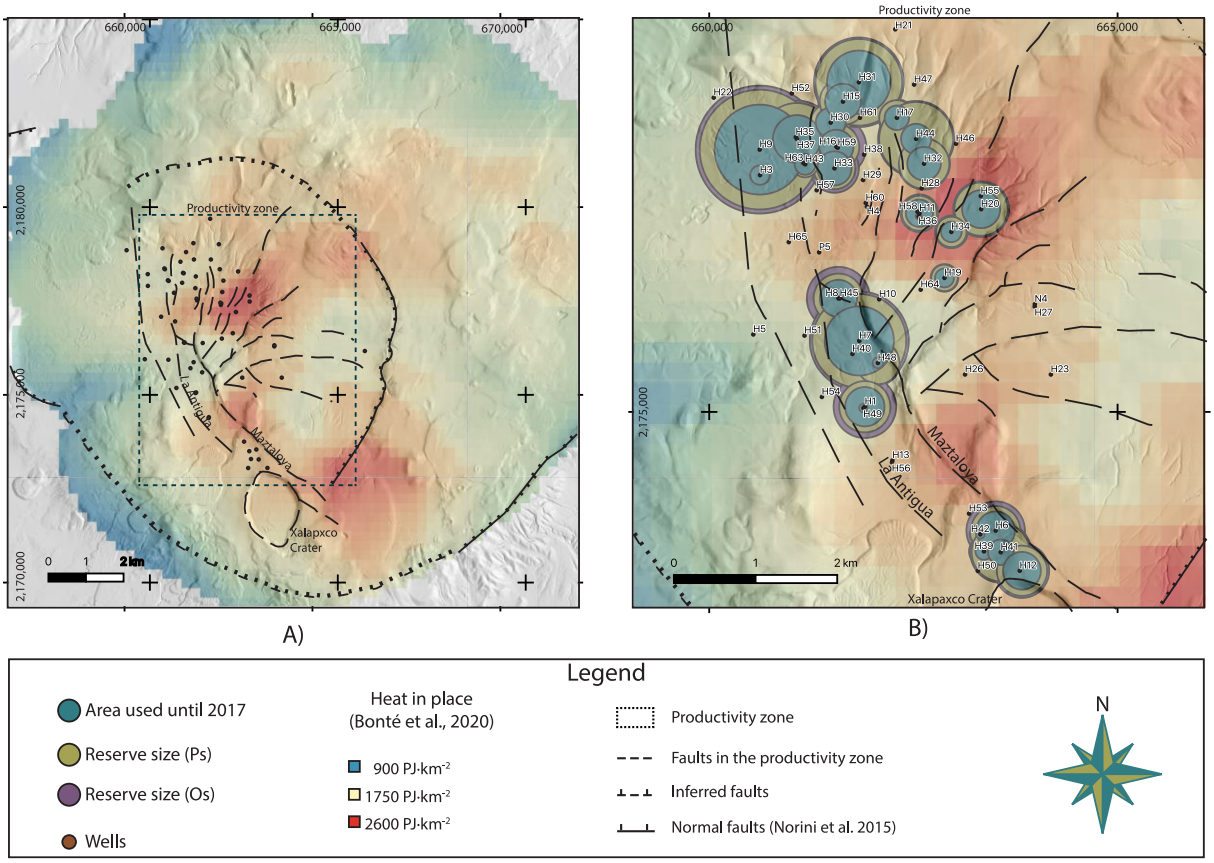

Figure 11 Affected theoretical area.

The calculation of the production based on historical data is not associated with any of the reservoirs' physical parameters. However, the surface conditions will be immediately affected when those dramatically change. Therefore, a forecast based on historical data is a feasible scenario for the future (75 % of accuracy according to the validation). Although the signs of overexploitation do not have a recognizable effect on fluid production, the forecast cannot represent the sustainable limit of fluid production. This is due to the subsidence and earthquakes associated with it. However, above this production rate, overexploitation can increase. In this scenario, the extraction will be compromised.

Figure 11 shows a theoretical representation of the effective size of the heat reserve, i.e., the heat that can be extracted under the current conditions. Rybach (2015) argues that the size of the sustainable potential of a geothermal reservoir is shorter than the technical, defined by the heat recovery factor and the economical one. The estimation presented here is the first attempt to constrain the renewable size of the Los Humeros reservoir. However, a better delimitation should include a calculation of the heat flux and water recharge. Both parameters will define the renewability rate of this reserve and declare if the extraction is below these rates.

This estimation is directly related to the environment and economics in terms of sustainable indicators. Reservoir's affectation is related to the environment. However, **natural hazards** affect the towns near the power station. Subsidence and earthquakes are negatively related to poverty, health, demographics, and education (all social

indicators). The **land** is affected by the subsidence. Moreover, the change in the use of the soil might affect local **biodiversity**.

As stated at the beginning of this section, the extracted geothermal steam is crucial to meet the necessities of the actual human generation. Within the next 30 years, another generation will need this reservoir. In that sense, exploitation under renewable limits is crucial. If exploitation is more extensive than this limit, steam production will decline, and electricity yield will be lower. In that sense, the **economics** of the power station could be affected. **Consumption patterns** will change due to a lower electricity yield.

The generation of electricity by a geothermal resource avoids using fossil fuels. Fossil fuels not only emit CO_2 to the **atmosphere** but also several other gases that are not only greenhouse but also many others which directly affect **human health**. Moreover, the presence of this power station might be a source of employment. Access to electricity promotes society's development by allowing the use of modern technology, which needs a stable electricity source. Both actions have a direct effect on the **poverty** of locals.

4. CO_2 footprint

Volcanoes and volcanic systems have a high contribution on the emission of greenhouse gases (GHG) to the atmosphere (Robock, 2000). This feature is shared by those geothermal volcanic systems. The GHG are usually contained in the geothermal brine as non-condensable gases. When the geothermal brine is extracted, these GHG accompanies it. Within this mixture CO_2 is the main contribution. However, due to the natural occurrence of this gas in geothermal systems, the IPCC protocol has excluded it as an indicator of atmospheric harm (Goldstain et al., 2011).

Recent studies have addressed the environmental impact as a consequence of the exploitation of geothermal systems (Table 6). Many of them are placed on active volcanic areas in which the major environmental affectation is a high CO_2 discharge to the atmosphere. GHG emissions also depends on the application and the technology used when exploiting the geothermal resource. Figure 4 shows the Lindal diagram with the corresponding CO_2eq value. The highest contribution is related to those volcanic geothermal systems using single flash technology. This conversion technology is a common choice for high enthalpy GS and it consist of steam turbines which use single or double flash processes. On the other hand, applications like heat pumps might have a lower GHG emissions in comparison with other types of technologies used for the same porpoise.

The estimation of the environmental damage due to any production activity is carried out by a Life Cycle Analysis (LCA). As mentioned in the introduction, this procedure is designed to estimate the affectation of any product at any phase of its lifetime (Hauschild, Rosenbaum, & Olsen, 2018). This is an ISO standardized protocol. It is based on all the items needed in every part of the lifetime of this particular product. For the case of geothermal resources, the usual products are heat and electricity. It can be both, for the case of a cogeneration geothermal station. The LCA is divided in four steps: definition of the goal and scope, inventory analysis, impact assessment and interpretation (ISO, 2016).

The ISO-14040:2016, demands the inclusion of all impact categories influenced by the life-cycle of the evaluated product. However, an estimation of the CO_2 footprint follows the same procedure of the LCA, but with the only difference that the impact category is climate change. For the case of Mexico, there is no LCA/CO_2 footprint studies carried out for power stations. Nevertheless, the government publish every year the average emission factor which includes all power stations in the country (Table 1).

This emission factor is about the use of fossil fuels to generate electricity. This means that the CO_2 due to the installation of the corresponding power station is not included. As mentioned above, the exploitation of geothermal volcanic systems is accompanied by a large CO_2 emission factor. Since, LCA studies done in other geothermal power stations concluded that the CO_2 is the biggest environmental damage caused by this activity, this chapter aims to evaluate the CO_2 footprint of the power station of Los Humeros.

4.1. Goal and scope definition

The product to be evaluated, known as the Functional Unit (FU), is each kWh_{el} of electricity delivered into the Mexican electricity grid per year. The goal of this part of the study is the evaluation of the footprint associated with this amount of electricity. The scope is the construction and operation activities in the power station. The time reference is when the operation of the GTPS started. Table 4 shows that several wells were drilled before this year and they have been under continuous operation for the last 30 years.

However, this extra time was not included for all the items. This was decided to have a starting point for all the units used or placed in the grounds of Los Humeros.

Table 6 Life cycle assessment for different sites and applications in the world. *Hypothetical case. ^do not include operation activities. G-gradient is Geothermal-gradient. EGS is Enhanced Geothermal Systems. ORC is Organic Rankine Cycle. SF is for single-flash.

Site	Type	Technology	Affectation	EF	EF	Reference
				$g_{CO2}eq/kWh_{el}$	$g_{CO2}eq/kW_{th}$	
Germany	G-gradient	Heat pump	Large emissions of CO_2	-	290	(Welsch et al., 2018)
Switzerland	G-gradient	Heat pump	Potential of terrestrial acidification	-	17.3	(A. S. Pratiwi & Trutnevyte, 2021)
France^	EGS	ORC	Low environmetal affectation	54.92	9.15	(A. Pratiwi, Ravier, & Genter, 2018)
Germany*	Not especified	ORC	Low environmetal affectation	62		(Frick, Kaltschmitt, & Schröder, 2010)
Germany	EGS	ORC	Seismicity risk	49.8		(Lacirignola & Blanc, 2013)
Spain*	Not especified	ORC	High potential of ozone layer depletion	5.79	2.25	(Martín-Gamboa et al., 2015)
French Caribbean	Volcanic	SF	Large emissions of CO_2 and Sulfur	47		(Marchand et al., 2015)
Iceland	Volcanic	SF	Low emissions of CO_2	23		(Paulillo et al., 2019)
Italy	Volcanic	SF	Large emissions of CO_2	1300		(Bravi & Basosi, 2014)
Italy^	Volcanic	SF	Large emissions of CO_2 and Sulfur	248		(Buonocore et al., 2015)
Japan^	Volcanic	SF	Large emissions of CO_2	15		(Hondo, 2005)
Mexico	Volcanic	SF	Large emissions of CO_2 and methane	580		(H. González-García et al., 2022b)
Türkiye^	Volcanic	SF	Large emissions of CO_2 and Sulfur	57		(Atilgan & Azapagic, 2016)
Türkiye	Volcanic	SF	Large emissions of CO_2	1200		(Layman, 2017)
USA^	Volcanic	SF	Low emissions of CO_2	74		(Sullivan et al., 2010)

4.2. Boundaries of the study

The boundaries were defined by the minimum requirements needed in order to generate one kWh_{el} of electricity by means of geothermal steam. A geothermal power station requires the extraction of steam. To extract it, at least one well has to be drilled. Then, the steam needs to be transported from the well to the conversion unit. This transportation is done through a steam distribution network. This network is formed by several elements, like pipes, separators, many valves, etcetera (Garcia-Gutierrez et al., 2015). And, finally the conversion units which are also formed by several pipes and valves, including a steam turbine. These elements defined what it is called the Unit Processes.

A Unit Process (UP) is a group or single operation that can be individually defined (Hauschild et al., 2018). In this sense, the unit processes related with the generation of the FU, i.e., each kWh_{el} are three:

- UP-1: heat extraction, defined by one well to extract geothermal fluids.
- UP-2: heat distribution, number of elements to have 1 m^2 of distribution network.

- UP-3: heat conversion, all the elements regarding the conversion units.

There is a fourth UP:

- UP-4: operation, related with all activities related with the operation of the power station. Here maintenance is included.

The dismantling of these UP was not included in the boundaries of this study. This exception was decided due to the misinformation about the treatment of the UP's when dismantling. Each one of these UP's have an input of energy and materials, they also have an output. The list of materials required to make a UP fully functional is known as the Life Cycle Inventory (LCI). For this particular study, the LCI was based on works made in Los Humeros in recent years.

4.3. Life Cycle Inventory

This is the list of all the elements required for the generation of each kWh of electricity. A couple of works have published an LCI for other GTPS (Karlsdóttir et al., 2015; Tosti et al., 2020). These lists are suggested to be applicable for any other GTPS on the world, however, this assertion might be wrong. As mentioned before, each GS is unique due to its geological context (I. S. Moeck, 2014). In that sense, the technology required for the exploitation can vary on several ways or perhaps it would be slightly different.

Nevertheless, the application of this mentioned LCI's might generate an over or underestimation of the CO_2 footprint of the subjected GTPS to study. If there is no other chance, the use of this list can be used to approximate the real number. For the case of Los Humeros, there are plenty of available contracts required by the owner company (CFE).

Los Humeros is part of the generation portfolio of the CFE. The CFE is a state company. Therefore, all the works required by this GTPS has to be submitted to a tender in which the cheapest option wins the bid and carries out the work (Diputados, 2010). The contracts related with each UP are found in the Tax Authority webpage. This portal is called COMPRAnet, and there, all the previous works related with public infrastructure can be found (HACIENDA, 2021a). Moreover, all the constructions also required an environmental report. In this environmental report the list of the works which includes an approximation of the materials to be used. This report is sent to the environmental authority in Mexico. They verify that all the works and materials are under the environmental protection law and rules (SEMARNAT, 2015).

This environmental report is called *Manifestacion de Impacto Ambiental* (SEMARNAT, 2006b). For Los Humeros two MIA were found. The first was done in 1992. It describes the installation of 4 conversion units of 5 MW_{el}, several new wells and a few km of pipes (SEMARNAT, 2006b). The second MIA was from 2006. It describes the installation of the first 25 MW_{el} unit, 12 more wells and 7.3 km of pipes (SEMARNAT, 2006b). Both reports also contain the analysis of non-condensable gases (NGC) contained in the geothermal steam (Table 7).

Table 7 Non condensable gases contained in the geothermal fluids from Los Humeros.

WELL	WEIGHT FRACTION OF NCG	COMPOSITION OF NCG %					
	%	CO_2	H_2S	NH_3	H_2	N_2	CH_4

	1989	2006	1989	2006	1989	2006	1989	2006	2006	2006	2006
			%		%		%		%	%	%
H1	5.69	10.8	98	97	0.92	3.14	0.64	0.0200	0	0.15	0.01
H3		8.6		96		3.88		0.0306			
H6	2.74	4.6	93	92	5.34	7.74	0.71	0.0610	0.07	0.45	0.87
H7	2.31	4.6	94	94	4.65	6.31	0.39	0.0199	0.04	7.94	0.01
H8	4.85	5.1	96	95	2.98	5.43	0.63	0.0171	0.03	0.69	0.01
H9	1.28	5.8	89	88	7.22	11.86	1.18	0.0907	0.18	2.42	0.03
H10	1.68		95		4.18		0.45		0.03	0.73	0
H11	2.13	4.8	95	93	3.99	6.92	0.49	0.0218	0.04	0.53	0.29
H12	7.97	10.6	95	97	3.59	3.35	0.37	0.0264	0.06	0.53	0.67
H13	2.81		93		4.46		0.64		0.07	1.26	0.30
H15	2.89	3.6	85	90	11.26	9.52	0.38	0.0750	0.14	3.18	0.18
H16	4.06		88		9.28		0.19		0.14	1.96	0.23
H17	2.92	2.4	96	86	3.21	13.88	0.24	0.1098	0.03	0.09	0.05
H18	46.3		98		0.47		0.03		0.08	0.13	1.48
H19	9.03	4.7	97	95	2.66	5.24	0.05	0.0165	0.03	0.54	0.01
H20	2.68	5.5	96	92	3.02	7.80	0.33	0.0596	0.06	0.60	0.47
H23	5.17		90		7.99		0.19		0.11	1.06	0.32
H30		1.8		81		19.20		0.1513			
H31		4.8		93		7.38		0.0582			
H32		2.6		88		11.68		0.0924			
H33		1.6		72		27.76		0.2188			
H34		4.9		87		13.24		0.1048			
H35		1.6		72		27.76		0.2188			
H37		3.2		89		11.17		0.0352			
H39		7.8		95		4.60		0.0363			

The construction reports and the MIAs were the base for the LCI. In these reports, it is stated that Los Humeros held two conversion technologies. From 1990 till 2008 there were eight conversion units with a capacity of 5 MW_{el}. It ended when the first unit of

25 MWel was installed and some of the 5 MW_{el} were shut down. The contracts included a list of the elements required for the work. However, this list cannot be directly used for the quantification of the CO_2 associated. The reason was that the manufacturer cannot be identified for all of them. Instead of using the item, the material was taken. The associated equivalent CO_2 (CO_2eq) was calculated from the supply chain data from Ecoinvent 3.7.1 (*cutoff*) (Wernet et al., 2016a).

4.4. CO_2 emission factor (EF)

The contribution per material was used to calculate the EF per Unit Process (UP). This procedure helped to identify the UP with the higher CO_2eq contribution. The CO_2 footprint for the entire power station was the sum of all the contribution of the UP (H. González-García, Francke, Göllner-Völker, et al., 2022a):

$$g_{CO_2eq} = \frac{1}{e}\left(\sum_{i=1}^{3} UP\text{-}i_{CO_2eq} + UP\text{-}4_{CO_2eq}\right), \qquad (4.1)$$

The sum was divided by the electricity yield (e) of the power station (Table 5). The contribution of the CO_2eq of the UP-4 was taken from the non-condensable CO_2 contained in the steam. This calculation was done with the nCO_2 content reported by the CFE and the steam mass flow rate (H. González-García et al., 2021):

$$\text{UP-}4_{CO_2} = \dot{m}'' \cdot \Delta t \cdot (nCO_2 + nCO_2eq), \qquad (4.2)$$

In this eq. Δt is the time, nCO_2 is the mass fraction of CO_2 contained in the steam and nCO_2eq is the contribution of methane, using an equivalence factor of 34:1 (Wernet et al., 2016b). This calculation was done for all the wells under operation (Figure 5).

4.5. Life cycle inventory and emission factor

The LCI of materials is in Table 8. The UP-3 was divided in two according to the capacity of the conversion unit, i.e., UP-3_{25MW} and UP-3_{5MW}. The UP that requires more materials is the heat extraction, associated with the wells. On the other hand, heat conversion is the UP with less materials. However, those UPs do not contain a detailed list of material input for the conversion units. Unfortunately, that information is highly classified.

On the other hand, for all the process, the 4-UP has the highest CO_2eq contribution (Figure 12). The lifespan of this study is 30 years, thus, the values shown in Figure 12 were divided by 30. For the construction, the biggest contribution comes from the distribution network. The emission factor per year was calculated considering the wells under operation and the constructions placed during that year. The year with the larger electricity yield was 2019 (Figure 13). The EF is within a range of 442 to 568 $g_{CO_2}eq/kWh_{el}$. This range for the EF is a consequence of the reported nCO_2eq (Table 7). The gas content was published covered only two years: 1989 and 2006. The approximation here proposed consider the average content of nCO_2eq for the wells. The lowest value corresponds to 1989 whereas the highest is for 2006 (since $\overline{NCG}_{1989} < \overline{NCG}_{2006}$).

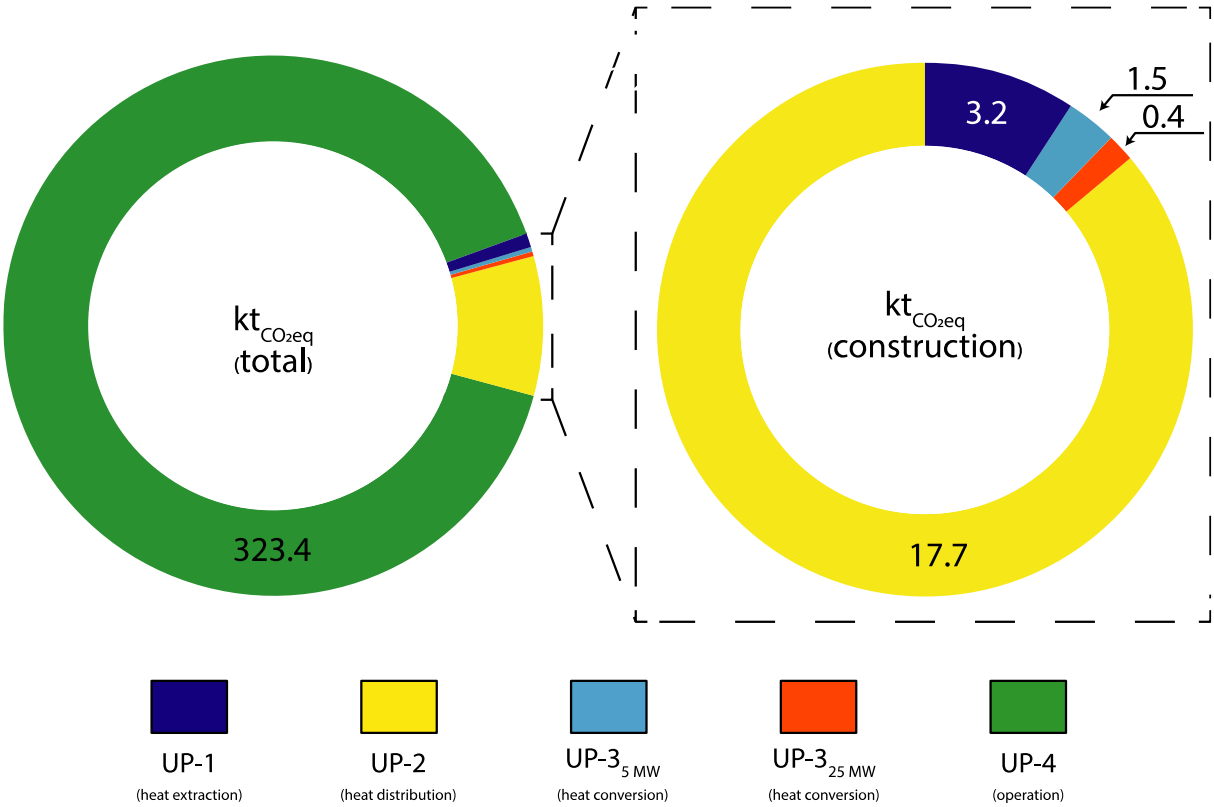

Figure 12 Yearly CO_2 contribution per Unit Process. UP-4 is the lower average of the nCO_2 content in the geothermal steam (Table 7).

Table 8 Life Cycle Inventory.

Materials	UP-1		UP-2		UP-3 5 MW		UP-3 25 MW	
	Total	$Kg_{CO_2}eq$	Total	$Kg_{CO_2}eq$	Total	$Kg_{CO_2}eq$	Total	$Kg_{CO_2}eq$
20 MW conversion unit							1 unit	530344
5.5 MW conversion unit					1 unit	163146		
Alkyd enamel			19.5 kg	130.2				
Aluminum					539.5 kg	8282		
Asphalt			0.02 m²					
Basalt	431.6 t	2353	143 kg	0.782				
Bentonite	290.1 t	11427						
Clay	10 kg	0.01	71 g	0.0005			3.5 t	25.2
Coal tar					25 t	13557		
Concrete	1.35 m³	416	2.01 m³	623	394 m³	121701	545 m³	168106
Copper	22 kg	129			159 kg	947		
Diesel	485.5 t	220717	226 kg	103	246.3 t	111980	53000 L	24092
Epoxy	84 t	425218			21 t	106304		
Filling Material			0.38 kg	0.003				

Glass fiber			96.7 kg	254.7				
Gravel			13 kg		92.4 t			
Lignite	125.9 t	2555						
Lignophosphate	13.6 t	?						
Mineral Fiber	101 kg	266	430 kg	1134	427 kg	1125	1.1 t	2903
Mortar	851.3 t	206095	269 kg	65	1055 t	255395		
Neoprene								
Paint			10.4 m^3		201 m^3	?		
Polyethylene	1254 m^3	12785	1.36 m^3	13.9			0.085 m^3	0.867
Portland Cement	72.2 t	63851						
PVC	790 cm^3	0.0020	100 cm^3	0.00026	0.364 m^3	0.9316		
Reinforcement Steel	3.8 t	7420	154 kg	296	34.3 t	65746		
Sand	270.2 t	953						
Sawdust	20.6 t	486						
Sodium Carbonate	1.9 t	2463						
Sodium Hydroxide	6.2 t	6639						
Steel	191 t	434091	853 kg	1936	3.3 t	7576		
Steel (black)			355 kg	805				
Steel (carbon)			7.7 t	17633	91805 t	208316	1935 t	4391348
Steel (Cr)	96.3 t	443186						
Steel (galvanic)	2.7 t	6273			13.4 t	30412		
Stones	0.034 m^3	?						
Thicking agent	975 kg	?						
Viscosifier	650 m^3	?						
Water	650 kg	0.10						
Waterproofing	82.5 m^3	?						

The yearly EF is shown in Figure 13. The EF is inversely proportional to the electricity yield, thus, the largest the yield, the lowest the EF. In 2019 the lowest value was registered, in contrast, the largest was observed in 2014. The conversion units installed in Los Humeros are single flash steam power plants (L. C. A. Gutiérrez-Negrín, 2020). This means that a great part of the extracted steam is released to the atmosphere. With this steam, the nCO_2eq also escapes to the atmosphere.

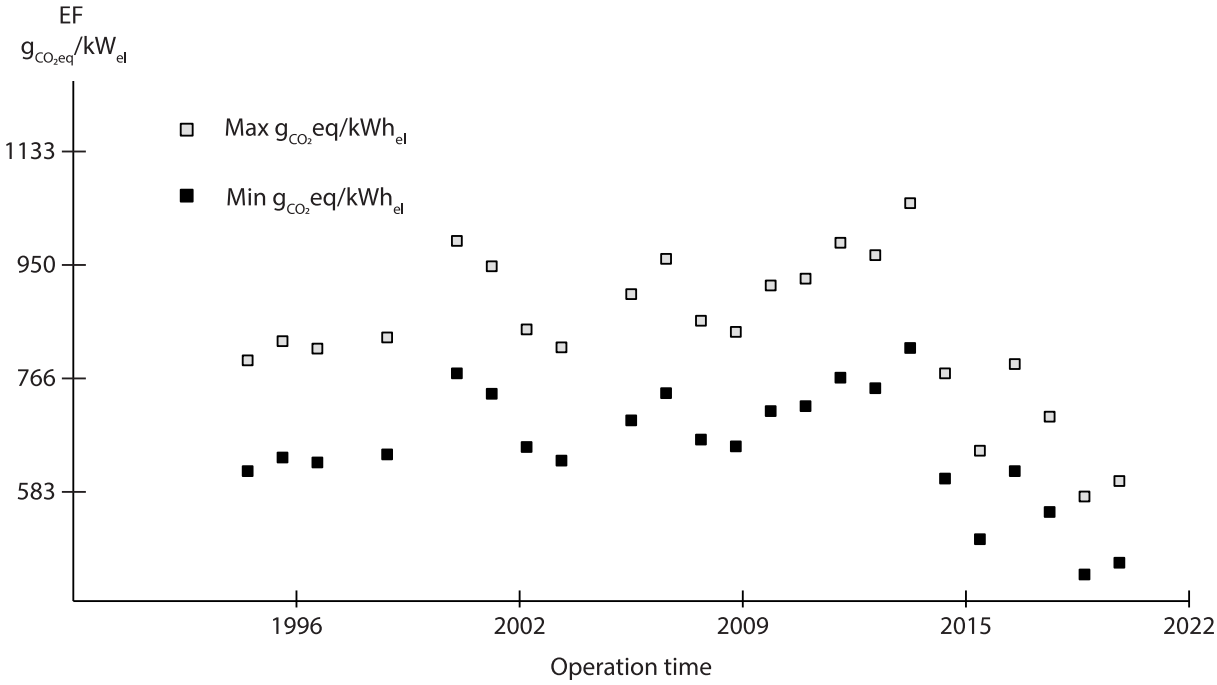

Figure 13 Yearly variation of the emission factor (EF).

4.6. Sustainability implications of the CO_2 footprint

One of the indicators mentioned before regarding the sustainability is the **atmosphere**. The EF of Los Humeros is on the same level as the average fossil Mexican EF (Table 1). This implies that the GTPS of Los Humeros emits CO_2 as an average fossil power station. It was mentioned that the IPCC suggested excluding the CO_2eq contained in the geothermal fluids. This is based on the fact that this CO_2 does not come from any fossil fuel.

However, the natural emission of CO_2 in the vicinity of the power station was calculated in 84 ton/day (Jentsch et al., 2020). In contrast, the CO_2eq released to the atmosphere due to the operation of 29 wells is ca. 890 ton/day (H. González-García, Francke, Göllner-Völker, et al., 2022a). Although, this CO_2eq occurs naturally due to the volcanic nature of the system, there is no doubt that the emission rate due to the GTPS operation is 10 times higher than the natural emission of these gases. This effect is absolutely anthropogenic and it must be considered for decarbonization schemes.

Regarding the sustainability indicators. The big branch related with the CO_2 footprint is the environment. However, this also has a direct implication on the society. In this sense, not only the **Atmosphere** is the indicator that takes the attention, but also in the long term the **Human Health** and **Natural Hazards** are affected as a consequence of climate change due to the CO_2 emissions. Perhaps many others can be linked to this problem, however those three are directly affected by the large CO_2eq footprint of Los Humeros.

Although, the resource can be used to meet the current necessities and it is very likely that it will continue to help future generations, the exploitation of the resource in the given circumstances increase the risk of the future generation welfare. Los Humeros geothermal system is a renewable source of energy; however, its exploitation is not sustainable so far.

5. Finance of geothermal projects

The finance of geothermal projects is a big hurdle to overcome when developing. They require a large amount of capital investment, and it is expected that at early stages, an enormous financial risk is associated with their development (Moore, 2016; S. K. Sanyal & Morrow, 2010; Sass 2016). The risk is a direct consequence of uncertainty when drilling a well. As geothermal requires at least one well to function, its success can be a matter of probability. Moreover, policies can contribute to stop their development (Sass 2016).

Getting finance for GP has always been complicated. This obstacle is not only a consequence of the risk, but GP need time to be ready which is translated into large periods of capital return. Although, the profitability might be positive in the long-run, large periods for return of capital are not attractive to investors. The attraction to geothermal energy (and renewables in general) increased during the oil crisis in the '70s (Tester et al., 2012). At that time, almost everywhere in the world, the electric industry was a government-controlled monopoly (Kahn, 1988). Under these circumstances, the state absorbed the risk involved in geothermal projects and the payment of the debt was not even considered (S. Sanyal et al., 2016).

In the case of Mexico, the first GTPS was developed at Cerro Prieto (North Mexico, see Figure 2). So far, this geothermal site has more than 100 wells drilled to run 600 MW_{el} of capacity. In contrast, the only private GTPS in Mexico, the Domo San Pedro, has 3 wells drilled to run 25 MW_{el} (L. C. A. Gutiérrez-Negrín, 2020). Although the geological settings are different and there is no public record about unsuccessful wells at Domo San Pedro, it is evident that a government geothermal project cares less about unsuccessful wells. This extensive drilling is not only for Cerro Prieto, but also for Los Azufres (50 wells (Torres-Rodríguez et al., 2005)), and Los Humeros (59 drilled wells, see Table 4).

Nevertheless, this risk usually decreases when the project development continues. When the power station is already installed at the latest stages, the financial risk reaches its lower value (Figure 14). For any project, investments can be made at any development stage. Besides, debt structures are designed to offer the best option to all the participants. These structures are thought to be applied according to the development stage (Moore, 2016)(Figure 14). The investment decision comes when the project's profitability is shown, i.e., when the project generates gain.

5.1. Profitability estimation

Profitability happens when there is a financial gain over an investment. This gain is defined by one parameter: interest. The interest is the value of choosing. An investor would choose the project with the highest interest offered in the same time interval among several options. In this sense, when profitability is evaluated, time is also necessary (but not essential). Thus, a private participant will put its money on a geothermal project if and only if there is a return on the invested amount.

There are several methods to measure the profitability of a project. In general, those methods are divided into two, those including time and those without it. In general, the ways that include time are preferred, and they are widely used to evaluate the profitability of any kind of project. For example, the Net Present Value (NPV) is a straightforward metric that shows a project's worth. The calculation of the NPV requires the cash flow (Cf_t), the interest (i), and the evaluation time (t):

$$\boldsymbol{NPV} = \sum_{t=1}^{T} \frac{Cf_t}{(1+i)^t} - \boldsymbol{I}, \qquad (5.1)$$

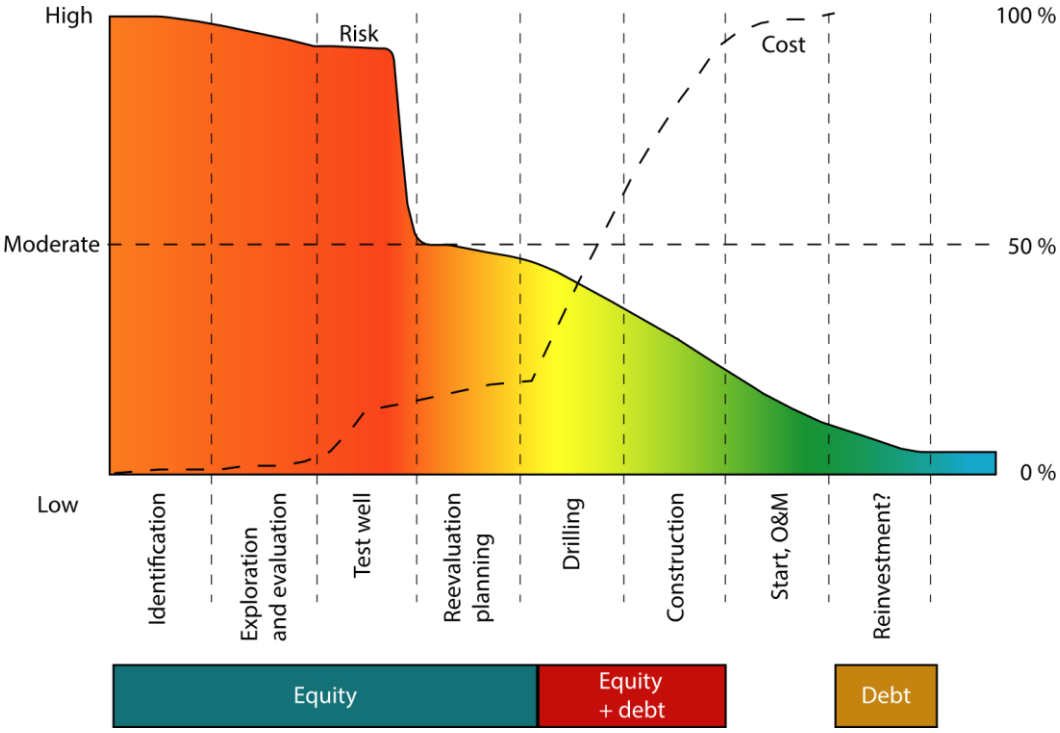

Figure 14 Behavior of risk and accumulation of cost along the development phases of a geothermal project. Financing structures are different according to the associated risk. Figure modified from Moore, (2016); and S. Sanyal et al., (2016).

After compounding, the sum is compared with the invested amount (I). The result of this subtraction tells how worth the project is. The rule of the NPV is:

- To invest if NPV>0
- To decline if NPV<0
- Indifference when NPV=0

However, the NPV does not clarify how much time is needed to cover the debt. In general, the financial break-even point (BEP) is calculated with the accumulated cash flow:

$$BEP = -I + Cf_1 + Cf_2 + \cdots + Cf_t, \qquad (5.2)$$

It is reached when BEP=0.

5.2. Los Humeros profitability analysis

These procedures were chosen to be applied in the GTPS of Los Humeros. In previous sections, the development of the GTPS was explained. This development not only had an environmental effect but also required a significant investment. Before, the contracts that helped with the LCA were mentioned. These contracts also included their cost. This cost defined the invested amount on Los Humeros.

The contracts were organized into different categories. Each category was based on the type of work described in the contracts:

- Conceptualization and monitoring: This category includes studies regarding the response of the reservoir against exploitation, and the performance of the GTPS.
- Connection to the electric grid: This is about all the work required to connect the GTPS with the Mexican electric grid.
- Ecologic restoration: This category includes works related to restoring the surrounding landscape.
- Maintenance: works related to the care, e.g., wells make up.
- Operation: All the activities required for the operation, e.g., the purchase of specialized clothing for workers.
- Transport of workers: rent of transportation for workers.
- Upgrading: this category is about the investment for the conversion units, new wells, and extra pipes.
- Others: this last one is related to payments made to actuarial-specialist (law people that verifies the works done on the site).

The monetary sum of all the contracts is in Table 9. The contracts were used to define the quantities to evaluate the profitability. The first quantity was the investment. It is the sum of conceptualization and monitoring, connection to the electric grid, others, and upgrading—the cash flow required in eq. (5.1) is defined by the income minus the production cost. The production cost includes Operation and Maintenance (O&M). However, some other quantities also represent the production cost.

Los Humeros belongs to a public company. However, the CFE became an autonomous state-owned company due to the electric reform. It means they have the right to keep information they consider sensible or data that can potentially put them at a disadvantage against any other Mexican Electricity Market (MEM) participant. This information includes the operational cost of the GTPS of Los Humeros. Almost 20 years ago, Hiriart & Andaluz (2000) reported the cost per kWh_{el} generated by each GTPS installed in Mexico. They stated four categories for the operational cost of Los Humeros.

Table 9 Summary of the contracts of the works required in Los Humeros since 2008. The contracts included were confirmed in COMPRAnet. This webpage has this information for free consultation. It belongs to the Mexican treasure Authority (HACIENDA, 2021b).

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
	MMXN	MMXN	MMXN	MMXN	MMXN	MMXN	MMXN	MMXN	MMXN	MMXN
Conceptualization and monitoring			3.5	3.4		0.14	5.6			
Connection to the electric grid			4.2	3.4				0.39		
Ecologic restoration					0.7		1.1	1.01		0.77
Maintenance	2.1	4.7	9.8	24.1	19.92	20.62	45.3	7.8	42.1	12.47
Operation			5			1.5	1.7	0.81	1.39	0.65
Others					0.18	0.3	1.3	3.15		
Transportation of workers				0.5	3.0	0.5	4.6		1.9	
Upgrading	120.5	184.9		5.8	264.5	644.9		390.3	300	

These were:

- O&M (Plant)
- O&M (Field)
- Steam Supply
- Power Plant Investment

This study used these cost divisions as a basis for another approximation. This decision was made due to the different schemes of investment. For the work of Hiriart & Andaluz, it is not clear if the state also made the investment at that time, but for the massive part of the investment in this study (Upgrading), this investment was made by the government (Tirzo, 2014). Therefore, the categories that defined the operational cost for Los Humeros were:

- O&M
- Steam supply
- Salaries
- Depreciation

O&M was defined by the sum of ecologic restoration, maintenance, operation, and transportation (Table 9). The steam supply cost and the salaries were requested to the *Instituto Nacional de Transparencia y Accesso a la Información* (INAI). The INAI is an autonomous institutional part of the government of Mexico. They provide information regarding all the institutions that belong to the government (including the CFE). The depreciation was assumed to be 10 % of the invested amount. According to the Mexican income law, depreciation for this kind of unit should be applied for ten years (Diputados, 2021). Thus, one-half of the cash flow was defined. For the other half, it is essential to make a brief explanation of the MEM.

5.3. Mexican electricity market (MEM)

Previously, the monopoly of the electric industry was mentioned. Under this business structure, the participation of private investors in new energy projects was scarce (Alpizar–Castro & Rodríguez–Monroy, 2016). However, in 2016 the Mexican electricity industry was reformed. The main change was the shifting from a monopoly to a regulated open market (Percino-Picazo, Llamas-Terres, & Viramontes-Brown, 2021). The change is aimed at private investors' participation and the electric industry's modernization ((GOB), 2022).

One of the main consequences of the electric reform was the creation of the *Mercado Eléctrico Mayorista* (MEM). The market is divided into five subsidiaries: electricity, power, transmission, clean energy certificates, and related services. As the MEM is an open regulated market, any entity (either a person or company) can participate in it. This participation includes electricity generation, distribution, and the trade of clean energy certificates or hot water in cogeneration stations (CENACE, 2022a).

The operator of the market is the *Centro Nacional de Energía* (CENACE). They regulate the electricity supply and dispatchment. They also issue clean energy certificates (CEL), the power incentive, and those related services. The energy subsidiary is a spot market known as the *Mercado de Energía a Corto Plazo* (MECP) (CENACE, 2022c). Although the power subsidiary is also part of the market, this is an ex-post-yearly incentive for those stations which cover the electricity demand during the 100 most intense hours of the year (CENACE, 2022d). The CEL is also traded in a different market, but the CENACE certifies their generation by renewable power stations. They also regulate their market price (CENACE, 2022b).

5.3.1. *Mercado de energía a corto plazo* (MECP), the Spot market

This market is analyzed day by day. The goals of this analysis are to define the electricity price in which the generators will sell their electric yield, the hourly supply schedule according to the demand trend of the previous day, and to determine the reserve needed

in case of higher demand (CENACE, 2022c). This procedure is known as the day ahead negotiation. The design of the electric supply schedule is based on the merit of order.

The cheaper production process is the first to be dispatched in this supply scheme. It is also used to set the selling price. The power station sets this price with the highest marginal production cost[1] connected to the same node. The merit of order is an open market dynamic that experiences energy price fluctuations (Figure 14). Electricity storage is expensive and low efficient. Besides, the demand is not constant throughout the day. Moreover, the final electricity price has three elements: marginal generation cost, Transmission quota, and Congestion fines. The three also vary throughout the day (CENACE, 2022c).

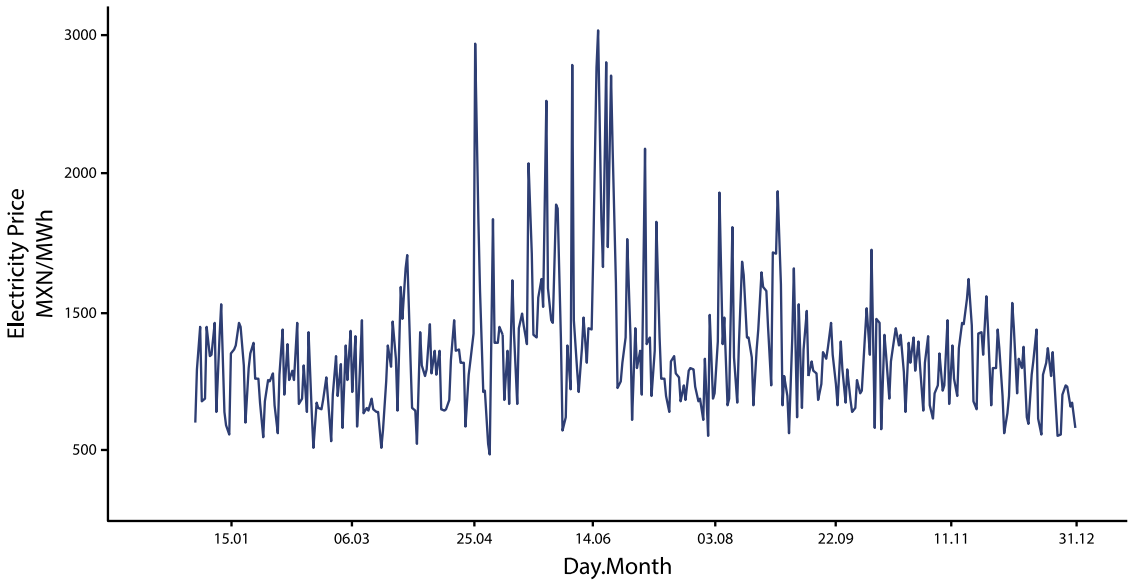

Figure 15 Electricity price reached in 2017 at the node "02TZT-115" where the GTPS of Los Humeros is connected.

5.3.2. *Mercado de balance de potencia*, power subsidiary (MBP)

This subsidiary gives an incentive to those power stations that helped to cover the demand when it was the highest. This is extra money at the end of the year for the installed capacity. The power stations that receive the incentive are defined by the 100 critical hours of the year. The price per MW_{el} of installed capacity is set by "the reference technology of generation."

The CENACE chooses this last one. The choosing criterion is the Levelized Cost (LC) for that specific year, i.e., the power station with the lowest LC sets the price per MW installed for all the Country. The price is equal to this LC (Diputados, 2016). The rules for this market branch are published for a free consultation on the CENACE web page (CENACE, 2022f). The price per installed MW_{el} since 2016 is in Table 10. The reference technology considers all the fossil power stations in Mexico. Since fuel prices are variable, forecasting the LC for the next year is extremely difficult. Thus, the MBP is given by the end of the year.

Table 10 Price of the installed capacity according to different reference technology.

Price of Installed capacity

[1] Marginal production cost ≠ operational cost.

	MMXN/MW
2016	0.12
2017	0.71
2018	0.12
2019	0.22
2020	0.63

5.3.3. *Certificados de Energía Limpia*, clean energy certificates (CEL)

The law states that a CEL is earned when 1 MWh_{el} is generated by the use of a renewable source of energy (Diputados, 2019b). During the creation of the MEM, these certificates were intended to motivate the use of renewables. A new trading market for these certificates was also planned. Nevertheless, no market has been opened yet, but renewable power stations generate CEL and sell them. This is because fossil power stations need a certain quantity of CEL per year, according to the law (Diputados, 2019a). As geothermal is considered a renewable energy source, Los Humeros generates CEL.

Los Humeros is a generator of electricity. It means that this GTPS is at the base of the MEM, and it participates in these mentioned subsidiaries. The other two are distribution and related services, but Los Humeros does not join them. These three elements, in principle, define the income of this GTPS. The generation of electricity using the geothermal system as a primary energy source has three implications.

The first one is that the GTPS of Los Humeros receives 1 CEL per MWh_{el} delivered into the node. The second implication is regarding the merit of order. As said before, the dispatching of electricity is scheduled according to the marginal cost of production of the different power stations connected to the same node. The generation process with the lowest marginal production cost is the first dispatched. The marginal production cost is the first derivative of the cost function ($c(\mathrm{K})$):

$$\frac{dc(\mathrm{K})}{d\mathrm{K}} = c_f + c_v(\mathrm{K}), \tag{5.3}$$

In this case, the cost function ($c(\mathrm{K})$) is defined by the sum of fixed production cost (c_f) plus variable production cost ($c_v(\mathrm{K})$), where K is the quantity produced. In Mexico, the variable production cost is defined by the price of the fossil fuels used in the generation process (SENER, 2015a). For the particular case of Los Humeros, the variable production costs are zero because it does not use fossil fuels to generate electricity, and all operation and maintenance costs are fixed.

The third implication is on the plant capacity factor. Among renewable options, geothermal does not depend on weather conditions and can run almost annually. Besides, due to the marginal cost being equal to zero, the electric production of these power stations is used to cover the demand in the most intensive hours of the year. Moreover, as is described in the power market rules, the GTPS of Los Humeros must receive the power monetary incentive. Thus, the revenues to Los Humeros would be formed by three elements:

$$Re = MECP_{12\,\mathrm{m}} + MPB_{\mathrm{y}} + CEL_{\mathrm{y}}, \tag{5.4}$$

However, there is a fourth element that has not been described. Although the GTPS of Los Humeros runs in a regulated open market, this power station and several others pose a vesting contract (GOB, 2014).

5.4. The vesting contract

The vesting contract is implemented in many countries that have just recently free their electric markets. This is a tool that helps in the scheme's transition. The Mexican electricity law was reformed in 2013. The main consequence was the creation of the MEM (Percino-Picazo et al., 2021), and the monopoly was shifted into a vertical structure (i.e., generation → distribution → commercialization). After this change, it was decided to implement vesting contracts during this transition. With their use, the price volatility is deadened, and the profitability of the power plants is ensured (Kee, 2001). In the case of Mexico, this contract is an agreement between the operator (CENACE) and the generator (Los Humeros)(GOB, 2014b).

The contract includes purchasing all the electricity produced by Los Humeros in exchange for coverage of all production costs reported by the GTPS. Within this contract, all the parameters defined in eq. (5.4) are already included, i.e., the Los Humeros does not receive extra money for the power and the CEL as they are already included in the vesting contract. Therefore, this contract protects the power station from the volatility of the prices, and also it diminishes the uncertainty associated with the spot market. Furthermore, although Los Humeros has ca. 90 MW_{el} of installed capacity, the contracted quantity is less. Therefore, the power incentive and the CEL do not contemplate the total capacity. The acquired parameters are described in Table 11.

Table 11 Elements described in the vesting contract of the GTPS of Los Humeros. This contract was agreed upon 2017, and it will run until 2030 ((GOB), 2014b). These parameters are described in the vesting contract. The document describes an update of these parameters, but no other document was found.

	Concept
Electricity	100% MWh
Installed capacity	54 MW_{el}/y
CEL	211,291 CEL/y

5.5. Cash flow of the power station

As said before, Los Humeros possess a vesting contract. In that contract, it is stated that this GTPS will have the reported costs covered in exchange for the electricity generated. Moreover, the vesting contract is designed to make the power station fully profitable. Thus, an evaluation of its profitability under this business scheme does not make sense. However, this contract will end in 2030, and after that, Los Humeros will participate in the MEM. Therefore, as this chapter aims to evaluate the profitability of this GTPS, this evaluation was done for two scenarios. The first scenario considers the vesting contract, and the second scenario assumes the participation of the GTPS of Los Humeros under the MEM.

The operational costs were 0.87 MMXN/day. It was obtained by the sum of:

- O&M: 0.34 MMXN/MW_{el}/y
- Steam supply: 1.31 MMXN/MW_{el}/y
- Salaries: 0.15 MMXN/MW_{el}/y
- Depreciation: 2.82 MMXN/MW_{el}/y

These costs were the basis for the vesting contract. These costs were also used to calculate the cash flow for the second scenario. The cash flow for the second scenario is defined by the difference between income and operational costs:

$$Cf_t = e \cdot eP - Ic \cdot Oc, \tag{5.5}$$

The electricity yield (e) is in Table 5. The electricity price (eP) was obtained in the CENACE portal (CENACE, 2022g). Finally, the installed capacity (Ic) is in Table 10 and the operational costs were already defined. Thus, the four elements are known. However, there is a substantial discrepancy between all the dates from the different aspects.

Electricity yield is per year, but electricity price is per hour. On the other hand, the contracts began in 2008, and the records of eP starts in 2016 with the launch of the MEM. Before this date, there is no information. Moreover, all these contracts belong to the last development phase of the power station. The electricity is generated by the power plants installed due to that investment. Therefore, a virtual zero was proposed to evaluate the BEP and the NPV, assuming that all the processes started simultaneously.

Electricity prices are hourly data known as "local marginal price." The income estimation took a monthly electricity yield (Figure 16). The estimate was based on the monthly heat extraction (Figure 9) and the average conversion efficiency (Figure 6):

$$e_{month} = \mathrm{K}_{month} \cdot \bar{\eta} \tag{5.6}$$

However, this procedure covers only 2016 and 2017. Therefore, for 2018, 2019, and 2021 the yearly electricity yield was divided by 12 and assumed constant per month. The INAI provided the monthly electricity yield for 2020.

The income is electricity yield (e) times electricity price (eP). It is well known that electricity prices fluctuate throughout the year (Figure 15). This variation was considered by taking the monthly quartiles 1, 2, and 3. Thus, the quartiles were used to calculate the income:

$$e \cdot eP \rightarrow e \cdot \begin{cases} eP^1 \\ \overline{eP} \\ eP^3 \end{cases} \tag{5.7}$$

Then, the power incentive and the income due to the CEL were added to eq.(5.5):

$$Cf_t = e \cdot \begin{cases} eP^1 \\ \overline{eP} \\ eP^3 \end{cases} - Ic \cdot Oc + P + CEL, \tag{5.8}$$

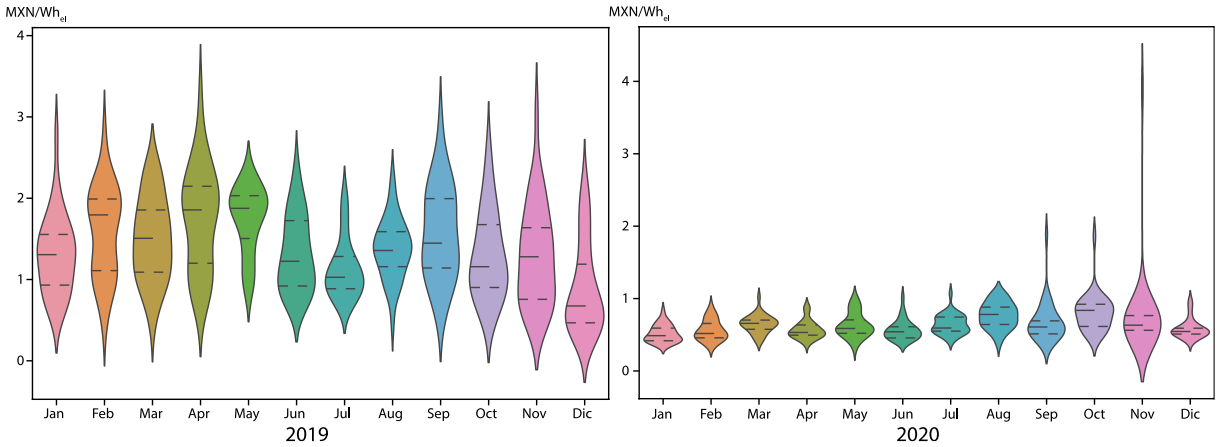

Figure 16 Electricity prices for 2019 and 2020 at the node "02TZT-115".

Before applying the NPV, and the BEP, the balance sheet was calculated. The balance sheet contains all the elements involved with the finance of any project:

$$\mathrm{Cf_t} = \mathrm{EBITDA}, \tag{5.9}$$
$$\mathrm{EBITDA} - \mathrm{depreciation} = \mathrm{EBT} - \mathrm{taxes}$$
$$= \mathrm{Earnings} - \mathrm{workingcapital} + \mathrm{depreciation} = \mathrm{net\ cashflow}$$

EBITDA is the acronym for Earnings Before Interest, Taxation, Depreciation, and Amortization (hereinafter cashflow will be named as EBITDA). Taxation for this kind of project is 30 % (Diputados, 2021). Thus, the final equation to determine the net cash flow for the second scenario is

$$Cf_t^{\mathrm{net}} = (Cf_t) \cdot 70\% + \mathrm{Dep\text{-}Sal}; \tag{5.10}$$

where Sal is the salaries of the workers, 70 % is the tax reduction, and Dep is the depreciation of the power plants. The EBITDA for the second scenario is shown in Figure 17. The EBITDA for the power station was negative during 2020. This was a consequence of the lockdown imposed by the COVID-2019 pandemics. This event changed the consumption rate of households and, therefore, the electricity demand. A negative EBITDA means that production costs were higher than income.

After calculating the EBITDA, the incentives were added, and the taxation + depreciation – salaries were applied. As a result, the balance sheet is positive after considering all the elements (Table 12).

Table 12 Net cash flow of the GTPS of Los Humeros.

	q1	**q2**	**q3**		**q1**	**q2**	**q3**		**q1**	**q2**	**q3**
	MMXN	MMXN	MMXN		MMXN	MMXN	MMXN		MMXN	MMXN	MMXN
2016	228.18	273.22	312.72	2018	231.46	293.07	381.69	**2020**	155.48	176.83	210.48
2017	276.02	350.46	416.31	2019	261.57	369.27	510.03	**2021**	211.91	263.31	318.36

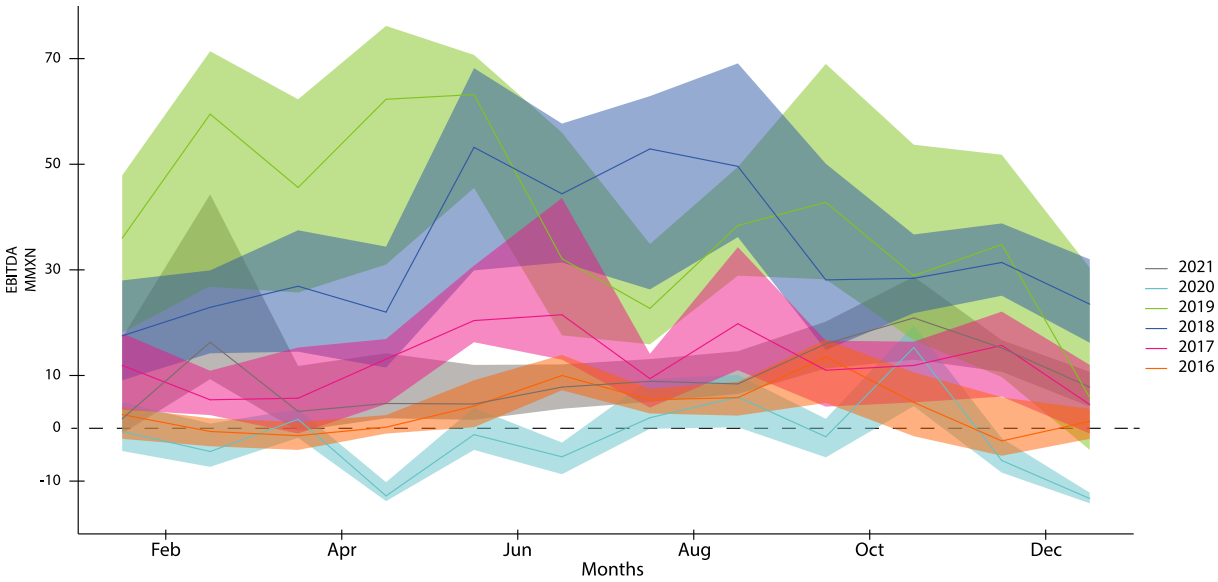

Figure 17 Earnings before interest, taxation, depreciation and amortization. It does not include the power and the CEL incentives.

5.6. Net present value and break-even point

The NPV had a different outcome for both scenarios. Both are presented in Table 13. The evaluation of the NPV considered 5 of the 25 of lifetime. However, in this shorter period, the assessment of the NPV for the second scenario and the highest electricity prices quantified a positive NPV. Unfortunately, as the rule states, the investment in this project is not a good idea.

Table 13 Net present value of both scenarios.

NPV	Vc	Regulated market		
MMXN		q1	q2	q3
5%	-758.4	-669.1	-70.9	303.6
8%	-861.8	-778.9	-236.8	102.5
10%	-895.8	-844.0	-335.2	-16.9

Regarding the BEP, it is also different for both scenarios. The vesting contract has not reached BEP in 5 years. On the other hand, the open market scenario offers a BEP of 4.5 years (Figure 18). Cash flow for the vesting contract is zero since the operational costs define the income. Thus, the net cash flow was determined by the incentives and depreciation.

The panorama looks pessimistic in terms of profitability. Almost all options for the NPV are negative, suggesting no investment in this project. Moreover, the BEP for both scenarios is not promising as well. Four years of BEP, the best price scenario might seem unattractive to any investor. The main barrier to forecasting for the next period is the electricity price. Due to its nature, a forecast for many years is inaccurate and inadequate (Weron, 2014). Nevertheless, a small experiment was conducted to see how this evaluation changes.

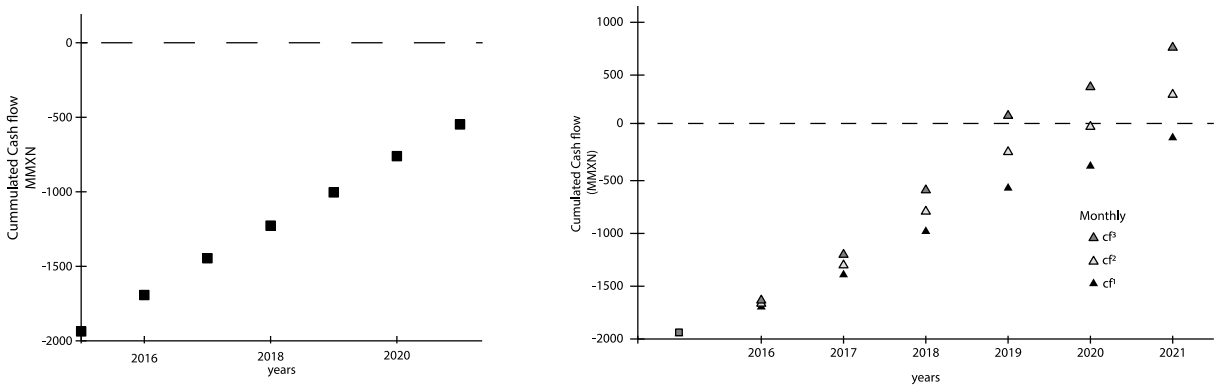

Figure 18 Break-even point for both scenarios.

The NPV was evaluated for the duration of the vesting contract (14 years). The results are in Table 14. All the results changed. Now there are all positive, indicating an excellent option to invest in. The BEP for the vesting contract is reached in 2024, eight years after the starting production point. However, the power incentive was not included since no data is available (last year was 2021 (CENACE, 2022e)).

Table 14 NPV for all the duration of the vesting contract (14 years)

NPV	**Vc**	**Regulated market**		
MMXN		q1	q2	q3
5%	603.2	1218.6	1874.1	2634.4
8%	256.2	676.3	1223.6	1848.2
10%	185.7	390.7	880.1	1433.6

5.7. Profitability and sustainability

The profitability of the GTPS is not favorable based on the available data. However, this panorama changed when the evaluation was extended for 11 years. This is unrealistic due to the nature of the electricity market. Nevertheless, it gave a clue about the financial performance of Los Humeros. **Economic development** and **consumption patterns** are the sustainable indicators related to this part of the study.

A power station has two costs: fixed and variable. In this sense, a project like this must be profitable to cover these expenses. A non-profitable power station will always require capital injection by the government. However, in the long run, this is not sustainable. If any other project (not related to electricity) is not profitable, it could be closed, and it will be a shortcut to the product that is being produced by it. Nevertheless, a power station cannot take this option unless another can cover that electricity yield.

Electricity is a very special product. The storage is expensive and inefficient on a large scale. Besides, the **consumption pattern** is not constant within the hours of the day. Under these bases, the electricity grid is designed to cover these requirements. Therefore, removing a power station would modify the electricity supply chain, and the final user would be affected.

Moreover, a lack of maintenance increases the chances of failure. Therefore, the production yield is also compromised. Ergo, the **consumption pattern** would be affected again.

A constant failure in the electricity supply disturbs the **economic development** of any region. Our society is based on electricity, and the lack of it modifies the quality of life.

Thus, a profitable power station can have a certain degree of financial independence and maintain itself. Using a renewable source to generate electricity creates a different dynamic. On one side, a renewable power station does not use fossil fuels to run. Then, it does not have any variable costs. On the other side, it reduces the environmental footprint of each kW generated by renewable means. It certainly has the immediate effect of a "cleaner" production process.

However, for the particular case of the GTPS of Los Humeros, the CO_2eq footprint is comparable with the averaged fossil Mexican emission factor. Therefore, more investment is needed to correct this problem. This new amount can be covered by the government again, although the investment scheme could include private investors this time. The profitability of the power station has to be demonstrated to do that.

Based on the available data, the profitability evaluation is primarily negative. However, there is a good chance for Los Humeros to be profitable. A vesting contract is a long-term contract. Despite the objective (to diminish the volatility of the spot price), it also ensures the profitability of the power station and, therefore, its maintenance and operation costs. So far, geothermal resource exploitation is not under sustainable limits. The next chapter offers an overview of the whole study to understand the connection between the three stepstones explored in this study.

6. Three pieces for a puzzle called Sustainability

Sustainability is a concept created to preserve human well-being. This is used to design public policies that ensure that all activities occur within a specific limit, the so-called sustainable limit. Another concept emerged to keep the development within these boundaries: sustainable development. Under this concept, all limits are set to preserve societal growth under the sustainable limit. Several indicators have been proposed to evaluate that. They are intended to measure the impact of every aspect of society related to human activity (UN, 2022).

In this way, sustainable limits depend on the respective indicator. Those related to the environment are generally low, i.e., it is sought that the damage to the environment is the least possible. In contrast, the economic limits are high, i.e., the aim is to increase the profitability and economic development of the population. The long-term goal of sustainability is to preserve the resource used for future generations (UN, 1987, 2022). The current generation must use the resource in question to meet their needs without overconsuming them so that future generations have the same opportunities. In turn, the future generation must use the resource to the same extent (or perhaps to a lesser one) that the next generation also has that opportunity. Sustainable development inherently involves perpetual exploitation.

Nevertheless, there is no infinite resource that will always allow a future generation to use it. One generation will no longer have the option to use this same resource. In this sense, setting a specific limit to declare a project sustainable is not helpful. Sustainability should not be seen as a state but as a process. This process must be monitored to ensure that future generations can continue using the resource. A limit can describe this process:

$$\lim_{t \to \infty} S(t) = 1 \qquad (6.1)$$

where S(t) is the project's sustainability when time t tends to infinity. In other words, the project in question is not sustainable, but it has the potential to be sustainable.

Changing the concept of Sustainability leads to a better interpretation; therefore, public policies could have an adequate vision and ensure the development of society under sustainable conditions. This statement was tested by assessing the sustainability of the exploitation of the Los Humeros geothermal reservoir in Mexico.

6.1. Geothermal and sustainability

Geothermal systems are geologically unique. Therefore, different utilization concepts and technologies must be applied to exploit this alternative energy source. In addition, not all systems have the same environmental impacts (e.g., La Primavera geothermal system in Mexico has a high discharge of arsenic into the local waters (Welch, 1999), an effect that has not been recognized in Los Humeros). These particularities make a consensus about what to include to declare the sustainable use of geothermal challenging to agree. As explained in the introduction, many authors position heat content as the primary indicator of the sustainable exploitation of any geothermal system. However, at least two other parameters must be included. These are the profitability of the project and the environmental impact. A project is not sustainable if it is not profitable. It is also not sustainable if the environmental damage is severe.

This dissertation addresses these three essential points. They are called essential because they are present in all geothermal projects:

- Heat is necessary to be called a geothermal system.
- The environmental impact of using geothermal energy cannot be avoided, but it must be low through appropriate utilization concepts.
- Profitability is a prerequisite for financing and, thus, for the implementation of the project.

This study is applied to a geothermal system under exploitation, the latest development phase. However, these three pillars are still applicable in the early stages since the three aspects are present in all phases. Once they are evaluated, the rest of the sustainable indicators are derived from them. Considering all the indicators from the beginning would result in wasting resources. Not all of them apply at all stages nor to all geothermal resources. Thus, this chapter integrates the three pillars from different studies to evaluate the potential for sustainability in exploiting the Los Humeros geothermal system.

6.2. Sustainability indicators

The introduction discussed the indicators to evaluate whether a project is sustainable or not (Table 2). It was also said that they could be derived from the three proposed pillars. The geothermal power station (GTPS) at Los Humeros uses the geothermal resource hosted in an active volcanic caldera. For instance, the amount of stored energy is enough to cover several generations. However, the exploitation rate might not.

For this reason, the first part of this dissertation is an attempt to define an adequate exploitation rate, a sustainable rate. This study is based on historical production data, and the results defined a limit on future production (H. González-García et al., 2021). The second part focused on evaluating the environmental impact, which revealed that the discharge of CO_2eq into the atmosphere is comparable with the fossil emission factor of Mexico. Finally, the third part examined the project's profitability, which was within a reasonable range (H. González-García et al., 2022c).

These three pillars represent a general overview of geothermal resource exploitation. From them, sustainability indicators are derived. The methodology proposed to evaluate the sustainability of geothermal systems involves three levels. The three fundamental pillars set the first level suggested here. The second level relates those pillars with the sustainable indicators, i.e., the effect of the pillars on the sustainable indicators. And the third level evaluates the affectation of each indicator with the rest of them (Figure 19). Each level has more detail regarding the effect (positive or negative) of each pillar on the sustainable indicators. From the first level, the exploitation of Los Humeros does not have the potential to be sustainable in the short or long term. This conclusion came after the high CO_2eq footprint that exploitation entails (H. González-García et al., 2022b).

The second level was discussed at the end of the previous three chapters. It is summarized in Table 15. The third level is the assessment of each affected indicator with the rest of them. The indicators affected by the pillars take the name of the project. For example, to clarify this relation, it is “Los Humeros-Poverty (LH-1)” instead of poverty. The analysis of how “LH-1” is related to the rest of the indicators is done in the columns of the relation matrix (Column “LH-1” of Table 16). The level of relationship proposed is three numbers -2,0 and 1. A positive impact is 1, a negative impact is -2, and no impact is 0. The negative impact is -2 to have a more significant effect in the final evaluation, which is sought to be 1 when $t \rightarrow \infty$ (eq. (6.1)).

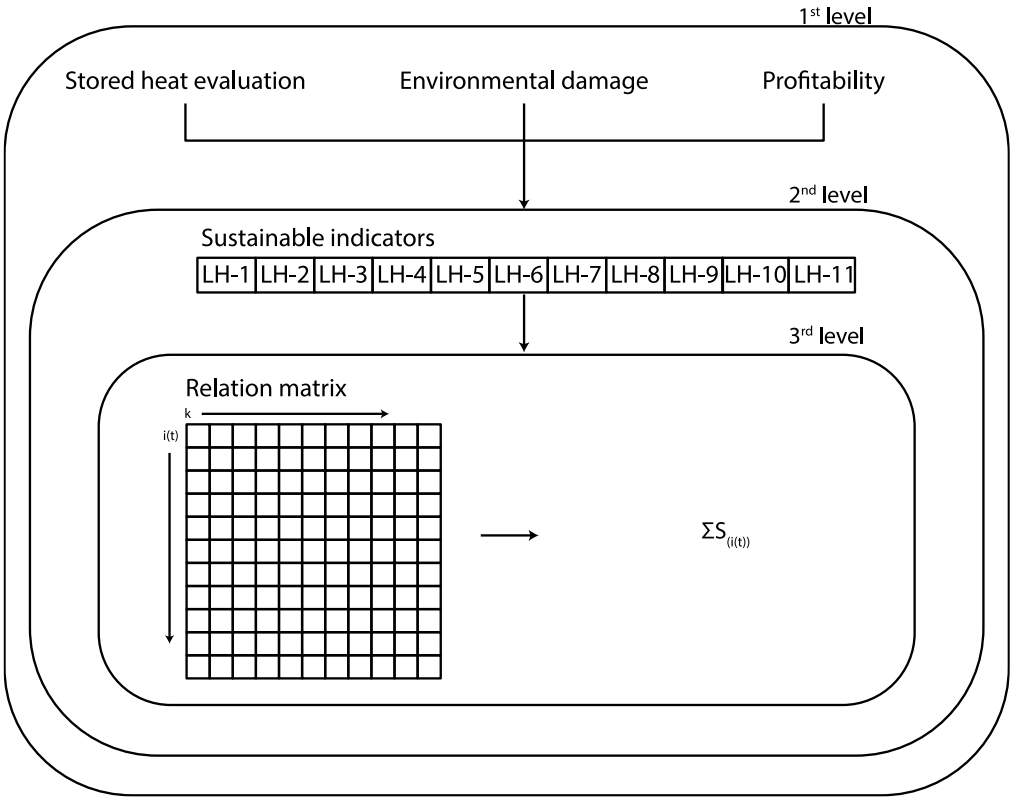

Figure 19 Different levels of sustainability evaluation

The third level of this evaluation helps to identify the indicators that are more affected by geothermal resource exploitation. The conclusion of non-sustainable exploitation came from applying the first level (i.e., heat content, CO_2 footprint, and profitability). Therefore, it gives an insight into the sustainable use of the process. However, it is still recommended to evaluate the affectation based on the indicators to follow the suggested procedure by the UN. This procedure gives a global vision of the interaction of the indicators. A global vision allows a general understanding of their current state and the implication of the sustainability potential of the project. It also helps to visualize those urgent attention areas. Subsequently, various solutions can be proposed and thus, reach a higher potential for sustainability.

The affectation of the indicators by the pillars depends on the project, but the relationship between indicators varies according to the project's operation. For example, the exploitation of Los Humeros has a high climate change potential due to the large footprint of CO_2eq. Although the geothermal fluids contain a large CO_2 amount, the release to the atmosphere can be avoided (this is discussed later). Thus, the **Atmosphere** (LH-6) indicator is negatively related to all other indicators (column LH-6 Table 16). On the other hand, there is no evidence of an affectation of the **Freshwater** (LH-8) availability due to the exploitation of the geothermal system. Thus there is no impact (column LH-8 Table 16). No evidence does not mean any affectation. However, at first glance, it is not directly related. For those negatively affected indicators, the goal is to have an impact of 1. Thus, the sum of all also gives 1 when eq. (6.1) is applied:

$$\lim_{t\to\infty} S_{k(i(t))} = 1, \qquad (6.2)$$

Table 15 Review of the conclusion of each previous chapter

		Exploitation (E)		
		Heat content (HC)	Carbon footprint (CO_2)	Profitability (P)
LH-1.	Poverty	-	Climate change	Better income
LH-2.	Heath	-	Climate change	-
LH-3.	Education	-	-	-
LH-4.	Demographics	-	Climate change	-
LH-5.	Natural Hazards	Earthquakes	Climate change	-
LH-6.	Atmosphere	CO_2 emission	Climate change	-
LH-7.	Land	Subsidence	-	-
LH-8.	Freshwater	-	-	-
LH-9.	Biodiversity	Change in soil use	Climate change	-
LH-10.	Economic	Production limits	Climate change	Reliable supply of electricity
LH-11.	Consumption patterns	Cheap electricity	-	Cheap electricity is available

where the S function is defined by the indicators. The indicators are defined by:

$$\sum \boldsymbol{i_j(t) = 1}. \tag{6.3}$$

The matrix (k,j) is made with the numbers by the indicator proposed in Table 16. But, of course, this assessment is merely subjective, and more rigorous research on this matter is necessary.

This matrix (Table 16) is the third level of sustainability evaluation, which is one indicator's relationship with others. The first indicator is **poverty** (Column LH-1 Table 16). After 30 years of exploitation, there is no evidence that Los Humeros' exploitation implies the **Poverty** of locals. However, there is something that might affect it. The only indicator related to this is **Economic** (column LH-1, row 10-Economic from Table 16). This would be affected if the station hired local workers. Then, those families would benefit from higher wages reducing their poverty level.

On the other hand, **health** (column LH-2) could be affected because the GTPS is directly installed in the town of Los Humeros. The emission of CO_2 is high, but also there are other harmful gases (Table 7) that can be a risk. If so, there could be a **demographic** decline due to deaths. Although the chances are low, it is a possible scenarios.

Table 16 The top row shows the study directly related to the specific indicator. LH-1, LH-2, LH-3, etc., are the indicators affected by the exploitation of Los Humeros. As said, each one of them is related to the rest. *Total sum $= \sum i(t)/11$.

Basic pillar (1st level)	**P**	**CO_2**	**P**	**E**	**E**	**CO_2**	**HC**	**-**	**P**	**P**	**P**
Los Humeros indicators (2nd level)	LH-1	LH-2	LH-3	LH-4	LH-5	LH-6	LH-7	LH-8	LH-9	LH-10	LH-11
1. Poverty	0	-2	0	0	-2	-2	-2	0	0	1	1
2. Heath	0	-2	0	0	-2	-2	0	0	0	1	1
3. Education	0	0	1	0	-2	-2	0	0	0	1	1
4. Demographics	0	-2	0	0	-2	-2	0	0	0	1	1
5. Natural Hazards	0	0	0	0	-2	-2	-2	0	0	1	-2
6. Atmosphere	0	0	0	0	-2	-2	0	0	0	1	0
7. Land	0	0	0	0	-2	-2	-2	0	0	1	0
8. Freshwater	0	0	0	0	-2	-2	0	0	0	0	0
9. Biodiversity	0	0	0	0	0	-2	-2	0	-2	0	0
10. Economic	1	0	0	0	-2	-2	-2	0	0	1	1
11. Consumption patterns	0	0	0	0	-2	-2	0	0	0	1	1
Total sum*	1	-2	1	0	-2	-2	-2	0	-2	1	0.57

As for **education** (Column LH-3), Los Humeros has been the subject of various national and international investigations (e.g., GEMex (Jolie et al., 2021)). The next indicator is **demography** (LH-4). The exploitation of Los Humeros has no impact on the local demography unless there is a significant health risk. The next indicator is **natural disasters** (LH-5). As a result of fluid extraction, subsidence occurs in some parts of the caldera (Békési et al., 2019). This subsidence is accompanied by local earthquakes (Urban & Lermo, 2013). The earthquakes can affect all indicators. Of particular note here is a possible change in the local stress field of the caldera, which can alter the permeability of faults and fractures, which in turn can have a positive or negative effect on the exploitation rate (Parisio, Vilarrasa, Wang, Kolditz, & Nagel, 2019).

Land (LH-7) modification or change of land use could harm **poverty** and **economic development** if, for example, the local population is denied the use of the land for agriculture. This activity also damages the local flora and fauna (SEMARNAT, 2006b). **Biodiversity** (LH-9) would be affected due to the change in the use of the land. In this sense, local fauna species could be displaced and invade other lands, competing with other species and modifying the ecological dynamics. The **economic** (LH-10) indicator has an important influence on the rest of the indicators. If the station hires local people, this opportunity will increase their standard of living, influencing **education**, **health,** and **demographics**. Besides, the profit from GTPS can be used to mitigate **natural hazards** and the large CO_2eq footprint. It can be used to restore the used **land**. In addition, if it has an **economic** surplus, it could be used to finance more studies related to geothermal

exploitation or another geothermal field. It can also be used to maintain local primary **education** schools. Besides, the electricity generated by the plant could feed schools or research centers.

On the other hand, higher income for the GTPS could imply a more intense extraction of fluids, which significantly increases subsidence and earthquake risks, i.e., it would have a negative impact on **natural disasters**. As a result, the **consumption pattern** is also modified. An increase in electricity generation leads to an increase in electricity consumption, as electricity could become cheaper on the market. This ultimately affects consumer behavior and could lead to lower awareness of energy consumption.

Finally, the **consumption pattern** (LH-11) would be modified by having the availability of electricity at a low cost. This has a direct implication for the economic development of the inhabitants. With a lower electricity bill, more money could be dedicated to health and education.

Each j column was divided by the number of affected indicators. For example, column LH-1 is only related to row 10-economic. Then, the value is 1:

$$\sum \boldsymbol{i_{LH-1}(t)} = \frac{\mathbf{1}}{\mathbf{1}}. \tag{6.4}$$

On the other hand, column LH-10 influences several indicators:

$$\sum \boldsymbol{i_{LH-10}(t)} = \frac{(\mathbf{1}+\mathbf{1}+\mathbf{1}+\mathbf{1}-\mathbf{2}+\mathbf{1}+\mathbf{1}+\mathbf{1}+\mathbf{1})}{\mathbf{9}} = \mathbf{0.67}, \tag{6.5}$$

For both cases, t=30, which is 30 years of exploitation. The next step is the sum of all the rows:

$$\sum \boldsymbol{S_9} = \frac{(\mathbf{1}-\mathbf{2}+\mathbf{1}-\mathbf{2}-\mathbf{2}-\mathbf{2}-\mathbf{2}+\mathbf{0.67}+\mathbf{0.57})}{\mathbf{9}} = -\mathbf{0.75}, \tag{6.6}$$

This last equation is an application of eq. (6.2) for t=30. the sustainable potential of the exploitation of Los Humeros is currently -0.75 when the goal is to reach 1 as close as possible. This section is just one example of the possible impacts of the use of the geothermal resource on each sustainability indicator. But once again, more detailed studies are needed in this matter to have a better understanding of these relationships.

6.3. Profitability: the primary link toward sustainability

The atmosphere is the most affected indicator due to the exploitation of the geothermal system of Los Humeros. This is due to the high CO_2eq footprint that this activity has. Some solutions were proposed to counteract this effect (H. González-García, Francke, Göllner-Völker, et al., 2022b). Therefore, the first and most immediate proposal is to use all the installed capacity in the GTPS. Recent reports stated that only two of the three big units of 25 MW_{el} are currently used (L. C. A. Gutiérrez-Negrín, 2020). The second proposal is a shift of the current single-flash conversion units for closed loop binary systems.

The first measure would reduce emissions by 39 % (H. González-García, Francke, Göllner-Völker, et al., 2022b). However, the earthquake risk would increase due to a higher fluid extraction. On the other hand, under the current business scheme (vesting contract),

using all the installed capacity does not increase the monetary profits of the GTPS (H. González-García, Francke, Huenges, & Sass, 2022b). However, once the vesting contract ends, it will benefit from it. Although, the use of all installed capacity will also require more maintenance.

The station's maintenance is already included in the generation costs, which are covered. However, new investment to change the generation technology requires positive profitability. Besides, a short payback on the invested amount would be necessary (in the case of private investors). In the previous chapter, it was suggested that an investment in a project of this kind has a low risk. This result can be derived from the production history, i.e., the production limits have been studied and tested. Therefore, new units will be installed under the proven production limits. Thus, the reinvestment for the binary system is evaluated by assuming that each binary plant had a similar cost to the single flash plants of 25 MW_{el}. The results of the evaluation of both scenarios to 14 years of duration of the vesting contract are in Table 14.

In the previous chapter, two business schemes were addressed. The accumulated cash flow for both cases is shown in Table 17.The payback time of the current investment was eight years for the vesting contract and 4 for the participation of Los Humeros in the open market. The reinvestment was done at the break-even point, assuming the exact boundaries. The revaluation of profitability offered different results. For the vesting contract, the project is profitable when 5 % of interest is applied (Table 17). In contrast, the project's profitability in the second scenario is better, giving a negative result only for one case, where the applied interest is 10 %, and considering the bottom quartile of the spot market prices (Table 17).

Table 17 Evaluation of the NPV with the new investment for the binary power stations. Vc is vesting contract.

NPV	**Vc**	**Regulated market**		
MMXN		Q1	Q2	Q3
5%	163.2	778.6	1434.1	2194.4
8%	-183.8	236.3	783.6	1408.2
10%	-254.3	-49.3	440.1	993.6

Furthermore, it is worth mentioning that the 25 MW_{el} plants can be sold to other stations. For example, a gas power station that is about to expand its installed capacity. There is also the case where the CFE rents its units to Central American countries (CFE, 2019). These options are not included in this evaluation. In this binary scenario, the reinvestment was made in one single exhibition. This strategy is not entirely adequate, given that a step-by-step development is a recommended scheme to ensure the project's profitability (Stefánsson, 2002). The amount considered for reinvestment is the same for the 25 MW_{el} power plants, which is 440 MMXN, approximately 22 MUSD using an exchange rate of 20.5 MXN for each USD (Banxico, 2022)2.

2 Conversion done on the 21.07.2022

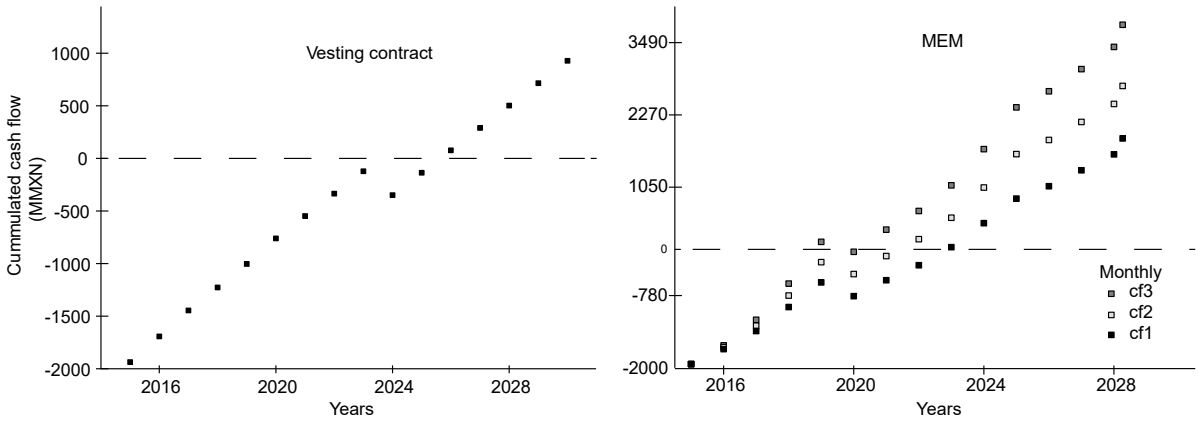

Figure 20 Cumulated cash flow after reinvestment for the binaries power plants.

Once the generation technology has been changed, the geothermal fluid would be in a closed loop, reinjecting much more mass than is currently being reinjected. In addition, CO_2 and CH_4 would also be returned to the reservoir, decreasing by 82 % the carbon footprint of this station (H. González-García, Francke, Göllner-Völker, et al., 2022a).

6.3.1. Price of the externalities

All the affectations provoked by exploiting the geothermal systems can be referred to as externalities. They can be either positive or negative. It just depends on the indicator. For example, a positive effect (i.e., 1) happens when local workers have better salaries (Table 16), whereas an earthquake caused by fluid extraction is a negative externality (i.e., -2). For the Los Humeros case, the most apparent externality is the carbon footprint, and its price varies according to the measurement applied to reduce it.

Although, the cost of the externalities caused by earthquakes is hard to quantify. There is no information or precise identification of the effects. Besides, all the environmental impact due to the exploitation requires extensive quantification based on complete life-cycle analysis. Once the quantification of these externalities has been completed, the profitability evaluation must be carried out again.

Then, there can be a large amount of stored heat in the reservoir. Although subsidence and earthquakes are signs of overexploitation, there has not been a dramatic drop in the pressure or the mass extraction rate. However, suppose there are not enough monetary resources to keep constant monitoring or to solve any other externality that appears due to the usage of this particular geothermal system. In that case, it cannot be sustainable due to the lack of money to keep the monitoring. On the other hand, the large carbon footprint of Los Humeros can be solved due to its potential profitability. However, it would be more challenging if the power project did not show any sign of a monetary gain.

Those are the most apparent affectations. However, there is no clarity about the impact on **demographics** or **freshwater**, for example. A complete evaluation of all the indicators is suggested in the long term. Although initial efforts should be directed at the most affected indicators, it is recommended that studies be conducted on all other indicators as well. For the case of **demographics**, some surveys on the locals can be done. For example, a questionary regarding their perception of the GTPS. Moreover, a social commission can also be formed in order to study how this indicator is damaged by the exploitation of the GS. The implementation of this surveys is costly. Ideally this should be covered by the surplus generated from a profitable power project. As this is a social

service, the GTPS and the government can make some kind of agreement in which both entities gain from it (less taxes for these studies, for example).

7. Conclusion

Sustainable development is the cornerstone of the UN's proposed strategy to mitigate climate change. Several methodologies have been published that include evaluating a series of indicators to ensure the sustainable development of any project, the so-called sustainability indicators. However, there is no consensus on what to consider when talking about their sustainable exploitation of geothermal systems.

This work proposes a sustainability assessment methodology applicably to any geothermal system. This methodology was implemented in the geothermal power station of Los Humeros, Mexico. The conclusions for this site resulting from this study are listed below:

1) Exploitation is not sustainable in the short term.
   This conclusion came after the implementation of the three pillars proposed here. The exploitation of the power station has a large CO_2 footprint which has a strong affectation for almost all the sustainable indicators due to the climate change potential.
2) The heat production forecast offers a production limit within the historical range already seen at the plant.
   Although the model verification resulted in 75 % accuracy, these results are based on a statistical approach relying on production data (i.e., surface data). However, no signs of production depletion have been registered in the last 30 years. Therefore, although the subsidence and earthquakes are signs of overexploitation, the forecast presented here can hint at the sustainable limits of the production. Still, a forecast based on the reservoir's pressure data is needed.
3) The carbon footprint per kWh is comparable to the average carbon footprint of fossil plants in Mexico.
   This large carbon footprint is attributed to the nature of the geothermal site. The contribution due to construction is below 10 % of the total emissions. Therefore, a solution to this problem can be to reinject the geothermal fluids including the non-condensable gases or capture them as seen in other geothermal sites (e.g., Türkiye).
4) Profitability shows signs of being positive, i.e., a reinvestment in the plant is a scenario with low risk.
   Los Humeros is a geothermal site that has been used for the last 30 years. Many parameters, including the limits of the production, have been explored and are well-known. Moreover, the investment aimed to replace the old conversion units. A few new wells were drilled. Ergo, the risk associated with this investment is rather low.
   The profitability evaluation showed negative results for the NPV, as the assessment was limited to a short period of lifetime. A longer timespan could not be considered since no data regarding the electricity price was found. However, an assessment where the price data gaps were filled assuming constant prices revealed an excellent chance to be profitable.
5) Combining the three studies offers a broader perspective on geothermal resource exploitation. Through this methodology, three different aspects can be evaluated for the same purpose.
   Implementing a multidisciplinary approach to determine the sustainability potential of the geothermal site is quite strong. Several aspects can be analyzed to identify and improve potential weak points.

6) Although the three aspects are necessary to reach sustainability over time $t \to \infty$, profitability is essential to achieve the maximum potential for sustainability at all times of the project's useful life.
   Many of the affectations (or negative externalities) generated by exploiting a geothermal site can be solved using the project's surplus. Profitability is used as a guide for investors. However, far from this conception, profitability is also necessary to pay for all the costs associated with the externalities. For example, a geothermal installation will need repairs of the wells, land restoration, non-condensable gases management, etc. For all these remediations, the power station must be profitable. First, to solve the debts, but also to cover the externalities.

The general conclusion regarding the methodology proposed is:

Exploiting the geothermal site of Los Humeros is not sustainable in the short term. However, this can be managed in time. Therefore, this activity could reach an excellent sustainable potential and assure its use for future generations.

8. Outlook

This cumulative dissertation addressed three aspects related to exploiting a geothermal resource: the amount of heat stored in the system, the environmental damage, and the same profitability in the short term. Each of these studies has different weaknesses, which will be explained in this section. These weaknesses open up a panorama of future work. The first of these is to ensure that the three proposed studies are the most basic and that these are also applicable in any other geothermal system.

This statement could be wrong. Although these three aspects are present, there could be others that are equally basic and important and are currently ignored. In this sense, applying this methodology to other sites is necessary to verify its generality.

Regarding heat production, it can be an overestimation. Although the forecast procedure is based on historical production data, it is not linked to any reservoir pressure parameters. Subsidence is a sign of overexploitation of the aquifer. Therefore, the forecast of production could be erroneous due to abrupt changes in pressure that would result in a decline in mass extraction. Therefore, a forecast based on pressure changes and constant monitoring is necessary.

In this sense, the carbon footprint estimation is based on two parts. The first part is based on the life cycle of the plant, whereas the second contemplates the activities for the extraction, distribution, and conversion of heat and operation. Unfortunately, only two databases of the content of non-condensable gases in the extracted geothermal steam could be found. Between them are 17 years apart. Due to exploitation, the system's pressure changes, with that also the temperature changes. With this effect, the interaction between rocks and water also changes. Therefore, a better estimate would be based on more frequent measurements of the content of these gases. Just as the Mexican emissions factor is calculated annually, it would be ideal for Los Humeros' emissions factor to be calculated annually. In addition, monitoring the gas content also helps to interpret the system's response to the exploitation and thus lengthen the use of the reservoir under ideal conditions.

Although the constant monitoring of the reservoir conditions has an inevitable monetary cost, the plant's profitability estimate is fuzzy due to the disparity of the dates of the data. The investment began in 2008, and the Mexican market started to operate in 2016. Therefore, much of the investment may have already been covered within this period. However, this study was carried out to explore the financial behavior of the plant and whether an investment of that size could be profitable. In this regard, it would be desirable for more detailed studies to be available on the financial performance of plants. Although these data are secret, understanding the market could result in more significant private investment and, therefore, an increase in the geothermal potential installed in Mexico. Although installing more power stations not only depends on the availability of financial resources, it is a good start to increase the interest in geothermal.

Finally, evaluating the potential for sustainability is undoubtedly a firm proposal of the concept. The statement about a never-reachable whole sustainable state can be a watershed in its use of it within the geothermal industry. The geothermal industry is relatively new, and given that geothermal energy is classified as a viable tool for sustainable development, the correct definition of sustainable geothermal exploitation is necessary.

In this sense, it is necessary to refine the proposed methodology to evaluate the sustainability of the exploitation of the geothermal system. In addition to applying it on other sites and identifying what other aspects can also be included as essential.

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10. Appendix A

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Geothermal Energy

RESEARCH Open Access

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 in place. The general recovery factor for 60 years of production was calculated as 37–44%. Due to the heterogeneity of the system, this study conducted individual assessments. The forecasted heat extraction for the next 30 years of production, amounts to 580 PJ assuming a constant extraction rate between 6 and 56 ton·[h]$^{-1}$ depending on the particular well. The results of this study potentially complement the existing models of the geothermal exploitation and offer an estimation of the future production of the Los Humeros, which could be a good basis for decision-making and management of the site.

Introduction

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).

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In Los Humeros, Mexico, a conventional geothermal system has been exploited since the early 1980s. During 30 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, 2019; García-Gutiérrez et al. 2002; Arellano-Gómez et al. 2008). 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 research project GEMex (Jolie et al. 2018). The objective of GEMex was the identification of critical parameters to utilize the superhot geothermal resources. 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 caldera is needed in order to extend and preserve its use for future generations.

Previous studies about the evolution of the volcanic system exploitation show changes on temperature, pressure and thus enthalpy at 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 (Gómez et al. 2003). The performance of the wells could be linked with both the grade of their connection with the deeper and hotter reservoir and with the physicochemical parameters of the brines (Aragon-Aguilar et al. 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 characterization of the system.

The main goals of this work are first to estimate the original amount of heat in the currently exploited reservoir of Los Humeros and second to forecast the mass extraction for the next 30 years. The extrapolation time is taken from the time frame suggested by development banks to these types of energy projects. The results of the goals allow us to calculate the heat recovery factor of the system for 60 years of continuous production. The forecasted production is assumed as economically exploitable, as the necessary technology is already installed. Hence, we consider this quantity to be the heat reserve of the Los Humeros (Muffler and Cataldi 1978; Rybach 2015).

The Los Humeros production history

The Los Humeros caldera is a liquid-dominated system. It is located in the Central part of Mexico, at the eastern part of the Trans Mexican volcanic belt (Fig. 1). The drilling activities began in 1986. After 4 years of exploration, drilling, well testing and constructing infrastructure and facilities, the power plant began operation in 1990 (Méndez et al. 2011). The power plant started with 5 MW of installed capacity and the reinjection of brine commenced in 1992 (Cendejas 1992). Today, the total capacity has increased to 95 MWe, 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 90 °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,

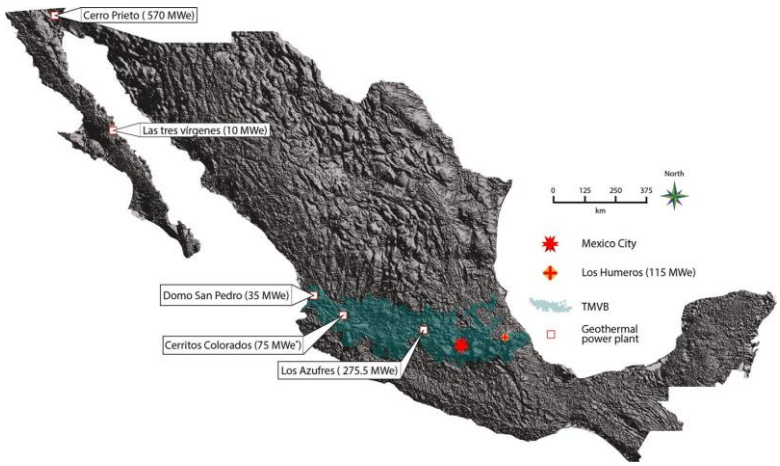

Fig. 1 Location of the Los Humeros, Mexico. Los Humeros caldera is located at the eastern part of the trans Mexican volcanic belt (Ferrari et al. 2012). Inside the TMVF are 2 more power plants under exploitation. The Cerritos Colorados power plant is under construction. The total installed capacity of electricity generation using geothermal sources in Mexico is 975.5 MWe (Gutiérrez-Negrín 2020). DEM: INEGI 2020.*Power plant under construction

the reinjection does not seem to affect the production of the hot fluid (Cendejas 1992; Iglesias et al. 2012).

The hot brine extraction network consists in 29 wells, with an average depth of 2100 m. Production wells use a pump to extract the brine 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 (López and César 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. Although the reports state the use of pumps, they do not offer any description of them. Our objective is to, based on this data, estimate the amount of heat that has been produced from the system, the prospects for future production and the implications for the sustainability of extraction.

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 these procedures analyzing the productivity data for different geothermal systems. Decline analysis takes a time series of one variable and looks for trends to adjust it and forecast the behavior systems (Atkinson et al. 1978; Nathenson 1975). This procedure helps to identify signs of reservoir's pressure depletion and therefore a consecutive decline in the future production by a trend analysis. The lumped parameter is a tool that considers the reservoir as a closed tank. It takes the average properties of the reservoir in order to find a declining trend between the joint analysis of cumulative production and reservoir pressure (Westwood and Castanier 1981; Ciriaco et al. 2020). Each methodology depends on the quality of the data and the goal of the estimation. For our case,

the available data were not sufficient to carry out these approaches. The time series of extraction rates used in this study do not show any kind of trend (Fig. 2).

The estimation using a volumetric heat in place model for the Los Humeros has already been made. In that study, the authors performed a numerical simulation including the heat flow and fluid transport equations (Bonté et al. 2020). From the geological model of the Los Humeros structure, 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. The estimation proposed here 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.

Gómez et al. (2003) suggested a pressure model to estimate the undisturbed distribution of pressure along the reservoir; later, Arellano-Gómez et al. (2008) calculated a decline pressure rate with values between 0.9 and 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 (Fig. 2), making the decline analysis difficult to perform.

In this sense, the method to forecast heat recovery presented in this study is based on the statistical evaluation of the data. In order to perform it, two quartiles of the heat production history of each well are calculated. The first quartile represents a pessimistic scenario, while the third quartile stands for an optimistic scenario of production performance. 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. The production was forecasted assuming the

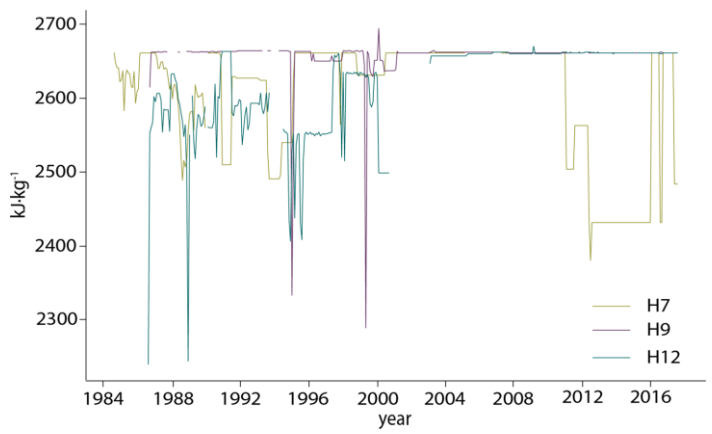

Fig. 2 Extraction history of the most productive wells of the system

established extraction regime for the next 30 years without any recharge by conduction or convection from below. Furthermore, the initial amount of heat with a sum of the reserve plus the accumulated production of heat is estimated. These two quantities allow the calculation of the heat recovery factor.

Methodology

This study involves the productivity analysis of 29 of 54 wells with the aim to estimate the heat reserve and the heat recovery factor of the Los Humeros productive geothermal system. Only 29 wells on Los Humeros were used for fluid extraction. The data were collected during 30 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 30 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 include mass extraction rate ($\dot{m}$), enthalpy (h), and well pressure. The data show two frequencies: from 1986 to 2000 it was recorded daily, but from 2000 to 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 (Δh). 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 (Δt):

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

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, 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 ($\Delta\xi$) times an area (A), i.e., an effective volume (Limberger et al. 2018). In our case, we are assuming that this area is the use that each well makes in the reservoir. Hence, this calculation was carried out by the combination of the volumetric heat in place and Eq. (1):

$$A = \frac{Q_e}{\rho c_p \Delta T_{fz} \Delta\xi}, \tag{2}$$

where ΔT_{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 ρc_{p} is the weighted average of the volumetric heat capacity of the rocks. This includes the isobaric heat capacity (c_{p}), the density (ρ) and the porosity (ϕ) for each different rock type (r) along the feed zone of the well:

$$\rho c_p = \frac{\sum_{n=1}^{N} \omega_n \left[\rho_{\mathrm{rn}} c_p^{\mathrm{rn}} (1-\phi_n)\right]}{\sum_{n=1}^{N} \omega_n} + \frac{\sum_{n=1}^{N} \omega_n \left[\rho_{\mathrm{wn}} c_p^{\mathrm{wn}} \phi_n\right]}{\sum_{n=1}^{N} \omega_n}, \tag{3}$$

where w is water; (N, n) are the number of different rock types along the feed zone, and the weight ω 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:

$$\rho c_p = \sum_{n=1}^{N} \omega_n \left[\rho_{rn} c_p^{rn} (1-\phi_n)\right] + \sum_{n=1}^{N} \omega_n \left[\rho_{wn} c_p^{wn} \phi_n\right]. \tag{4}$$

We calculated the depth percentage of rocks from the borehole reports of the CFE. The values to feed each member of ρc_p are shown in Table 1, it also includes the porosity of the rocks (ϕ) measured at laboratory conditions. It has to be noted that these values are vulnerable to change due to the pressure exerted by ca. 1.8 km of rocks (which corresponds to the average depth of the wells' feed zones) (Petford 2003). Moreover, the Los Humeros caldera is within a highly complex geological site, resulting in a heterogeneous productivity zone. With this in mind, the criteria to choose the petrophysical values were based on the location of the samples reported on the source (Weydt et al. 2020). Those samples inside the productivity zone were chosen. Then, the stratigraphic classification of the rock samples was tied with the CFE boreholes reports in order to approximate the best candidate which fits with the feed zone depth. In order to measure how this reduction in porosity affects the calculation on the area, a sensitivity analysis was carried out. This analysis took three minor values that are reported in Table 1: 80%, 50%, and 20%.

As previously mentioned, the difference $\Delta T_{\mathrm{fz}} = T_{\mathrm{fz}} - T_{\mathrm{inj}}$, 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} (Fig. 3).

Table 1 Physical parameters of rocks, σ is the standard deviation (Weydt et al. 2020)

Rock unit	ρ [kg m^{-3}]	σ	ϕ	σ	c_p [J kg^{-1} K^{-1}]
Basalt lava	2420	–	0.32	0.01	761
Andesite	2150	–	0.22	0.04	784
Limestone	2320	0.01	0.14	0.06	793
Ash fall deposits	1170	–	0.51	–	861

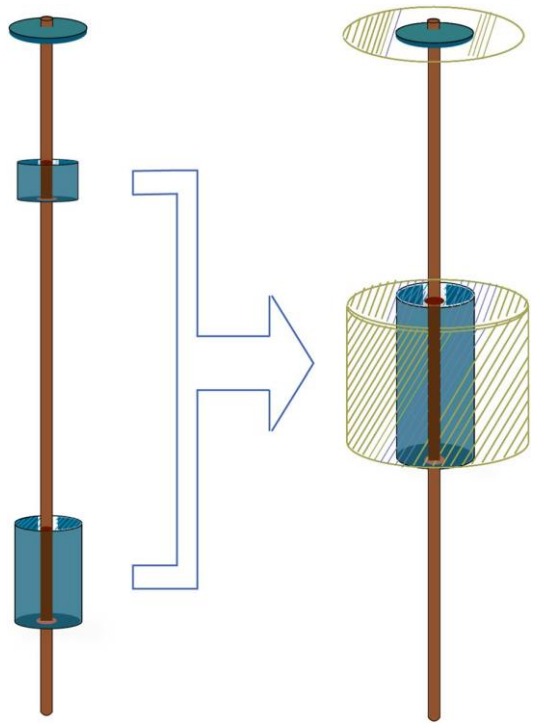

Fig. 3 Sketch showing the assumption of merging of the feed zones. The outer cylinder is the resulting volume of the forecast

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:

$$Q_{\mathrm{ex}}(t_{\mathrm{ex}}) = \begin{cases} Q_{\mathrm{opt}} = \dot{m}''_{\mathrm{C3}} \Delta h''_{\mathrm{C3}} \Delta t_{\mathrm{ex}} \\ Q_{\mathrm{pes}} = \dot{m}''_{\mathrm{C1}} \Delta h''_{\mathrm{C1}} \Delta t_{\mathrm{ex}} \end{cases}, \tag{5}$$

where the subscripts C1, C3 are first and third quartile of the production flow rate, which define the optimistic (opt) and pessimistic (pes) scenario. Δt_{ex} is the extrapolation time, in this case 30 years. Q_{ex} is the production forecast for the next period. In our case, we are considering 30 years as the duration of a production period, therefore $Q_{\mathrm{ex}} \rightarrow Q_{30}$, and $\Delta t_{\mathrm{ex}} = 30$ years. The theoretical used area was also calculated with Eq. (2). The initial reserve of heat (Q_0) was calculated with the sum of the extracted (Q_{e}) plus the forecasted heat (Q_{30}):

$$Q_0 = Q_{\mathrm{e}} + Q_{30}. \tag{6}$$

To validate Eq. (6), we performed a test using the known production data. We applied this methodology to the first 20 years of production to forecast the last ten. After calculating the results, the forecast was compared with the monitoring data.

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 average 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 and Cataldi 1978; Williams 2007; Garg 2010; Grant 2014):

$$R_f = \frac{Q_{wh}}{Q_R}. \tag{7}$$

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):

$$R_{60} = \frac{Q_e}{Q_0}. \tag{8}$$

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

Some of the statistics of the data are shown in Fig. 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 steam productivity ranges from 6 to 56 ton·h^{-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 production variability among the wells. The validation of the forecast model shows that 75% of the production lies within the forecasted value (shown in Fig. 5).

After 30 years of continuous production, the extracted heat from the system is calculated as approximately 340 PJ until 2017. The forecasted total heat production for the next 30 years 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 Fig. 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. A single sensitivity calculation was carried out in order to demonstrate the influence of the porosity on the results of Eq. (2).

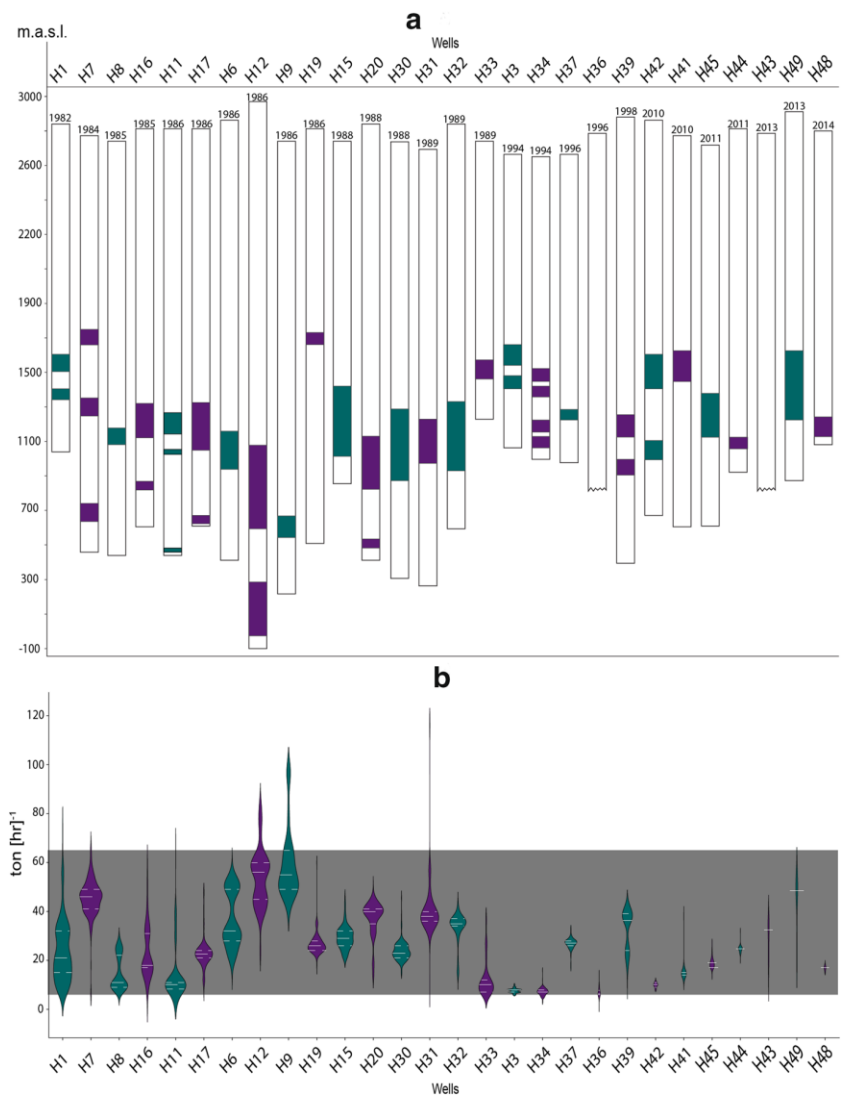

Fig. 4 **a** Well depths and feed zones visualized as colored squares. On the top of each well is the year of the first extraction record. **b** Violin chart showing the distribution of the production rates. The widths are proportional to the number of data points with the given flowrate. The median, 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

The map in Fig. 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 covered by the reservoir beneath is supposed to be 4.1 km^2, calculated with Eq. (2). The average value of the heat in place is 1750 PJ km^{-2}. Therefore, the resulting Q_R is 7175 PJ and the R_f is 4.75% (Table 3).

Table 2 Estimation of the extracted heat, forecast of production and recovery factor per well

Well	Date of the first record	UTM (14 N)		Extracted heat (2017)	Forecasted production		Initial heat reserve		Radius	Radius (forecast)		Thickness	R_{60}	
	m-yy	X	Y	PJ	PJ		PJ		m	m	m	m	Q1 (%)	Q2 (%)
					Q_1	Q_3	Q1	Q3		Q1	Q3			
H1	Jun-82	661906	2175064	8.2	6.6	13.9	14.8	22.1	211	284	346	160	55	37
H7	Jul-84	661838	2175871	34.4	27.5	34.3	61.9	68.7	390	523	551	250	56	50
(H8)	Aug-85	661582	2176392	7.3	5.6	13.5	12.9	20.8	265	353	448	100	56	35
(H16)	Dec-85	661557	2178250	8.2	9.1	21.3	17.4	29.6	209	303	395	250	47	28
H11	Jan-86	662574	2177436	8.9	5.8	8	14.7	16.9	242	311	334	170	60	52
H17	Jul-86	662298	2178606	13.3	14.4	17	27.7	30.3	165	239	249	350	48	44
H6	Jul-86	663508	2173545	22.1	17.6	33.8	39.7	55.9	251	337	400	250	56	40
H12	Jul-86	663830	2173053	34.5	30.8	42	65.4	76.5	204	281	304	800	53	45
H9	Aug-86	660618	2178216	41	34.6	45.2	75.6	86.3	627	851	909	100	54	48
H19	Oct-86	662881	2176643	16.4	15.4	18.3	31.9	34.8	128	179	187	600	52	47
H15	Jan-88	661638	2178804	15.8	18.2	22.3	34	38.1	238	350	370	400	47	42
H20	Jan-88	663330	2177486	25	24.2	28.8	49.2	53.9	265	371	389	300	51	46
H30	Oct-88	661488	2178547	14.3	14.3	18.1	28.6	32.4	204	289	308	400	50	44
H31	Mar-89	661832	2179041	24.5	24.7	28	49.2	52.6	447	632	654	150	50	47
H32	Apr-89	662631	2178043	18.3	23.4	25.6	41.7	43.9	249	376	386	400	44	42
H33	May-89	661534	2177986	5.7	4.7	8.5	10.5	14.2	214	289	337	100	55	40
H3	Oct-94	660622	2177903	3.5	4.6	5.5	8.1	9	126	191	202	175	43	39
H34	Oct-94	662965	2177207	3.6	4.4	5.6	8	9.2	140	208	223	130	45	39
H37	Feb-96	661074	2178346	9.4	15.5	19.1	25	28.6	301	490	524	70	38	33
(H36)	Feb-96	662564	2177396	0.5	4.1	5.3	4.7	5.9	44	128	143	–	12	9
H39	Apr-98	663365	2173291	10.3	14.6	25.8	24.9	36.1	84	131	158	920	41	29
H42	10-Jul	663320	2173500	1.5	6.1	6.8	7.6	8.4	62	139	146	300	20	18
H41	10-Jul	663570	2173280	2.5	9.6	10.7	12.1	13.1	246	543	566	150	21	19

Table 2 (continued)

Well	Date of the first record	UTM (14 N)		Extracted heat (2017)	Forecasted production		Initial heat reserve		Radius	Radius (forecast)		Thickness	R_{60}	
	m-yy	X	Y	PJ	PJ		PJ		m	m	m	m	Q1 (%)	Q2 (%)
					Q_1	Q_3	Q1	Q3		Q1	Q3			
H45	11-Jan	661600	2176392	2.8	11.6	13.4	14.3	16.2	157	358	380	250	19	17
H44	11-Oct	662534	2178347	3.2	16.1	17.1	19.4	20.4	205	502	515	50	17	16
H43	13-Apr	661175	2178035	1.2	16.5	26.8	17.7	28	79	304	382	–	7	4
H49	13-Nov	661888	2175048	1.7	20.5	23.4	22.2	25.1	64	228	242	400	8	7
H48	14-Nov	662067	2175602	1.1	11.4	12.2	12.5	13.2	86	294	303	100	9	8

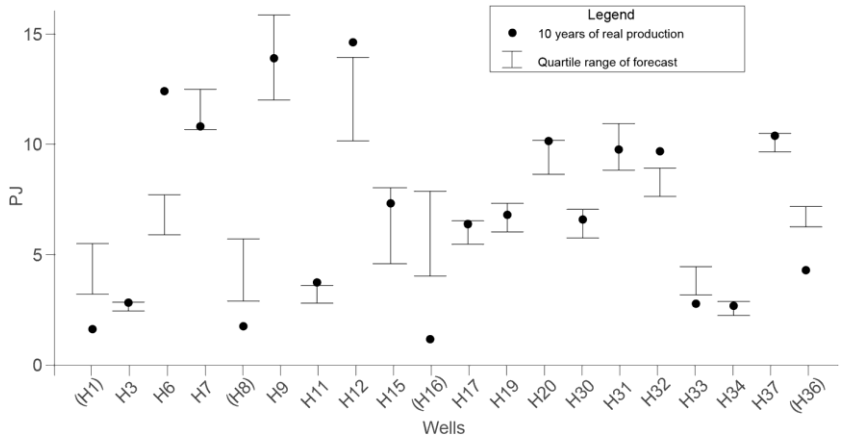

Fig. 5 Validation of the model given by Eq. (6). The observed value for the extraction is represented as a dot. Forecast using our model with 80% of the data for training is shown as a range whisker. The model is considered to be appropriate when the observed value is inside the range. Wells enclosed in parentheses operated for 22 years and they are not considered for validation as they do not have enough data

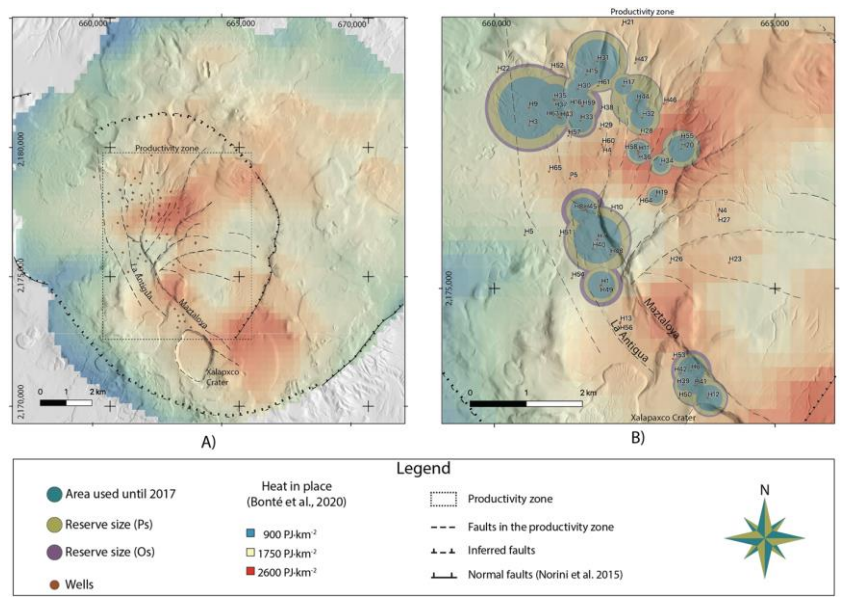

Fig. 6 **a** Full extension of the Los Humeros caldera color indicating the density of the heat in place (Bonté et al. 2020). **b** Resulting area affected by the production

Discussion

The exploitation of the Los Humeros geothermal reservoir has been the subject of several studies (Aragon-Aguilar et al. 2005; 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

Table 3 Sensitivity of the area against changes in porosity

Well	$r(\phi_{100\%})$ (%)	$r(\phi_{80\%})$ (%)	$r(\phi_{50\%})$ (%)	$r(\phi_{20\%})$ (%)
H7	100	+3	+8	+13
H12	100	+2	+6	+10
H9	100	+2	+5	+9

From the lack of a proper porosity–depth model for Los Humeros, this comparison took 3 different values of ϕ. $r(\phi_{100\%})$ represents the porosity average for this well considering the value at lab conditions reported by Weydt et al. (2020). The entries $r(\phi_{80\%})$, $(\phi_{50\%})$, $(\phi_{20\%})$ show the sensitivity on the radius calculation when the porosity decreases by 80, 50 and 20%, respectively. It can be seen that the radius is sensitive to these changes and the highest level of variation is when only 20% of the original value is considered

of the heat reserve of the Los Humeros nor the extraction of heat in the future. This study addresses these topics and related arguments. The energy extraction forecast based on the history of production and the estimate of the theoretical spatial size of the original reserve of heat was discussed in brief. The forecast for energy was 430–580 PJ with a model accuracy of 75%. The original reserve is 770 and 920 PJ depending on a pessimistic or optimistic scenario, respectively. Assuming no recharge, the recovery factor for 60 years and 29 wells, under a production rate of 6–56 ton·h^{-1}, suggests that less than 45% of the system's heat can be harvested.

Past and future of production

Past

The violin charts in Fig. 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 to two different regimes of production, just like its neighboring wells (H6 and H39). The extraction history for the well H12 (Fig. 2), shows a lot of variation for older records than the year 2000. Although both plots were made 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 change was the consequence of the bimodality, these three wells should to 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 zones 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 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 the decrease of the temperature of the produced fluids 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

The model used to forecast the production of the data is very simple. It is based on a constant future extraction rate set by the two quartiles. Despite its simplicity, the validation of the model shows that 75% of the forecasted heat production values are within the quartile range (Fig. 5). Nevertheless, when comparing this result with the forecast calculated with the decline analysis and lumped parameter method, the approach of this study looks inaccurate. 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 the presented model herein.

Since the presented 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 rough perspective about where the limits of the production could take place in the future. Still, this forecast is not entirely meaningless. It helps to estimate the reserve of the heat of the Los Humeros.

The reserve magnitude calculated for the Los Humeros equals 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 (Rybach 2015). The cumulative heat production per well tells us how much heat has been already taken (heat loss is neglected therein). By the premise of a constant production rate, the model forecasts 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 requires precise pressure monitoring.

Influence of the wells in the reservoir

To estimate the reservoir expansion projected onto the topographic surface, a geometrical concept was applied using Eq. (2). This expression calculates an 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 turn is the 2D surface projection of a 3D subsurface cylinder (Fig. 3). The circles traced per well show the resulting area calculated with Eq. (2) assuming a radial and steady flow (Fig. 6). Equation (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 boundaries 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 have to grow faster.

The results of the model show that the wells H15, H30, and H31 might be good candidates to represent this effect. Figure 4a shows the feed zone of these three wells. Since it is at the same depth these wells could share 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 the presented consideration.

As previously stated, recharge is not considered. However, when the recharge of fluid is included, this effect will 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 increases in well Hy (Fig. 7), this change on fluid demand could take fluid supply from the well Hx, diminishing the whole performance of Hx. In any case, this encounter effect results in an extra demand of fluid.

Here is another consideration. Although the injection wells do not seem to affect the temperature of fluid (Cendejas 1992; Iglesias et al. 2012), to satisfy this demand the cold front of injection could move faster towards these wells. If this new fluid is colder, then the temperature might be decreased affecting the performance of the implicated wells. Although no decrease in heat production has been recorded yet, it could happen within the next 30 years of production.

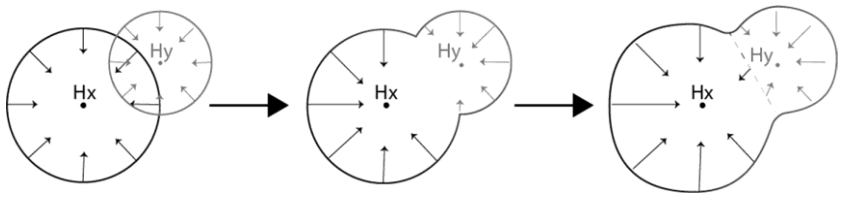

Fig. 7 Sketch of the circles' deformation when two wells share the same aquifer. The size of the arrows is proportional to the heat flow into the well. In the central sketch, these arrows are larger. The right sketch represents the circles' deformation as a consequence of a higher extraction rate. The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

The 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, it was assumed that the geothermal brine is streaming into the well in all the feed zones. This model is extremely simple, but it might offer a very rough visualization of the possibility of wells interruption. Therefore, there is no evidence of this interruption measurable at the surface since the productivity of all the wells has not decreased. Thus, if there is any interruption in extraction between the wells, nothing at the surface could indicate the effectiveness of the recharge of hot fluids.

Finally, the porosity changes with depth have an implication on the results of Eq. (2). Taking the three most productive wells as an example, it can be seen that the area of each well increases up to 13% when the porosity is reduced by 80% of its measured value at lab conditions. The inverse of this relation is set by Eq. (2), where:

$$A \approx \frac{1}{\phi}.$$

Technical potential extension

The size of the circles represents the used area, it also could be seen as the affected surface area of the system. The affected surface 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 equivalent reserve extension $[A(Q_0)]$. The difference between $A(Q_0)$ and $A(Q_{30})$ is the potential area to be claimed 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 reservoir 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. It is just considered the effective thickness of the aquifer with 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 and Muffler 1975; Muffler and Cataldi 1978; Rybach 2015).

Technical recovery factor

The recovery factor based on 60 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; 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 close up 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. Equation (6) implies that the size of the reserve as demonstrated in this study is defined by the extraction rate and the production time. In this sense, when this production phase ends in 30 years, another recovery factor could be defined (in that case R_{90}).

Sustainability of the system

The presented approach requires a stationary concept of operation. Since neither heat nor fluid recharge was considered, the production cannot be claimed as 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 et al. (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 cylinder extensions.

In this work, we assumed 30 years as the duration time per production phase. The forecast of energy offers an assessment of the productivity of the system over this particular or other defined time spans. 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 location, 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 this activity is highly recommended. 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 permanent monitoring of the aquifer.

In this sense, at this stage it is difficult to define the sustainable limit of production of the Los Humeros. In this study estimation, the future production is achieved under a fixed operation limit. 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.

Outlook

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.

These results offer:

- A comprehensive overview of the future production limits. These values show the quantity needed in order to extract similar amounts of heat and maintain the power production.
- The operation limits can also be combined with pressure monitoring to keep the extraction rates within the lowest production depletion.
- Stakeholders can take this information to clarify the limitations of the production and therefore meet the risk associated with new investment in the system.
- A data-based methodology, which is a good basis for the applying of machine learning methodologies.

Finally, the technical recovery factor states the maximum level of heat production attained for 30-year-old wells under a defined extraction rate. 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

A: Area [m^2]; CFE: Federal Commission of Energy; a.s.l.: Above sea level; c_p: Specific isobaric heat capacity [$kJ\cdot(kgK)^{-1}$]; °C: Degree celsius; C1: First quartile; C3: Third quartile; h: Specific enthalpy [$kJ\cdot kg^{-1}$]; h_0: Specific enthalpy of water at 21 °C [$kJ\cdot kg^{-1}$]; Δh: Enthalpy difference [$kJ\cdot kg^{-1}$]; h'/h'': Specific enthalpy of geothermal brine/steam [$kJ\cdot kg^{-1}$]; $\dot{m}$: Mass flow [$ton\cdot h^{-1}$]; $\dot{m}'/\dot{m}''$: Brine/steam mass flow [$ton\cdot h^{-1}$]; Q: Heat [J]; Q_e: Available heat at the well head (J); Q_R: Theoretical heat in place (J); $\dot{Q}$: Heat flow (W); Q_0: Initial reserve of heat (J); Q_{30}: Forecast of heat for 30 years (J); R_f: Heat recovery factor; R_{60}: Technical recovery factor; Δt: Time difference; ΔT: Temperature difference (K); Δt_{ex}: Extrapolation time; $\Delta\xi$: Effective thickness (m); ρ: Density (kg·m3); σ: Standard deviation; ω: Depth percentage; fz: Feed zone; inj: Injection; Opt: Optimistic; Pes: Pessimistic; rn: Different layers of rock; wh: Well head; wn: Water at different pressure/temperature.

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Authors' contributions

HG-G: writing original draft, conceptualization, visualization, methodology, validation, formal analysis and project administration. HF: conceptualization, visualization, methodology, formal analysis. IS: project administrator, methodology, conceptualization. EH: data acquisition, conceptualization, project administrator. All authors read and approved the final manuscript.

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Availability of data and materials
The productivity data on which we based our investigation belong 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.

Declarations

Competing interests
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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11. Appendix B

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CO_2 emission assessment of the geothermal power station Los Humeros, Mexico

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ABSTRACT

This work presents the estimation of the CO_2eq emissions of the geothermal power station in Los Humeros, Mexico. The calculation takes the emissions of the CO_2 contained on the extracted geothermal brine plus the CO_2 footprint by the power station construction. The carbon footprint estimation is based on technical reports generated by the owner company. It considers all the commissioning activities and also the operational phase of the power plant, which is assumed to span a lifetime of 30 years. The results indicate a total emission from 442 to 568 $g_{CO_2}eq/kWh_{el}$. Of these emissions 9 to 12% are contributed indirectly by the power station construction whereas 88 to 91% are released directly during operations due to the natural content of CO_2 in the steam. When comparing the results with the natural discharge of CO_2 in the production area, the emissions of CO_2eq is 10 times faster. Solutions are proposed to reduce the footprint of CO_2eq per kWh_{el}. In the short term the use of all the installed capacity in the field reduces the footprint by 25%. Another option is to use closed cycle technology with a binary power station instead of the single-flash power plants. This showed 82% reduction of CO_2eq emissions; accompanied by a reduction of electricity production by 16% due to the lower conversion efficiency.

1. Introduction

A geothermal system is a renewable energy source usually with a low environmental impact when exploited (Goldstain et al., 2011). The output from 6 geothermal fields in Mexico accounts for 1.7% of electricity production. Moreover, the installed capacity was nearly 1 GW_{el} in 2018 (Gutiérrez-Negrín, 2020). These make it an important source of renewable energy in the country (SENER 2020). Nowadays, in addition to supplying the energy demand, reducing Greenhouse Gas (GHG) emissions is a target that the government of Mexico has set (SRE 2022). The exploitation of geothermal systems can help in this task.

A metric that helps in the accounting of GHG emissions is the Emission Factor. Designed and applied for the Mexican electric system, the Emission Factor registers the sum of the emissions of all the GHG of a power station and it is normalized by the total production of electricity (de M (GOB), 2022). This factor reports the GHG as CO_2 equivalent and the calculation for 2021 was 423 $g_{CO_2}eq/kWh_{el}$ (SEMARNAT 2021). However, this emission factor does not consider the CO_2 footprint during the life cycle of the construction activities and it is not clear if the calculation includes any renewable power station. The aim of this work is to calculate the Emission factor of the geothermal power station of Los Humeros. This calculation not only includes the NCG contained in the extracted geothermal fluids, but also the CO_2 footprint due to the construction activities.

The quantification of the Carbon footprint of a product is conducted through a Life Cycle Assessment (LCA) (ISO 2018). The LCA is a powerful tool for analyzing the environmental effects of any project. The results can be a guide to designing an effective decarbonization scheme since this methodology is used to identify factors of high-carbon emissions during the project lifetime. LCA on a Geothermal Power Station (GPS) is a recent activity in the literature (Paulillo et al., 2019; Sullivan et al., 2010). These works not only included the CO_2 footprint estimation, but they presented a complete LCA assessment. A couple of studies have generated their own datasets, suggesting its use to evaluate other GPS (Karlsdóttir et al., 2015), (Tosti et al., 2020). This suggestion is based on the argument of a complete and relevant database that can be adjusted for any other GPS (Tosti et al., 2020). For the case of Mexico, no LCA on a GPS has been yet applied and therefore no dataset exists.

The GPS subject of this study is located in Los Humeros (LH), in the

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Nomenclature

CFE	comisión federal de electricidad
d	day
e	electricity
EF	emission factor
eq	equivalent
$\dot{E}x$	exergy rate
g	grams
GHG	greenhouse gasses
GPS	geothermal power station
GW	gigawatt
GWP	global warming potential
h	hour
h''	steam enthalpy
km	kilometer
kt	kilotons
kW	kilowatt
LCA	life cycle analysis
LCI	life cycle inventory
LH	Los Humeros
m	meter
MIA	manifestación de impacto ambiental
MW	megawatt
$\dot{m}'$	steam flow rate
NCG	non-condensable gasses
$\overline{NCG}$	average non-condensable gasses
nCO_2	non-condensable CO_2
Q_{th}	thermal energy
S''	steam entropy
t	time
T	temperature
UP	unit process

Greek letters

η	efficiency

Subindex

el	electric
Min	minimum
Max	maximum
in	input
th	thermal
II	second law
0	dead state

western Trans-Mexican Volcanic Belt. Given the aim of this study, in the following sections the methodology and results of its application are described. Before this, a brief overview of the development of the power plant is given.

1.1. Los Humeros development history

All geothermal installations in Los Humeros cover an area of 10 km^2. The exploration and early evaluation of the site was performed in 1968. The construction activities began years later and the power production started in 1990. These activities are summarized in Table 1. The geothermal field is extensive and has been continually developed. The development caused changes in the landscape and the installation of many components for the power plants. Today, the installed capacity of the power station is about 85 MW_{el} divided in three units of 25 MW_{el} and 2 units of 5 MW_{el}. These power plants have the advantage of running continuously by means of the geothermal vapor (often with a plant capacity factor above 90%) (Gutiérrez-Negrín, 2020). This means the Los Humeros GPS can be used to cover base load demand. The vapor used in the turbines is distribuited by an extense pipes network and it is extracted by an average of 19 wells in the entire production history (Fig. 1).

According to the listed dates, construction was divided in three different stages. During the first two stages, almost all the wells were drilled and 7 units of 5 MW_{el} were installed together with ca. 10 km of pipes. The second phase of development ended in 1998. The final configuration of the power station began 2008, when the installation of the first 25 MW_{el} power unit was started. This event also marks the beginning of the third phase of development, which continues till today. As shown in Table 1, along the history of development several wells were drilled, but not all of them were under operation. The number of wells under operation, per year is in Fig. 1. The mentioned construction timeline was collected from the construction and environmental reports (explained later) and the history of wells' operation were obtained by production data provided by the owner company under the GEMex consortium (Jolie et al., 2021), (Jolie et al., 2018). The plan described in the environmental reports for the last phase of development is to migrate to a new operational regime, which is based on higher efficiency technology and a larger steam distribution network (SEMARNAT 2006).

Table 1
Los Humeros' history of development.

	Years	Construction
1st phase	1984–1991	Wells drilled: H-(1, 2, 4, 5, 7, 9, 12, 8, 6, 10, 11, 16, 17, 14, 18, 19, 20, 21, 22, 13, 15, 23, 24, 25, 26, 27, 28, 29,30, 31, 32, 33). Conversion units: U-(1, 2,3, 4). Pipes installed: 3134 m
2nd phase	1993–1998	Wells drilled: H-(3, 34, 35, 36, 37, 38, 39, 40) Conversion units: U-(5, 6, 7) Pipes installed: 6000 m
3rd phase	2008–today	Wells drilled: H-(41, 42, 43, 44, 45, 46, 49, 48, 50, 55, 56, 59) Conversion units: U-(8, 9, 10, 11) Pipes installed: 13,300 m

1.2. Los Humeros conversion technology

Los Humeros is a liquid-dominated system (García-Gutiérrez et al., 2002; González-García et al., 2021). Since operations started, LH has had two different types of conversion units all driven by geothermal steam. The first type consisted of 8 small power units of 5 MW_{el} built adjacent to the wells and, the second type consist of 3 bigger units of 25 MW_{el}. The future plan is to install 4 units of 25 MW_{el} and dismantle the old 5 MW_{el} units (SEMARNAT 2006). These changes also had an effect on the production of electricity.

Garcia-Gutierrez et al. (2015) divided the generation of electricity into three parts: distribution, separation, and conversion. The distribution part covers the geothermal fluid extraction from the reservoir by the production wells and the conducion from the wellhead to the fluid collector. Then, the geothermal fluids separated into steam and brine. In the last part the thermal energy in the steam is converted into electricity. Each one of these parts has its own thermal and exergetic efficiencies. According to them, the smallest exergetic and temperature losses are found in the fluid distribution for feeding the conversion units. However, high losses are found in the overall processes of electricity production with an energetic efficiency of 8.3% and 23.4% of exergetic efficiency.

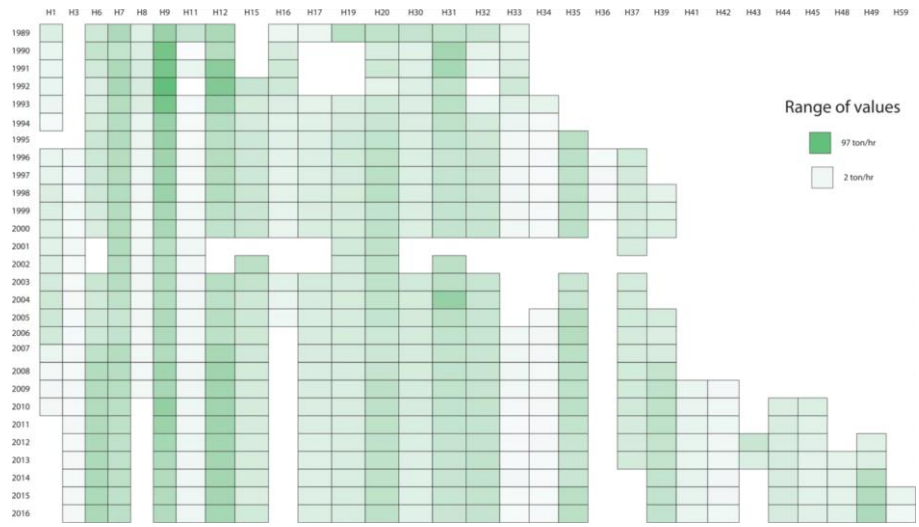

Fig. 1. Wells under operation. The graph shows the averaged mass flow rate per year.

2. Methodology: CO_2 footprint estimation by means of a life cycle analysis

In order to analyze the CO_2eq footprint, this study adopted the guidelines ISO-14,040:2006 and −14,067:2018 (ISO 2018) (ISO 2016) to assess the carbon footprint of each kWh_{el} by means of a LCA. It follows an attributional approach, which means that in this case the GWP can be attributed to the power station during construction and during operation. The ISO-14,040:2006 standard consists of four steps: definition of the goal and scope, the life cycle inventory (LCI), the impact assessment and the interpretation. The impact assessment in this study only considers the impact category GWP, in this case the priority is to evaluate the CO_2eq emissions in the generation of electricity. The software Open LCA (GreenDelta GmbH 2021) was used for the impact assessment. The background data of the supply chain of energy and materials was derived from the Ecoinvent 3.7.1 *cutoff* database (G. Wernet et al., 2016), and the impact method was the RECiPE 2016 (Huijbregts et al., 2017). The following sections describe each part of the methodology, as well as the data used.

2.1. Goal and scope

The goal of this work is to estimate the CO_2 emissions associated with the electricity production in Los Humeros, Mexico, assuming a plant life time of 30 years. The study's scope considers the construction and operation, and the aim is:

- To assess the carbon footprint associated with the generation of electricity: i.e., to quantify the yearly emissions in $g_{CO_2}eq\ /kWh_{el}$ for all the construction and operational activities of the power station.

The functional unit of the study is one kWh_{el} delivered to the grid per year. The time reference for the evaluation is the beginning of the operation (1990). Although the lifetime of some wells already exceeds 30 years (they were drilled between 1984 and 1990), this extra time is not considered in the LCA. The dismantling of the power plants is not included since there is no information regarding the disposal of the different elements. For the backfill of abandoned wells a lid made of concrete was considered.

2.2. LCA boundaries

The complete system consists of 4 established Unit-Processes (UPs):

- 1-UP: heat extraction, which is referred to the drilling, construction and operation of the wells to cultivate the field.
- 2-UP: heat distribution, which are all the elements needed per the construction of 1 m of pipes.
- 3-UP: heat conversion, which deals with the construction per conversion unit. This UP is divided in two (1 unit of 5 MWel and 1 unit of 25 MWel).
- 4-UP: operation, related with the non-condensable gasses contained in the extracted geothermal steam.

Each one of the UPs has an input of materials and energy. The input is defined by the Life Cycle Inventory (LCI) which is based on available official data of the power plant and supplemented by Ecoinvent data. The output is assumed to be the sum of CO_2eq contributions from each UP and the electricity generated. The electricity distribution is excluded from this analysis. The boundaries of the LCA are presented in Fig. 2.

2.3. Life cycle inventory

The standard ISO-14,040 states that the LCA must include all inputs and outputs of energy and materials used in the generation of the functional unit. This list of elements is referred to as the LCI of this process. In the case of LH, the LCI is based on public company reports. These documents are environmental reports and descriptions of works conducted on the site, either by the owner company, the *Comisión Federal de Electricidad* (CFE), or by third parties.

The environmental reports are called *Manifestación de Impacto Ambiental* (MIA). They are mandatory for any construction project in Mexico (SEMARNAT 2015). By this document, the environmental authority evaluates the planned changes in the landscape and the materials to be used. Furthermore, it verifies that all constructions and materials follow the proper guidelines to minimize the damage to the

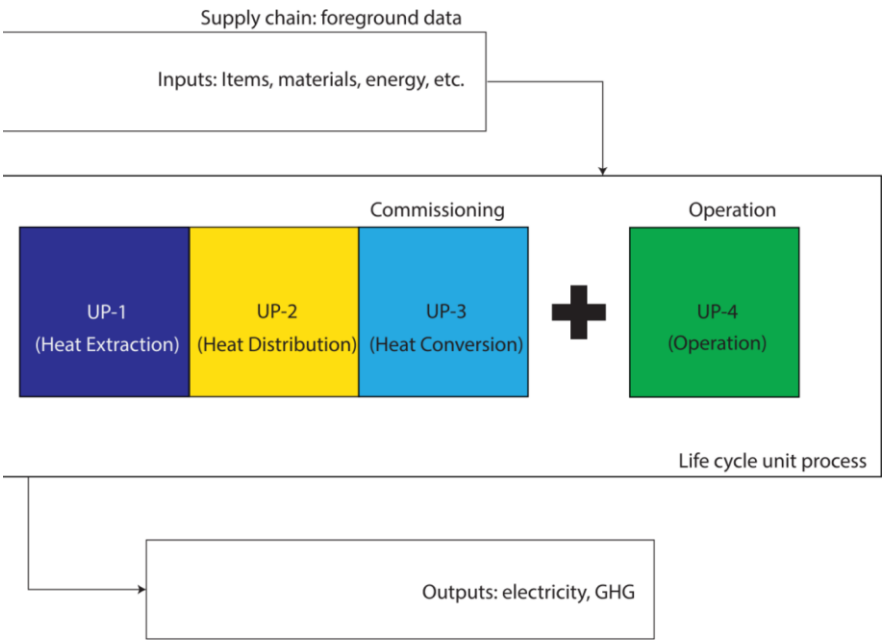

Fig. 2. Boundaries of the LCA. The distribution of the generated electricity is not considered.

environment. Once the evaluation ends, the project is either approved or rejected with the possibility of being submitted again when the suggested changes have been implemented (SEMARNAT 2015). For Los Humeros 2 MIAs were compiled: 1992-MIA, and 2006-MIA (SEMARNAT 2006). Since these documents are the basis for the approval or rejection of the project, it is assumed that they contain a good estimate of the materials used for the construction.

Additionally, there are construction requests which were published by the CFE with the aim of creating an open tender, i.e. all the contracts are published on the web portal of the treasury authority for consultation (C. de Diputados 2010). There, 11 construction reports were available, and, according to the description of the work they were divided according to the UPs: construction of wells, and well platforms, steam pipes and machine rooms for the conversion units (5 MW_{el} and 25 MW_{el}).

The construction specifications included a list of elements to be replaced or built. Furthermore, a lot of construction activities were defined. From the MIAs and the construction reports, ca. 990 items could be obtained in total. These items included activities and materials used. Although this large list of items is the basis for the LCI (as it describes all the components for each part of the power plant) it cannot be used directly for the quantification of CO_2 emissions, because there are many components (e.g., valves) whose origin or manufacturer could not be identified. Instead, for these items the quantity of the material used was taken. Once all the material quantities were obtained, the associated CO_2eq emissions were determined based on the supply chain data from Ecoinvent 3.7.1 *cutoff* (G. Wernet et al., 2016). The smallest element to quantify the energy and material flow is the Unit Process (UP), the 4 UPs were mentioned above. For each one of the UPs a separate LCI was created.

2.4. CO_2 emission factor (EF)

The emission factor for the considered time is the sum of the g_{CO_2}eq contribution per UP related with construction plus the contribution per operation activities over the same time:

$$g_{CO_2}\text{eq} = \frac{1}{e}\left(\sum_{i=1}^{3} UPi_{CO_2eq} + UP4_{CO_2}\right), \quad (1)$$

this equation divides the sum of CO_2 per UP by the electricity generated (e) (Table 2).

The CO_2 contained in the steam was calculated with the content of non-condensable gasses reported by the CFE and the extraction rate ($\dot{m}'$)

Table 2
Annual net production of electricity in Los Humeros. The data was collected from previous works (Gutiérrez-Negrín, 2012, 2019; Gutiérrez-Negrín et al., 2010; Gutiérrez-Negrín and Quijano-León, 2003; Quijano-León and Gutiérrez–Negrín, 2000; Negrín, 1997) and it was completed with data requested from the Transparency data service of Mexico (INAI 2021).

Year	Net electricity production	Year	Net electricity production
	GWh_{el}		GWh_{el}
1995	286	2010	326
1996	337	2011	336
1997	343	2012	303
1999	351	2013	336
2001	127	2014	321
2002	146	2015	408
2003	285	2016	508
2004	295	2017	416
2006	295	2018	501
2007	278	2019	574
2008	313	2020	549
2009	325		

from González-García et al. (2021):

$$UP4_{CO_2} = \dot{m}'\cdot\Delta t\cdot nCO_2 + nCO_2eq, \quad (2)$$

where Δt is the time, nCO_2 is the non-condensable CO_2 mass fraction of the steam, and nCO_2eq is the sum of the GWP contribution of Methane (using a conversion factor 34:1 (Huijbregts et al., 2017)). This calculation was made for all the wells as shown in Table 3. However, some of the wells in this table were closed down soon after the measurement, whereas others were not open yet in 1989. Therefore, the assessment covers both dates of used and unused wells. To get a reliable approach in the calculation the average NCG content was taken. Table 3 shows two different dates (1989 and 2006). To consider both values it was decided to have two results: the minimum value takes the 1989 average, whereas the maximum takes the 2006 average, since $\overline{NCG}_{1989} < \overline{NCG}_{2006}$.

2.5. Efficiency analysis

The production data used by González-García et al. (2021) was used to calculate the plant conversion efficiency. The extracted thermal energy was calculated with:

$$Q_{th} = \sum_{n=1}^{25} \dot{m}'_n(\Delta h'_n). \quad (3)$$

Where $\dot{m}'_n$ is the steam extraction rate and $\Delta h'_n$ is the enthalpy difference between the steam at the wellhead and pure water at LH environmental conditions (21°C (Vidal-Zepeda, 1990)). Since the electricity output is reported per year, so are the calculations of Q_{th}. The energetic efficiency (η_{th}) was calculated with the ratio of electricity output and the extracted thermal energy per well:

$$\eta_{th} = \frac{e}{Q_{th}}, \quad (4)$$

in this case, e is the net electricity generated per year (Table 2).

The exergetic efficiency was calculated with:

$$\eta_{II} = \frac{\dot{E}x_{in}}{e}, \quad (5)$$

where, $\dot{E}x_{in}$ corresponds to the exergy rate of the geothermal steam at the well head (DiPippo, 2015):

$$\dot{E}x_{in} = \dot{m}'[h' - h_0 - T_0(S' - S_0)] \quad (6)$$

where, $h'$and S' are the geothermal steam enthalpy and entropy; the subscript 0 refers to the *dead state*. In this study the dead state is set by LH average environmental conditions.

3. Results

The following sections present the life cycle inventory that was used to estimate the CO_2eq emission per UP. The results are presented in two parts. The first part shows the contribution for the construction of the power plant (the UP-4 was not included in this analysis). The second part includes all the 4 UPs. The full list of elements that were the base for the LCI is provided by González-García et al. (2022).

3.1. CO_2eq footprint estimation

The carbon footprint is reported per each one of the elements of the LCI. The LCI is based on the environmental/construction reports generated for the power plant, the full inventory and the emission of CO_2eq is listed in Table 4 (González-García et al., 2022) . The evaluation of the GWP is based on background data collected from Ecoinvent (G. Wernet et al., 2016). The Ecoinvent database does not have any Mexican dataset. To deal with this, the dataset from North America/US had the highest preference. If these data were not available, the global dataset was chosen. The contribution of CO_2eq associated with the transport of materials could be neglected when compared with the total CO_2eq. Since the manufacturer of the different materials is unknown, the transport was assumed from the closest highway to LH (ca. 23 km). This short distance implies a low contribution of the CO_2eq for the transport.

Table 3
non-condensable gasses content. All the information was taken from the environmental impact manifesto (MIA) developed by the CFE. All the measurements were carried out in the dry steam part of the geothermal fluid.

well	Weight fraction of NCG	Composition of NCG%									
	%	CO_2	H_2S	NH_3	H_2	N_2	CH_4				
	1989	2006	1989	2006	1989	2006	1989	2006	2006	2006	2006
			%	%	%	%	%	%	%	%	%
H1	5.69	10.8	98	97	0.92	3.14	0.64	0.0200	0	0.15	0.01
H3		8.6		96		3.88		0.0306			
H6	2.74	4.6	93	92	5.34	7.74	0.71	0.0610	0.07	0.45	0.87
H7	2.31	4.6	94	94	4.65	6.31	0.39	0.0199	0.04	7.94	0.01
H8	4.85	5.1	96	95	2.98	5.43	0.63	0.0171	0.03	0.69	0.01
H9	1.28	5.8	89	88	7.22	11.86	1.18	0.0907	0.18	2.42	0.03
H10	1.68		95		4.18		0.45		0.03	0.73	0
H11	2.13	4.8	95	93	3.99	6.92	0.49	0.0218	0.04	0.53	0.29
H12	7.97	10.6	95	97	3.59	3.35	0.37	0.0264	0.06	0.53	0.67
H13	2.81		93		4.46		0.64		0.07	1.26	0.30
H15	2.89	3.6	85	90	11.26	9.52	0.38	0.0750	0.14	3.18	0.18
H16	4.06		88		9.28		0.19		0.14	1.96	0.23
H17	2.92	2.4	96	86	3.21	13.88	0.24	0.1098	0.03	0.09	0.05
H18	46.3		98		0.47		0.03		0.08	0.13	1.48
H19	9.03	4.7	97	95	2.66	5.24	0.05	0.0165	0.03	0.54	0.01
H20	2.68	5.5	96	92	3.02	7.80	0.33	0.0596	0.06	0.60	0.47
H23	5.17		90		7.99		0.19		0.11	1.06	0.32
H30		1.8		81		19.20		0.1513			
H31		4.8		93		7.38		0.0582			
H32		2.6		88		11.68		0.0924			
H33		1.6		72		27.76		0.2188			
H34		4.9		87		13.24		0.1048			
H35		1.6		72		27.76		0.2188			
H37		3.2		89		11.17		0.0352			
H39		7.8		95		4.60		0.0363			

Table 4
Life cycle inventory (González-García et al., 2022). This table shows all the materials used in the power plant. Each line presents the material needed per Unit Process; blank space means that this Unit Process does not use this particular material. These results show the total contribution of each material, without considering their useful lifetime. No transportation was considered for any material. Elements with a question mark were not found in Ecoinvent, therefore, they were not considered in the final calculations.

Materials	UP-1	UP-2	UP-$3_{5\ MW}$	UP-$3_{25\ MW}$				
	Total	Kg_{CO_2} eq	Total	Kg_{CO_2} eq	Total	Kg_{CO_2} eq	Total	Kg_{CO_2} eq
20 MW conversion unit							1 unit	530,344
5.5 MW conversion unit					1 unit	163,146		
Alkyd enamel			19.5 kg	130.2				
Aluminum					539.5 kg	8282		
Asphalt			0.02 m^2					
Basalt	431.6 t	2353	143 kg	0.782				
Bentonite	290.1 t	11,427						
Clay	10 kg	0.01	71 g	0.0005			3.5 t	25.2
Coal tar					25 t	13,557		
Concrete	1.35 m^3	416	2.01 m^3	623	394 m^3	121,701	545 m^3	168,106
Copper	22 kg	129			159 kg	947		
Diesel	485.5 t	220,717	226 kg	103	246.3 t	111,980	53,000 L	24,092
Epoxy	84 t	425,218			21 t	106,304		
Filling Material			0.38 kg	0.003				
Glass fiber			96.7 kg	254.7				
Gravel			13 kg		92.4 t			
Lignite	125.9 t	2555						
Lignophosphate	13.6 t	?						
Mineral Fiber	101 kg	266	430 kg	1134	427 kg	1125	1.1 t	2903
Mortar	851.3 t	206,095	269 kg	65	1055 t	255,395		
Neoprene								
Paint			10.4 m^3		201 m^3	?		
Polyethylene	1254 m^3	12,785	1.36 m^3	13.9			0.085 m^3	0.867
Portland Cement	72.2 t	63,851						
PVC	790 cm^3	0.0020	100 cm^3	0.00026	0.364 m^3	0.9316		
Reinforcement Steel	3.8 t	7420	154 kg	296	34.3 t	65,746		
Sand	270.2 t	953						
Sawdust	20.6 t	486						
Sodium Carbonate	1.9 t	2463						
Sodium Hydroxide	6.2 t	6639						
Steel	191 t	434,091	853 kg	1936	3.3 t	7576		
Steel (black)			355 kg	805				
Steel (carbon)			7.7 t	17,633	91,805 t	208,316	1935 t	4,391,348
Steel (Cr)	96.3 t	443,186						
Steel (galvanic)	2.7 t	6273			13.4 t	30,412		
Stones	0.034 m^3	?						
Thicking agent	975 kg	?						
Viscosifier	650 m^3	?						
Water	650 kg	0.10						
Waterproofing	82.5 m^3	?						

Table 4 shows that the UP using the most material is UP-1 (Heat extraction); while UP-$3_{25\ MW}$ is the UP with least material. It is worth mentioning that UP-3 refers to the construction activities to install a conversion unit, either 5 MW_{el} or 25 MW_{el}. The information regarding the materials used for the manufacturing of the turbines themselves is considered secret by the producing companies. However, two steam turbines are available in Ecoinvent (G. Wernet et al., 2016): One of 20 MW_{el} and a second of 5.5 MW_{el}. Although they are not the turbines installed in LH, they were considered similar to offer a close estimation of what is actually present in the plant. Their data was used as is, i.e., the resulting CO_2eq emissions were not scaled to the turbines installed in LH. The yearly emissions per UP is shown in Fig. 3.

3.2. CO_2eq emission factor and global conversion efficiency

Table 4 shows the CO_2 emissions per material used in the construction phase of LH. To calculate the total CO_2 emission per UP a sum of all its components was calculated:

Table 5 shows that the UP-$3_{5\ MWel}$ had the largest sum of CO_2eq, whereas the highest contribution to CO_2 emission is due to the construction of the UP-2. The average extracted CO_2 in one year per 29 wells on operation is: 8.1 and 11.1 kt_{CO_2},as Min and Max values. The largest annual yield of electricity from 1995 till 2020 is 574 GWh_{el}, whereas the total CO_2eq emissions per year due to construction is 21.1 kt_{CO_2}eq. The contribution per the operation of 24 wells are from 233 to 305 kt_{CO_2}eq. These quantities give a toal of 254 to 326 kt_{CO_2}eq, for minimum and maximum value, respectively. The EF of g_{CO_2}eq per kWh_{el} are from 442 (EF_{Min}) to 568 (EF_{Max}), this calculation is using the largest yield of electricity. The yearly emissions are shown in Fig. 4. The highest values are observed in 2014, whereas the lowest values happened in 2019. This increase/decrease of values is directly related with the electricity production and the number of wells under operation (Fig. 1). The yearly variations of thermal and exergy efficiency are shown in Fig. 5.

4. Discussion

The development of a local database for Los Humeros (LH) allowed the estimation of the emission factor of the production of electricity by means of a geothermal energy source. The contribution of each one of the Unit Process (UP) were estimated with a high level of detail. One of the most remarkable differences is that the highest contribution of CO_2eq comes from the UP that uses the less quantity of materials, whereas the lowest CO_2eq contribution comes from the UP that uses the largest quantity of materials (Table 5). The discussion of the results also addressees some options for reducing the g_{CO_2}eq footprint per kWh_{el} generated in the power plant.

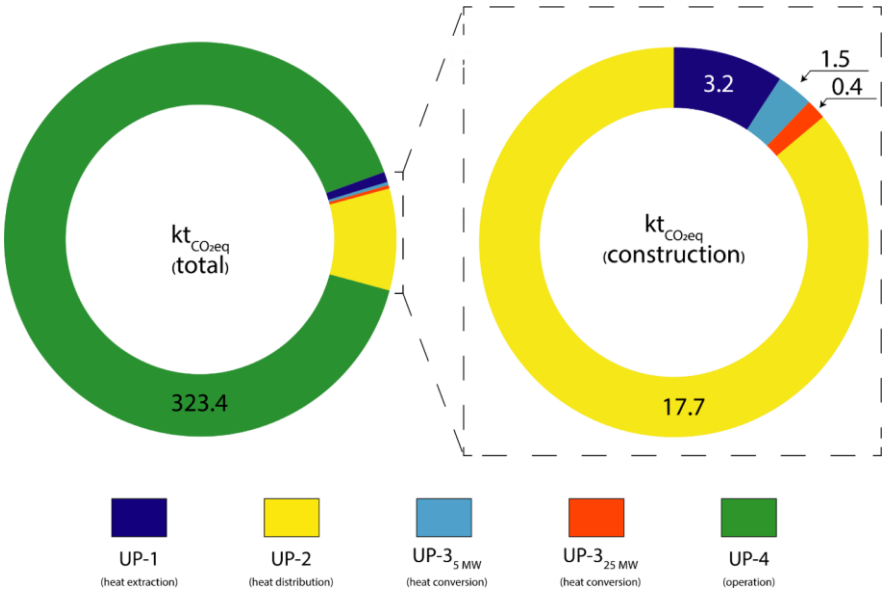

Fig. 3. Distribution of the CO_2eq emissions per year. The left circle is the total contribution of CO_2eq in the power plant. The right circle shows that the major contribution comes from the distribution network in the power plant. This Figure shows the MaxCO_2eq calculation.

Table 5
sum of the CO_2 emission per material reported in Table 4. The total contribution for 30 years of lifetime is shown in the last column, the last column is represented in Fig. 2.

Process	$\sum(kg_{CO_2}eq)$	Total elements	$kt_{CO_2}eq$
UP-1	1864,820	52 wells	3.2
UP-2	22,998	22.4 km (pipes)	17.7
UP-3$_{5\ MWel}$	9347,185	8 conversion units	1.5
UP-3$_{25\ MWel}$	5114,015	3 conversion units	0.4

4.1. Reduction of the CO_2 footprint per kWh_{el}

In the short time scale, one option to reduce the CO_2 footprint per kWh_{el} is to increase the general efficiency of the generation process. Fig. 4 shows the more electricity is produced, the less CO_2eq footprint per kWh_{el}. Higher efficiency means more electricity produced. One possibility to achieve this is highlighted by Frick et al. (2010). They showed that hotter geofluid can lead to larger electric yield and therefore to higher efficiency and lower specific CO_2eq emission factor. Nowadays, the power plant in LH is using the conventional geothermal resource, however it has been demonstrated that LH hosts a supercritical geothermal system which is not under exploitation (Jolie et al., 2021). From supercritical systems, it will be possible to get hotter fluids, however with a challenging highly corrosive nature (Reinsch et al., 2017). Also, the efficiency can be increased by improving the plant's capacity factor.

To evaluate the increment on the plant capacity factor, two scenarios were outlined. Gutiérrez-Negrín (2020) broke down the electricity generated in LH in 2018 in the single units' contributions. According to this report, 3 units of 25 MW_{el} were installed, but only two of the three units were fully operational. The assumption for the first scenario S1 is that all three conversion operates under the same production conditions. If that is the case, the electricity yield would increase by 200 GWh_{el} (according to the electricity yield of theOthertwo units which is ca. 200 GWh_{el}). Assuming optimistic forecast values of heat extraction to be 4597 GWh_{th} (González-García et al., 2021), the efficiency would increase to 15% (Table 6).

The second scenario S2 assumes there are four 25 MW_{el} units instead of three (which corresponds to the original plan described in the MIA). In this case, the efficiency would increase to 18%. In both scenarios the CO_2eq emissions decreased accordingly. These results do not imply a reduction of the CO_2 content in the steam.

4.2. Avoidance of emissions

Another option is to eliminate the main source of CO_2 emission by keeping the geofluid in a closed circuit (DiPippo, 2015). In this case the heat of the geofluid is transferred using a heat exchanger to a second cycle with a working fluid which drives the turbines, i.e. a binary power plant (DiPippo, 2005). To explore this scenario, several geothermal power stations in various countries were considered for which an LCA is available. These stations are presented in Table 7. Las Pailas is included although it does not have an LCA, as it is a novel binary power plant installed in a high enthalpy geothermal resource (DiPippo and Moya, Oct. 2013).

The comparison of the variation in efficiencies with the inlet fluid temperature is shown in Fig. 6-A. In this graph, LH appears with the scenarios described in Table 6. Fig. 6-B visualizes the exergetic efficiency of the power plants considered here. It shows that the energetic efficiency of LH calculated in 2018 is even lower than the efficiency calculated for the Molasse Basin and the Rhine valley (Heberle et al., 2016). In theOtherhand, the exergetic efficiency for Las Pailas is higher than both configurations of LH, although their fluid inlet conditions (as mixture of brine and steam) are similar (Table 7). To investigate the possibility of having a binary system in LH, the design of the power station installed in Las Pailas was taken. To consider this, the exergetic efficiency of Las Pailas was used for LH.

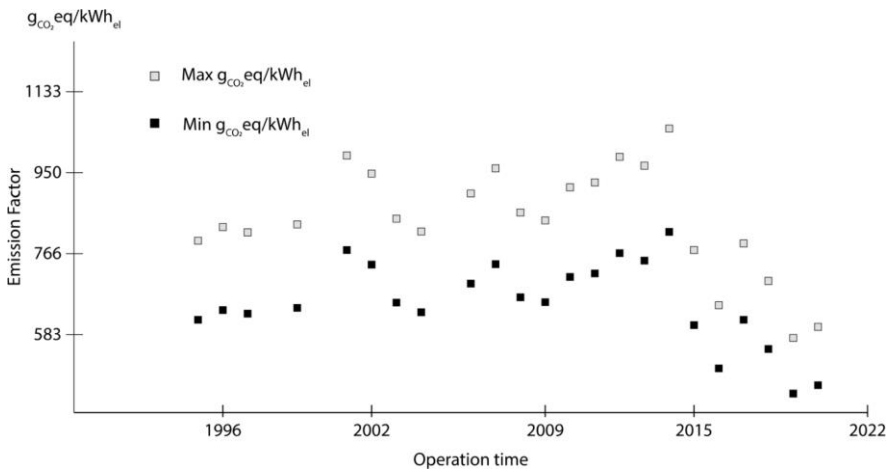

Fig. 4. Temporal variation of the CO_2eq emissions for the LH geothermal power station.

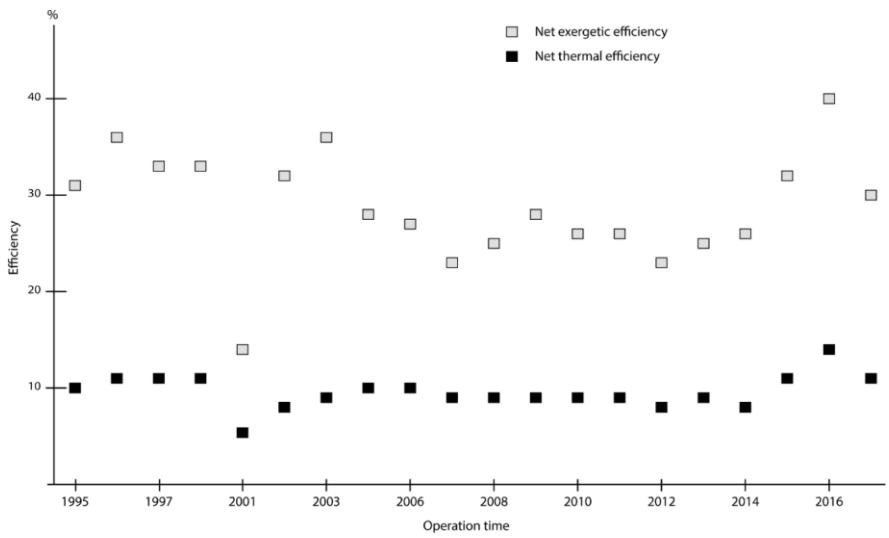

Fig. 5. Yearly variations of energetic and exergetic efficiency. The lowest values are found in 2001, according to Gutierrez-Negrín (Gutiérrez-Negrín, 2007), many of the conversion units were out of work due to maintenance.

Table 6
Variations on the emissions of the g_{CO2eq} according to the increase of the thermal efficiency.

	2018	S1	S2
Thermal Efficiency	10%	15%	18%
Min gCO_2eq	580	439	333
Max (gCO_2eq)	767	581	440

The average yearly exergy rate in the geothermal brine is 148.2 MW_{th} (Table 7). According to the considered exergetic efficiency of Las Pailas, the electricity yield could reach 480 GWh_{el} per year (16% smaller than the 2020 yield). Although, the electricity production might be smaller, the advantage of using a binary closed loop is the re-injection of the fluid that contains CO_2 (Manente et al., 2019). The EF for the different power plants is shown in Fig. 6-C. LH has a higher EF than theOtherbinary power plants, however it should be noted that LH has more pipes and more wells than the rest of power plants.

The EF of the different scenarios presented above in LH is shown in Fig. 6-D. The EF for a binary plant in LH was calculated with a sum of the CO_2eq due to the construction activities plus the average of the different binary power plants presented in Table 7. Assuming that dismantling would have a similar CO_2eq footprint, the result includes the consequential amount of CO_2eq of the actual power station, and the extra

Table 7
Binary power plants with an LCA (except for Las Pailas). Los Humeros is not a binary power plant, but it is shown here for comparison proposes. The emission factor of all the power plants is only for the commissioning, excluding operation activities. NA: non-applicable. Minus sign means non available.

Case	Inlet brine temperature	Mass flow	Output brine temperature	installed capacity	EF	Lifetime	Thermal efficiency	Exergetic efficiency	Country
	K	kg/s	K	MW_{el}	gCO_2eq	years	%	%	
As (Frick et al., 2010)	436	138	323	1.75	48	30	11.7	–	Germany
Bs (Frick et al., 2010)	470	138	343	1.75	50	30	13.2	–	Germany
Kirchstockach (SM) (Menberg et al., 2021)	411	120	330	5.5	38.2	30	–	–	Germany
Las Pailas (LP) (DiPippo and Moya, Oct. 2013)	435	135	–	35	NA	NA	10.6	37	Costa Rica
Los Humeros (LM)	453	15.50	363	85	75	30	–	11	Mexico
Madrid (M) (Martín-Gamboa et al., 2015)	400	72	363	2.9	5.79	30	16.3	–	Spain
Molasse Bassin (MB) (Heberle et al., 2016)	400	141	308	0.25	22.1	30	–	48.8	Germany
Rhine Valley (RV)(Heberle et al., 2016)	428	98	338	0.45	13.2	30	–	42.8	Germany
Wairakei Binary (W) (Rule et al., 2009)	400	770	360	14	35.6	100	–	–	New Zealand

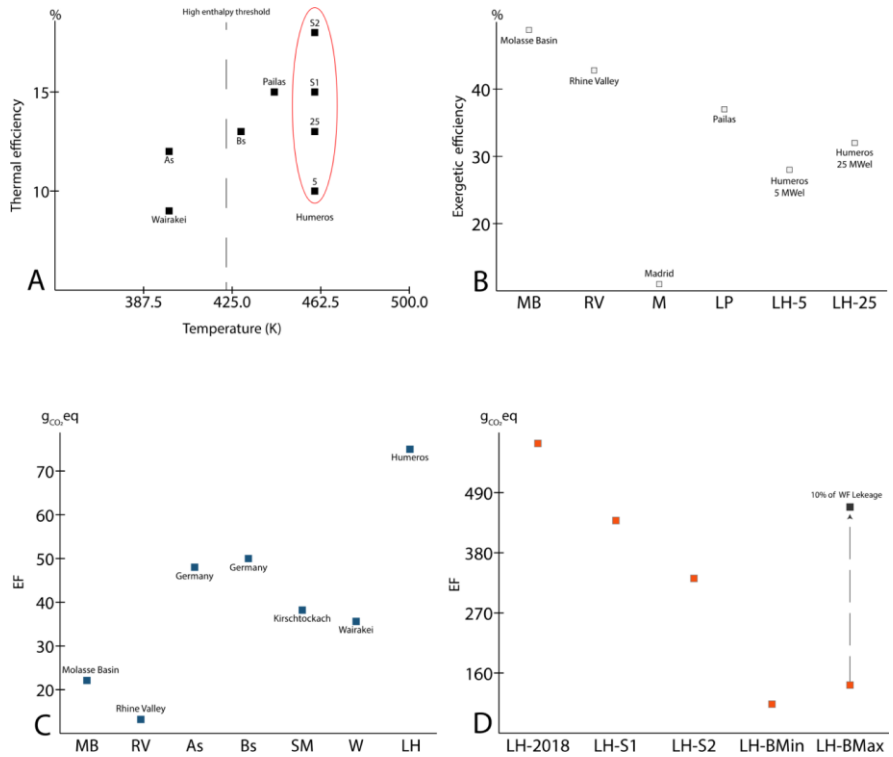

Fig. 6. A) Thermal efficiency vs temperature. This plot shows all the cases considered for Los Humeros: 5 corresponds to the conversion of heat into electricity using 5 MW_{el} units. 25 refers to the 25 MW_{el} units. S1 and S2 are the short-term scenarios considered (Table 6). B) Exergetic efficiency for different binary power station and Los Humeros. C) Emission factor for considered binary power plants and the commissioning emissions of Los Humeros (LH). D) Reduction of the CO_2eq footprint for Los Humeros according to the different scenarios. LH-Bmax is the maximum emission of g_{CO2}eq from a binary power plant built in Los Humeros. A leakage of 10% of the working fluid R245fa is plotted, having a contribution per kWh_{el} of 460 g_{CO2}eq.

Table 8
Assessment of the CO_2eq emissions for the different options suggested. LH-2018 is the power plant set-up for 2018. LH-S1 and LH-S2 corresponds to the first and second scenario (see Table 6). LH-BMin and LH-BMax are the labels for the binary power plant in Los Humeros. The minimum contribution is the sum of the EFMin plus the average EF of the binary plants presented in Table 7.

	$g_{CO_2}eq/kWh_{el}$
LH-2018	580
LH-S1	439
LH-S2	333
LH-BMin	103
LH-BMax	138

amount generated by a new binary power plant. The scenario with the lowest specific CO_2 emission is the binary power plant (see Table 8). This might be a promising option towards decarbonization of LH, however a leakage of the working fluid of the binary power plant must be avoided, because it can result into a higher CO_2eq emission factor (Heberle et al., 2016; Martín-Gamboa et al., 2015; Menberg et al., 2021). For example, Menberg et al. (2021) estimated that an annual leakage up to 10% of the refrigerant R245fa would add 323 g_{CO_2}eq to the final calculation.

Another possible solution is to consider reinjection of CO_2 from geothermal plant as it is demonstrated in Iceland (Frick et al., 2010). This technique allows the permanent storage of CO_2 by its mineralization. According to the authors, the NCG must be separated from the geothermal steam and transported to a suitable geological setting (where Calcium, Magnesium and Iron cations are available, e.g., in basaltic environments). However, the concentration of NCG in LH is much higher than at the project mentioned above (Reinsch et al., 2017). LH brine is saturated in CO_2, and therefore reinjection of the brine requires more investigation to avoid any obstacle.

4.3. Life cycle inventory

The cornerstone of this study is the LCI. Prior work has developed and published a list of elements needed to build a GPS (Buonocore et al., 2015; Heberle et al., 2016)(. These authors have claimed that their lists can be applied to any other GPS. However, the GPS are designed according to the geological setting where the geothermal system is hosted and the local environmental conditions. Thus, each GPS is unique and the use of a data base for anyOtherpower plant would result in a wrong estimation of the CO_2eq. In this work a local data base was created and a comparison with the datasets reported by Karlsdóttir et al. (2015), Tosti et al. (2020) is shown in Table 9.

Table 9
Differences between three LCI.

	Humeros	Hellisheiði	Bagnore	
Acrilic paint	0.011			m^3/m
alkyd enamel	19.5			kg/m
aluminum		6.2		kg/m
Asphalt	0.029			m^2/m
Basalt	143.6			kg/m
Clay	0.1			kg/m
Concrete	2.0	0.3		m^3/m
Diesel	226.8			kg/m
Excavation		18	0.34	m^3/m
Filling Material	0.4	8.3		m^3/m
Mineral fiber	96.7	43	3.06	kg/m
Gravel	13.4			kg/m
Mortar	269.8			kg/m
Paint	10.4			m^3/m
Polyethylen	1.4			m/m
Portland cement		556	kg/m	
Reinforecement Steel	154.9			kg/m
Steel	853.5		120	kg/m
Steel (black)	355.2	197		kg/m
Steel (carbon)	7771.3		53	kg/m
Stones	0.035			kg/m

It was found that LH has a larger input of materials. These findings are true for the diversity of materials and for the quantity of them. This confirms that the use of another data base may lead to a wrong calculation of the CO_2eq emissions. A notable difference is in the use of the insulation, where it is surprising that LH required more insulation than the Hellisheði power plant. This surprise arises from the notable contrast between the environmental temperature of LH and Hengill, Iceland. Although, this insulation is the reason for the high efficiency on the vapor distribution network (Garcia-Gutierrez et al., 2015).

Nonetheless, some limitations are worth noting. In this paper, the conversion units found in the Ecoinvent background data were taken. Those units are not the ones installed in LH. Karlsdóttir published a list of elements needed for a flash unit-conversion. Using this dataset, the calculation for the CO_2eq per a single flash conversion unit of 25 MW_{el} is 5.7 kt_{CO_2}eq. The CO_2eq calculated in this work per one unit of 20 MW_{el} is 5.1 kt_{CO_2}eq. Although, a 25 MW_{el} unit might have a bigger CO_2eq emission, the result here obtained with the conversion unit of Ecoinvent is 0.6 kt_{CO_2}eq smaller than the same assessment using the database provided by Karlsdóttir. Even though this difference is really small, an evaluation taking into account the real materials in LH would likely result in better outcome.

In the methodology of this study, it was mentioned that Ecoinvent 3.1 *cutoff* has no Mexican dataset available. To solve this problem, both the North American and USA background was chosen. North America shares a trade agreement, in which not only goods are exchanged, but also several manufacturing rules are shared between Mexico, the USA and Canada (Ducasse et al., 2022). This market situation would imply that the North America or USA background is not that far from a Mexican background dataset. Even though a local background process is still needed to provide a better estimation, the one used should be a good approximation.

4.4. CO_2 footprint estimation

In this work, the last phase of the project i.e., the de-commissioning, was not considered. The decision to exclude it was based on the lack of data for tracing the dismantling and deposition of those materials. Moreover, the production forecast for LH showed a reliable limit of future production (González-García et al., 2021). Thus, the lifetime of the project can be extended. Which means that the power station can still be working and it might not be dismantled but refurbished in future maintenance projects.

This last argument leads to another point. The quantification of the CO_2eq just included the construction of the different elements that forms the power station; and, it is necessary to clarify that maintenance was not included in this calculation. Fig. 3 shows that the contribution of CO_2 due to construction is a small fraction. Thus, maintenance works would add a small contribution to the mentioned fraction. Information regarding the frequency of maintenance works is not available. In this sense, adding maintenance works would add higher uncertainty to the final calculation. Although this quantity is small the owner company must choose low CO_2eq materials and procedures for future maintenance.

4.5. Natural CO_2 discharge vs release due to exploitation

The calculation of the CO_2 contained in the steam was done with only two measurements taken by the CFE. There are several years of difference between these two measurements, and not all the actual production wells are reported. Hence, a detailed and continuous monitoring of the CO_2 is needed in order to have a more accurate calculation.

The contribution by the construction of the power plant in LH is

small in relation to the CO_2 originating in the operational phase (Fig. 3). Since this CO_2 is contained in the geothermal steam, and it is not a consequence of burning fossil fuels, the IPCC suggests considering it as part of the natural release of CO_2 from the underground (Goldstain et al., 2011). Jentsch et al. (2020) calculated the natural emission of CO_2 as 84 t/d in the 10 km^2 used by the production zone. In comparison, the daily extraction of CO_2 by 29 wells can reach ca. 890 t The emission from the wells is 10 times bigger than the natural release and thus, this cannot be considered to be part of such. Hence, as long as these emissions are not mitigated, the accelerated release of CO_2 has to be considered in global decarbonization management.

5. Outlook

Some options to reduce the CO_2 footprint of the GPS of LH were here evaluated. However, the real chances of having these options in LH requires much more research. For the as-soon-as-possible application, the solubility and further re injection of CO_2 should be investigated. If the idea of having a closed loop in the site is taken, then the research must include the design of a binary power plant. For both cases a complete assessment of the negative effects on the general performance should be included.

6. Conclusion

A calculation for the CO_2eq emission factor was done for Los Humeros (LH), a 30 years old Mexican power station with an installed capacity of 85 MW_{el}. The EM included the CO_2eq contained in the extracted geothermal brine and, the life-cycle CO_2eq resulted from the constructon activities of the power station. The life-cycle CO_2eq of the construction of the geothermal power station (GPS) yielded 36 g_{CO_2}eq per kWh_{el} considering a lifetime of 30 years. This work presents the first Life Cycle Inventory (LCI) for a GPS in Mexico and it is based on public company reports.

This LCI could be adapted toOtherMexican GPS, using the respective MIA (since each GPS has at least one). The CO_2eq Emission Factor (EF) of the power plant is 442 (EF_{Min}) and 568 (EF_{Max}) g_{CO_2}eq /kWh_{el} for the minimum and maximum value. In comparison, the Mexican Emission Factor for 2021 is 423 g_{CO_2}eq/kWh_{el} (SEMARNAT 2021). However, it is not clear if this factor only considers fossil power stations. But what is clear is that CO_2eq footprint due to the construction of the power stations is not included. But it should be noted that the CO_2eq footprint of the geothermal power station of Los Humeros is less than 10% of the entire calculation. Therefore, the inclusion of this quantity does not represent any disadvantage when comparing with the Mexican emission factor.

Some possible CO_2eq mitigation measures for LH have been elaborated. The year 2018 was chosen as reference year. The options are:

1. To use all the installed units: according with the scenarios proposed, if all the installed units are under operation, the plant capacity factor increases and the CO_2eq footprint is reduced up to 25%
2. The use of a binary power station: if the current conversion units were changed into a binary power plant, the closed brine loop would prevent the CO_2 contained in the steam from escaping to atmosphere. This scenario could reduce the CO_2eq footprint by 82%.

This analysis was conducted only for one out of six geothermal power stations in Mexico. To ensure a full overview of the CO_2eq emissions of the geothermal power stations, more life cycle analyses are needed. By doing that, the main contribution can be identified and therefore decisions can be made in order to design a successful decarbonization plan. In this sense, these studies should be done also for theOtherpower plants using a renewable energy source.

Data and materials

All the data presented here, related with the LCA, is open and free for consultation. 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 exergy analysis and the green squares of Fig. 1.

CRediT authorship contribution statement

H. González-García: writing original draft, conceptualization, visualization, methodology, formal analysis and project administration. **H. Francke:** writing original draft, conceptualization, visualization, methodology, formal analysis. **L. Göllner-Völlker:** conceptualization, formal analysis and editing. **S. Kranz:** conceptualization and formal analysis. **B. Welsch:** conceptualization. **L. Schebeck:** formal analysis, software. **E. Huenges:** conceptualization, editing and formal analysis. **I. Sass:** project administrator, methodology, conceptualization, formal analysis and editing.

Ethics declaration

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.

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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12. Appendix C

Geothermics

Financial performance analysis of the Geothermal Power Station of Los Humeros, Mexico

--Manuscript Draft--

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Abstract:	This work presents the analysis of the financial performance of the Los Humeros geothermal power station. Currently, the power station has 68 MWel of installed capacity under operation. The study was performed using two scenarios. The first scenario took the current business scheme, known as the Vesting contract, whereas the second scenario simulated the participation of the power station in the regulated market. The operational and invested amount was based on actual contracts incurred by the owner company. The results showed that the investment is amortized in 6 and 4 years for the vesting contract and the regulated market, respectively. The Net Present Value evaluated with three different interest rates showed positive values for the Vesting contract and negative values for almost all the combinations of the open market. However, this last evaluation was done for 5 of the 25 years of the project's lifetime. A small experiment for the rest of the time was done. It showed high chances of profitability when the 25 years are considered.
Suggested Reviewers:	Michal Moore, PhD mcmoore@ucalgary.ca Professor Moore is an expert of geothermal energy and finance evaluations
	Diez Martinez C.V cvdiezm@bu.edu C. V. is an expert on economic analysis of different technologies, he has done several works regarding this topic under the Mexican framework.
	Rodoles Amaro Fabiola frodiles@afh.com.mx Prof. Rodiles is a financial engineer who has plenty of experience when applying the financial metrics here described and used.

Financial performance analysis of the Geothermal Power Station of Los Humeros, Mexico

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Abstract

This work presents the analysis of the financial performance of the Los Humeros geothermal power station. Currently, the power station has 68 MW_{el} of installed capacity under operation. The study was performed using two scenarios. The first scenario took the current business scheme, known as the Vesting contract, whereas the second scenario simulated the participation of the power station in the regulated market. The operational and invested amount was based on actual contracts incurred by the owner company. The results showed that the investment is amortized in 6 and 4 years for the vesting contract and the regulated market, respectively. The Net Present Value evaluated with three different interest rates showed positive values for the Vesting contract and negative values for almost all the combinations of the open market. However, this last evaluation was done for 5 of the 25 years of the project's lifetime. A small experiment for the rest of the time was done. It showed high chances of profitability when the 25 years are considered.

Key words: Profitability, geothermal power plant, Los Humeros, spot electricity market, long-term contract.

Introduction

The structure of the commercial distribution of electric power is changing. On the one hand, continuous development of the society demands a larger supply of electricity; on the other, the industry is leaving the monopoly-state structure and is adopting an open regulated market. Moreover, due to climate change, the generation of electricity must use cleaner and modern processes, ensuring the availability of all of it with a minimum environmental cost (Nations 2021). With the industry leaving state ownership, a great business opportunity appeared for private investors. Especially renewable power stations caught their attention (Azhgaliyeva et al. 2022). Recent works address the analysis of the profitability of different electricity generation technologies to provide a better insight into their financial behavior, therefore promoting the investment (Talavera et al. 2017; Roldán Fernández et al. 2021). Some other works have explored profit maximization according to variations in the power station management (Niu and Insley 2013; Hong and Lee 2018). Our work aims to estimate the profitability of a renewable power station in Mexico.

Although the presence of renewable power stations has increased in recent years, the vast majority of electricity in the world is still generated by using fossil fuels as a primary energy source. Moreover, the transition toward low-CO_2 power stations has been slow despite the constant investment rate (IEA 2021). Nonetheless, that is not the same for all renewable resources. For example, solar farms have experienced exponential growth. This growth is partly

due to cheaper solar cell production (IEA 2022). More affordable production is translated into higher profitability and, therefore, more propensity for investment. Unfortunately, despite the energy potential, geothermal resources are not under the same conditions.

Geothermal systems are renewable sources of energy. They usually have a low CO_2 footprint when the natural contribution is neglected (González-García et al. 2022). Moreover, they do not use any fuel to run, and due to their nature, a geothermal power station can be used to cover base load demand. Generally, these attributes make geothermal resources a precious renewable option. However, geothermal projects have a considerable uncertainty at the early exploration stages and, therefore, an enormous financial risk (Sanyal and Morrow 2010) (Witter et al. 2019). Besides, the wells needed to harvest the heat contained in geothermal reservoirs increases the development cost (Stefánsson 2002; Sanyal 2004).

However, this risk is lower when development is at the latest phases (Sanyal et al. 2016). Many works have addressed feasibility studies on geothermal projects, including a financial or economic approach (Kanoglu and Yunus 1999; Lovekin 2000; Stefánsson 2002; Sanyal 2004; Erdogmus et al. 2006; Oktay and Dincer 2009; Ngugi 2012; Gerardi and Hinchliffe 2015; Moore 2016). However, only a few take real cases of geothermal projects (Kanoglu and Yunus 1999; Erdogmus et al. 2006). Even more, to the best of our knowledge, there are no studies about the reinvestment on proven geothermal resources (i.e., upgrading geothermal power stations).

In the case of Mexico, the electric industry has just migrated from a monopoly to a regulated open market (Percino-Picazo et al. 2021). However, before the market liberalization, almost all geothermal power stations belonged to the government, and the state absorbed the financial risk associated with their development. Although many private companies now own renewable power stations, only one company has put effort into developing a geothermal one (Gutiérrez-Negrín 2020).

Despite the transformation process of the Mexican electricity market, almost all the power stations are still owned by the government, and all the maintenance and upgrading processes are financed by public money. That happened to the Geothermal Power Station of Los Humeros (GPS of LH) (Tirzo 2013). It is a 30-year-old facility located in the western part of Mexico. The reinvestment in this project was made to modernize the conversion technology. The present work aims to analyze the profitability of this investment in a low-risk geothermal project and demonstrate its financial attractiveness.

Case of study: geothermal power station of Los Humeros (GTPS of LH)

The development of this station started in the late 60s with site exploration. Since then, several works have been done on the site, from the drilling of 59 wells to the installation of 11 conversion units and 22 km of pipes (González-García et al. 2022). In 2006 the *Comisión Federal de Electricidad* (CFE), the owner company, decided to install new bigger power plants to increase the plant capacity (SEMARNAT 2006). The plan included the expansion of the vapor network and the installation of 4 new 25 MW_{el} conversion units, which were thought to replace the old eight units of 5 MW_{el}. So far, only three units have been installed on the grounds, 12 km of pipes were built, and five new wells were drilled (SEMARNAT 2006; González-García et al. 2022).

These works not only incurred environmental costs but also required a significant investment. The total investment adds up to 1950 MMXN (Millions of Mexican Pesos), which are ca. 104

MUSD (Nominal) in 2022[1] (Table 1). This capital cost is the amount to execute the latest phase of development on the site. This phase started in 2008 with the installation of the first unit of 25 MW_{el} (González-García et al. 2022).

This context opened two essential questions: when the breakeven point is reached, and what is the general profitability of the project?

After the start of this construction phase, the works in LH followed a step-by-step development scheme. This framework has two main advantages. The first one is to estimate the system's production capacity, and the second is to take care of the financial health of the power station (Stefánsson 2002). So far, this power station already has 30 years of continuous operation, and some works have explored the limits of the production (Gómez et al. 2008; Aragon-Aguilar et al. 2019, 2020; González-García et al. 2021). In this sense, the staged-wise construction could be associated with financial performance. The goal of this work is to answer the mentioned questions by the analysis of the profitability with the Net present value. The breakeven point is also part of the goal. This analysis is conducted through the Mexican Electricity market rules and functioning. The following sections are intended to offer a brief explanation of part of the functioning of the market to define a financial model of the GTPS of LH.

Table 1 Records of works made in Los Humeros since 2008. This list represents all the works that could be traced and confirmed in COMPRAnet, the webpage where all infrastructure works can be found (HACIENDA 2021).

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
	MMXN	MMXN	MMXN	MMXN	MMXN	MMXN	MMXN	MMXN	MMXN	MMXN
Conceptualization and monitoring			3.5	3.4		0.14	5.6			
Connection to the electric grid			4.2	3.4				0.39		
Ecologic restoration					0.7		1.1	1.01		0.77
Maintenance	2.1	4.7	9.8	24.1	19.92	20.62	45.3	7.8	42.1	12.47
Operation			5			1.5	1.7	0.81	1.39	0.65
Others					0.18	0.3	1.3	3.15		
Transportation of workers				0.5	3.0	0.5	4.6		1.9	
Upgrading (including drilling, pipes, and conversion units)	120.5	184.9		5.8	264.5	644.9		390.3	300	

Mexican electricity market

The operation of this market started in 2016, known as the *Mercado Eléctrico Mayorista* (MEM). It is divided into five branches: electricity, power, transmission, clean energy certificates (*Certificados de Energía Límpia* or CEL), and related services. A competitor can participate in several forms within these options according to the specified branch. In the case of the GTPS of LH, as a generator of electricity, it participates in three components of the market: energy, power, and clean energy certificates (CENACE 2022a). However, the GTPS of LH does not have full participation in the market. The electricity supply offered by this station is considered in the day ahead analysis, which implies the schedule planned for the rest of the power stations. Nevertheless, it does not receive income from this measure.

[1] 20.1195 MXN = 1 USD on 28/03/2022 (https://www.banxico.org.mx)

The energy branch is known as the *Mercado de Energía a Corto Plazo* (MECP). This is a spot market operated by the *Centro Nacional de Control de Energía* (CENACE) (CENACE 2022b). The power branch is known as *Mercado de Balance de Potencia* (MBP), and it is an ex-post-yearly incentive. It is for those plants covering the electricity demand during the 100 most intense hours of the year (CENACE 2022c). Moreover, the last branch where LH participates is the CEL market. A CEL is awarded when 1 MWh_{el} is generated using a renewable primary energy source (CENACE 2022d).

MECP (Energy Spot Market)

The CENACE analyses the demand and determines how much electricity is needed to cover it. This operation is known as the day ahead negotiation. The general structure of the MECP is based on the merit of order, in which the cheapest option is the first to be dispatched, and the power station with the highest marginal production cost connected to the same node sets the selling price of the electricity. The merit of order is an open market dynamic that experiences energy price fluctuations (Figure 1). This variation is not only consequential to the demand and the natural no-storage feature of the electricity, but it also has three elements: marginal generation cost, Transmission quota, and Congestion fines (CENACE 2022e).

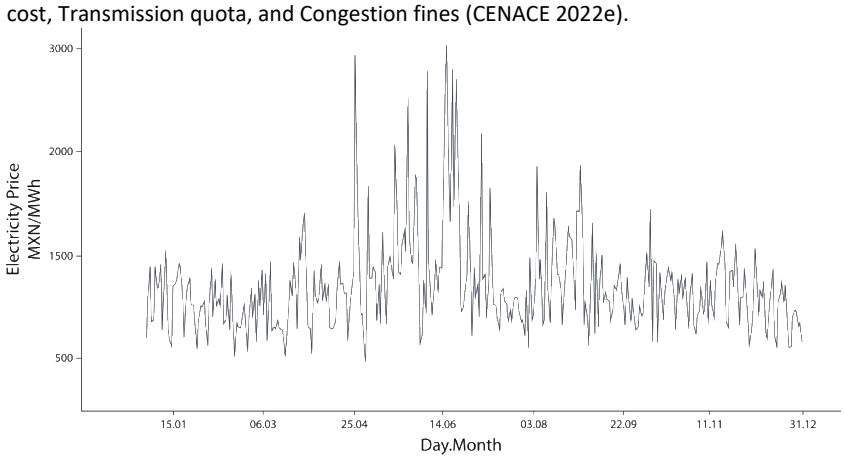

Figure 1 Electricity prices for 2017 in the PNode "02TZT-115", where the GTPS of LH is connected

MBP (Power Market)

As mentioned before, this is a monetary incentive to those power plants that covered the demand when it was the highest. This incentive considers the 100 critical hours of the year and the reference technology of generation. CENACE chooses this reference technology. According to them, it must be the power plant with the lowest Levelized cost for the specific year (Diputados 2016). The rules for this market branch are published for a free consultation on the CENACE web page (CENACE 2022e). The price per installed MW_{el} since 2016 are in Table 2. The choice of the reference technology takes all the fossil power stations in Mexico. This specification makes this parameter extremely difficult to predict.

Table 2 Price for the installed capacity. Each year has a different reference technology.

	Price of Installed capacity MMXN/MW
2016	0.12
2017	0.71
2018	0.12
2019	0.22
2020	0.63

CEL (Clean Energy Certificate)

A CEL is earned when 1 MWh_{el} is generated by the use of a renewable source of energy. These certificates were intended as a motivation to increase the use of renewables. During the planning of this tool, a trade market was also included (Diputados 2019a). However, no market has been opened yet, but renewable power stations generate CEL and trade them. This is because fossil power stations need a certain quantity of CEL per year, according to the law (Diputados 2019b).

Los Humeros under the MEM (Mercado Eléctrico Mayorista)

Using the geothermal system as a source of primary energy has three implications. The first one is that the GTPS of LH receives 1 CEL per MWh_{el} delivered into the node. The second implication is regarding the merit of order. As said before, the dispatching of electricity is scheduled according to the marginal cost of production of the different power stations connected to the same node. The cheaper is the first dispatched, and the more expensive generation process is the last. The marginal cost is the first derivative of the cost function ($c(Q)$):

$$\frac{dc(Q)}{dQ} = c_f + c_v(Q), \qquad (1)$$

In this case, the cost function ($c(Q)$) is defined by the sum of fixed production cost (c_f) plus variable production cost ($c_v(Q)$), where Q is the quantity produced. For the particular case of LH, the variable production costs are zero because it does not use fossil fuels to generate electricity, and all operation and maintenance costs are set as fixed costs ((SENER) 2015).

The third implication is on the plant capacity factor. Among renewable options, geothermal does not depend on weather conditions and can run almost the entire year. Besides, due to the marginal cost equals to zero, the electric production of these power stations is used to cover the demand in the most intensive hours of the year. Moreover, as it is described in the power market rules, the GTPS of LH has to receive the power monetary incentive. Thus, the revenues to LH would be formed by three elements:

$$Re = MECP_{12\,\mathrm{m}} + MPB_{\mathrm{y}} + CEL_{\mathrm{y}}, \qquad (2)$$

The subscripts, in this case, refer to 12 months (12 m) and yearly payments (y). However, there is a fourth element that has not been described. Although the GTPS of LH runs in a regulated open market, this power station, along with several others, poses a vesting contract ((GOB) 2014).

Vesting contract

In 2013 the Mexican electricity law got reformed, and the main consequence was the creation of the MEM (Percino-Picazo et al. 2021). With the MEM, the electricity market structure shifted from a monopoly to a vertical structure. After this change, it was decided to implement vesting contracts during this transition. A vesting contract is a tool to help transition from a monopoly to an open market. With this tool, the price volatility is deadened, and the profitability of the power plants is ensured (Kee 2001). For the case of Mexico, this contract is an agreement between the operator (CENACE) and the generator (LH).

This contract states that CENACE agrees to purchase all the electricity generated by the power station. In exchange, the total operation cost reported by LH is covered. This contract includes the three branches of the MEM previously described. It means that the money for the power market incentive and the CEL trading is already included. This means that the power station who owns a vesting contract is not affected by the volatility of the price. The contracted parameters are described in Table 3.

Table 3 Elements included in the vesting contract for the GPS Los Humeros. This contract was agreed upon in 2017, and it will run until 2030 ((GOB) 2014)

	Concept
Electricity	100% MWh
Installed capacity	54 MW/y
CEL	211,291 CEL/y

Vesting contract vs. regulated price

An evaluation of the profitability of any project requires a balance sheet. It is created with the history of cash flow, interest rate, and time. Unfortunately, for LH, the cash flow history and the production cost are considered a national secret. Moreover, the vesting contract is designed to make the power station fully profitable (since all the cost are covered). Then, an evaluation of its profitability would not make sense.

On the other hand, the structure of the regulated electricity market is much more complex. The spot market adds a massive uncertainty to the price, and the prices reached in the spot market could be lower than the operational cost of LH. Marginal cost is not the same as operational cost. While operation cost is fixed and more than zero, any other plant running simultaneously and operational costs are cheaper than LH, and eq (2) $\neq 0$ will create a negative income for this power station.

With these in mind, the profitability analysis will be addressed for two scenarios: the vesting contract and the regulated market, i.e., simulating full participation of the GPS of LH in the regulated spot market. This analysis compares the performance of both business schemes and demonstrates the power station's profitability.

Methodology

As mentioned before, the parameter to be calculated is the Net Present Value, which offers how worth is a project with time:

$$NPV = \sum_{t=1}^{11} \frac{Cf_t^{\text{net}}}{(1+i)^t} - I. \quad (3)$$

where Cf_t^{net} is the net cash flow at period t, I is the investment (which is the sum of conceptualization and monitoring, connection to the electric grid, others, and upgrading (Table 1)), and i is, the interest rate. In the following sections, each part of eq. (3) will be described.

Cashflow (Cf_t)

Before calculating the net cash flow (which includes taxation and depreciation), the cash flow is first calculated. In this work, the cash flow is the rest between income (money received by the sale of electricity referred to as MXN/MWh$_{el}$) and outcome (operation cost referred to as MXN/MW$_{el}$):

$$Cf_t = e \cdot eP - Ic \cdot Oc \quad (4)$$

where e is the electricity produced (MWh$_{el}$), eP is the electricity price (income); Ic is the installed capacity (MW$_{el}$), and Oc is the operation cost. This equation is only valid for the second scenario. The cash flow for the second scenario is defined by the operational cost of the power station. The monthly electricity yield from 2016 to 2020 in LH was requested to the *Instituto Nacional de Transparencia y Acceso a la Información* (INAI). This public entity provides any data regarding the government of Mexico. The installed capacity (Ic) is in Table 3. The electricity price (eP) was obtained from the CENACE portal, and the operational costs (Oc) were estimated from Table 1.

Operational cost (Oc)

A complete statement of the operational cost of the GPS of LH was requested to the INAI. Unfortunately, they did not fully display the operational costs, but the "cost of steam supply" and the numbers of workers, including their monthly salaries, were provided. Hiriart and Andaluz (2000) published four main components for the operational cost of LH:

- Power plant investment (Capital cost).
- Operation and maintenance (plant).
- Steam Supply.
- Operation and maintenance (field).

The works made in the power station were financed by the government (Tirzo 2013). So then, the capital cost is not considered as part of the production cost of LH. Furthermore, O&M was not divided into two. Instead, the operational cost considered here was divided into four branches according to the data perceived (Table 1):

- O&M: which is the sum of ecologic restoration, maintenance, operation, and transportation.
- Depreciation: assumed to be the 10 % (according to income tax law) of the sum of conceptualization & modeling, connection to the electric grid, others, and upgrading.
- Salaries: Los Humeros has 68 workers. Total monthly expenses due to salaries add up: 0.86 MMXN.
- Steam supply: it costs 89.5 MMXN per year.

Each element was divided by the installed capacity of LH specified in Table 3.

Electricity yield (e) and its price (eP)

Electricity prices were obtained from the CENACE portal (CENACE 2022e). They are hourly data known as "local marginal price." The electricity yield of LH is reported per year. Therefore, the income estimation took two ways. One using monthly electricity yield and a second, using yearly data. The monthly estimation was based on the heat extraction data reported by González-García et al. (2021). And the conversion efficiency (González-García et al. 2022).However, this procedure covers only 2016, 2017. For 2018, 2019 and 2021 the yearly electricity yield was divided by 12 and assumed constant per month. Monthly electricity yield for 2020 was provided by the INAI. To calculate the income, the electricity yield was multiplied by the price. Before that, the average price per day was obtained. It is well known that electricity prices fluctuate throughout the year (Figure 2). We dealt with this variation by taking the monthly quartiles 1, 2, and 3; then, the quartiles were used to calculate the income:

$$e \cdot eP \rightarrow e \cdot \{ \begin{matrix} eP^1 \\ eP \\ eP^3 \end{matrix} \quad (5)$$

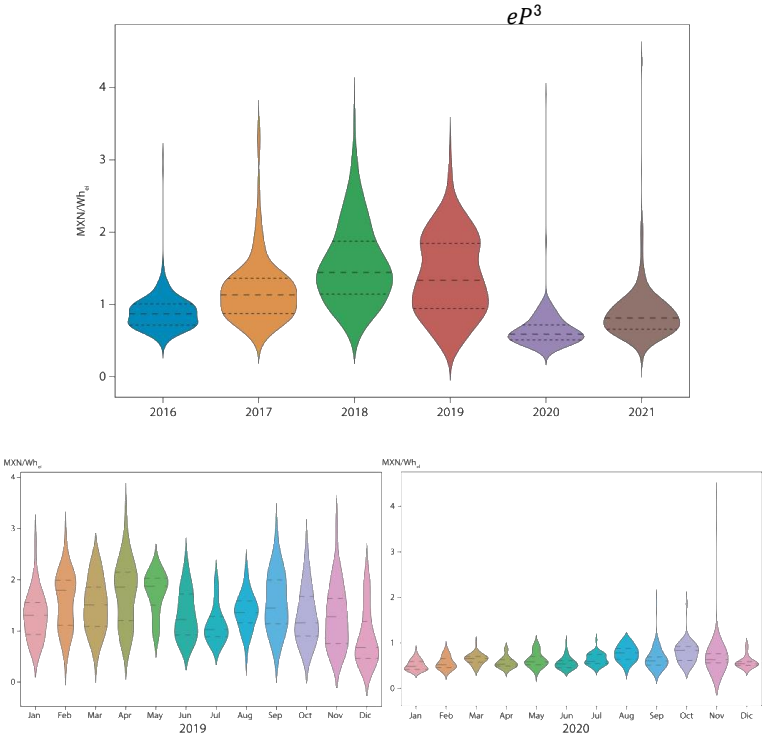

Figure 2 yearly variation of the electricity price in the node "02TZT-115". In 2020 COVID-2019 pandemics happened. This event changed the electricity demand and, therefore, the electricity price. The divergence between the years with the highest and lowest

prices is at the bottom. However, the variation in electricity prices in 2019 was more extended than in 2020. The quartiles of the data are represented by the lines inside the violins. Bottom line is the first quartile, top line is the third.

Net Cashflow estimation

Once the four variables of eq (4) were estimated, the cash flow was calculated. To eq. (4) the power incentive (P) and the CEL were added:

$$Cf_t = \mathrm{e} \cdot \begin{cases} eP^1 \\ \overline{eP} \\ eP^3 \end{cases} - Ic \cdot Oc \; + P + CEL; \tag{6}$$

Operational costs (Oc) were assumed to be constant throughout the evaluation. The power incentive P (Table 2) and the income produced by the sales of the CELs (Table 3) were also constant. The price per CEL is 200 MXN (CENACE 2022f).

The net cash flow requires taxes and depreciation. Therefore, the net cash flow is:

$$Cf_t^{\mathrm{net}} = (Cf_t) \cdot 70\% + \mathrm{Dep} \tag{7}$$

where 30 % is the income tax (Diputados 2021) and Dep is the depreciation (described in Operational cost (Oc)). Finally, the net present value could be applied (eq.(3)). For this estimation, the investment was considered an overnight cost (i.e., no interest rate was involved during construction).

Results

This work aimed to analyze the financial performance of the geothermal power station of Los Humeros for two scenarios. The first scenario was for the vesting contract, and the second simulated an open market situation for the power station. The results are presented as a series of plots in which the breakeven point can be identified. In addition, the net present value for all scenarios is also shown.

Operational cost and breakeven of the vesting contract

The sum of operational expenses is 0.87 MMXN/day. This cost resulted from the sum of:

- O & M: 0.34 MMXN/MW/y
- Dep: 2.82 MMXN/MW/y
- Salaries: 0.15 MMXN/MW/y
- Steam: 1.31 MMXN/MW/y

All these categories are annual costs and are multiplied by the installed capacity of Table 3. As stated by the vesting contract ((GOB) 2014), the earnings perceived by the power station are equal to the sum of the cost, i.e., 0.87 MMXN/day or 317.21 MMXN/year. Under this business model, the financial breakeven point would be reached after six years of continuous operation (Figure 3).

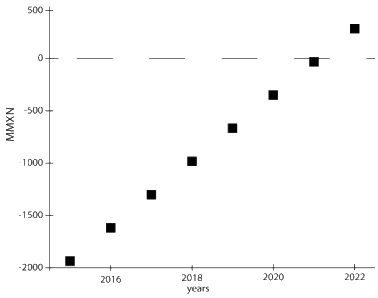

Figure 3 Cumulated cash flow for the GTPS of LH using the vesting contract. The breakeven is reached at period six approximately.

Breakeven of Los Humeros in the MEM

The power station's income is defined by eq. (4) and shown in Figure 4, the results of eq. (6) are in Table 4. The year with the highest values is 2019. In contrast, the lowest input of money happened in 2020. This year, Mexico was under lockdown due to COVID-19 pandemics. The accumulated cash flow is in Figure 5. After five years, the breakeven is reached, considering the median value of eP. The top quantile went breakeven in 4 years, and the bottom has not reached breakeven yet.

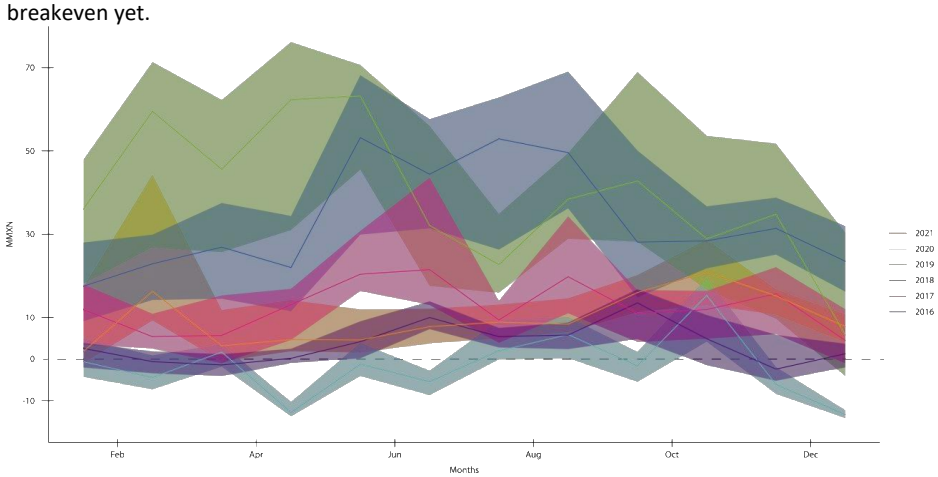

Figure 4 Monthly cashflow defined by eq. (4). The solid line is the mean, whereas the quantiles define the shadow. The bottom of the shadow is the q1, whereas the top is the q3.

Table 4 Annual net cash flow plus incentives. These results were obtained with eq. (6).

	2016	2017	2018	2019	2020	2021
	MMXN					
Q1	84.8	158.9	301.4	317.0	21.6	107.7
Q2	130.0	241.1	451.0	529.3	64.8	157.8

Q3	173.1	341.7	595.6	730.8	112.4	257.9

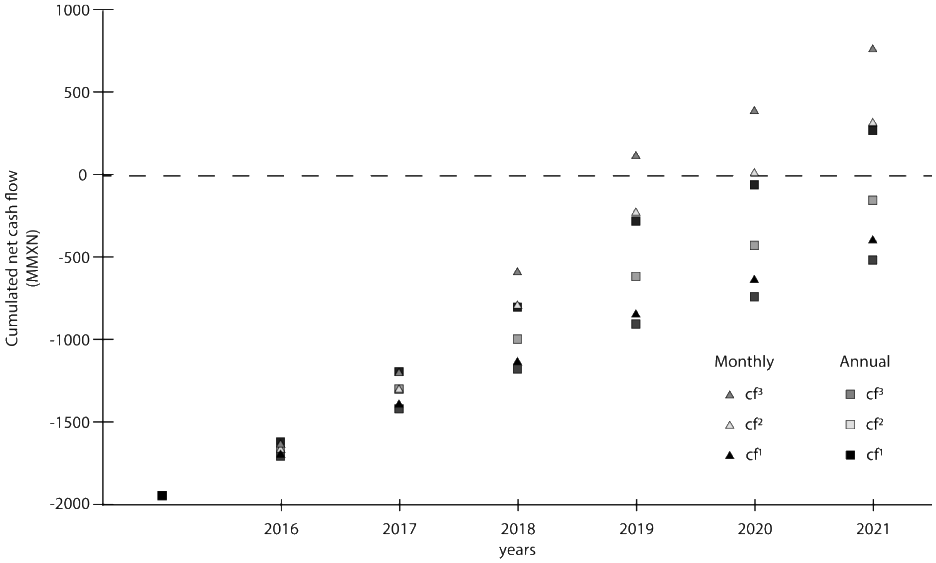

Figure 5 Cumulated net Cashflow defined by eq. (7). Break-even is reached after five years of operation.

Net present value

Three values for the interest rate were considered in eq. (3) for the NPV calculation. As expected, the NPV is always positive for the vesting contract scheme (Table 5). However, this is not the situation when LH participates in the open market. Therefore, for the period here considered, the NPV is primarily negative. However, when high prices are considered (i.e., third quartile), all the NPV values are positive (Table 6).

Table 5 Net present value for the Vesting contract. The net present value is evaluated with different interest rates (i).

i	NPV MMXN
5%	698.4
8%	328.1
10%	123.8

Table 6 Net Present Value for second scenario.

NPV (MMXN)	5%	8%	10%
q1	363.30	502.61	585.23
q2	18.38	188.94	290.16
q3	356.15	150.29	28.15

Table 7 Net pressent value using yearly electricity yield and yearly quantiles of electricy price.

NPV (MMXN)	5%	8%	10%
q1	721.23	825.40	887.18
q2	413.90	544.88	622.59
q3	56.74	220.44	317.56

Discussion

The data obtained for the investment made in the Geothermal Power Station (GPS) of Los Humeros (LH) and its operational costs allowed the analysis of the financial performance of this project. In the current business scheme, i.e., with the vesting contract, the results showed a 6-year breakeven point and a positive Net Present Value (NPV) for different interest rates. The last development phase of the GPS started in 2008 and continued till 2017 (González-García et al. 2022).

Due to the discrepancy time of the data (hourly electricity price vs. yearly/monthly electricity yield), much uncertainty is involved with this analysis. This uncertainty is evident when the results of the Net Present Value of the second scenario are compared (Table 6 and Table 7). When using the yearly quartiles, a lot of information is lost. It can be the case when the production is high for a high price reach on the spot market. An ideal evaluation should be based on hourly data for both the electricity prices and electricity yield from the power station.

Moreover, the investments started even before the creation of the MEM. Considering this would require a deflation or other financial techniques. This would add more unnecessary uncertainty, especially in an unknown situation (no market information was available before 2016). Under these circumstances, the financial analysis assumed that all the investment was made one day before the operation started (overnight cost) and began in a virtual zero for both parts of the study. Then, this work analyzed the project's profitability and compared two different business models: the vesting contract and the open market.

Profitability

The importance of knowing the financial performance of energy projects lies when electricity matrices are designed. In the long run, metrics like the Levelized cost of energy (LCOE) are used to identify and opt for those low-cost technologies (Ueckerdt et al. 2013). In the short run, however, the net present value or internal rate of return is used to highlight those promising technologies (Azhgaliyeva et al. 2022). Due to the private status of the great majority of power stations worldwide, an evaluation using actual data from it can be complex. In this work, the profitability of a reinvestment made in a geothermal station was explored to demonstrate that it is profitable and attractive to private investors. This evaluation was based on contracts incurred by the owner company, and prices reached in the spot Mexican market.

The analysis addressed two scenarios; the first scenario is for the actual business scheme on Los Humeros: the vesting contract. In this, the breakeven is reached in ca. six years (Figure 3),

whereas the open-market scenario gave a 4-year breakeven when the top quantile of tariffs is considered (Figure 5). Although the operational cost did not include any payment for the debt (See Operational cost and breakeven of the vesting contract), it would add cost and, therefore, delate the breakeven. An attractive project should profit from invested money in the shortest time possible. To go for this decision, both parameters, the NPV, and the breakeven, play an essential role.

For the case of the vesting contract, the NPV is always positive, but six years of breakeven might represent a hurdle. The NPV was evaluated with three different interest rates (Table 5). This project provides a higher return when comparing it with the interest offered by the government of Mexico in the low-risk national bonds[2]. Due to the vesting contract, it can also be secure (i.e., low-risk). Long contracts are found among the options designed to reduce the financial risk of geothermal (Ngugi 2014). Due to the characteristics of the vesting contract, this is a lengthy contract aimed at reducing the volatility of the spot price. However, it reduces the financial risk by covering the operational cost (including the debt payment). Thus, an investment made here can represent a safe and long investment.

In contrast, a shorter breakeven for the second scenario was found, but the NPV was not favorable for all the applied interest (Table 6). However, the time frame was only five years (defined by the electricity prices data), and the lifetime of this project is 25 years. Therefore, a proper NPV evaluation should consider the entire lifespan. If that is the case, an assessment along the whole period might generate a positive NPV for all the interest rates. Although, that also depends on the spot price. The prices on the spot market were increasing until 2019. After that, the COVID-19 lockdown and 2020 registered negative income (Figure 4). It is hard to predict another lockdown due to COVID or another pandemic. In that case, the electricity prices might have similar behavior. On the other hand, a reliable forecast for electricity prices would cover months, which means that a forecast for the next 20 years is doubtful to be accurate (Weron 2014). However, an estimation was carried out.

This experiment was done for the monthly analysis. The following 20 years took the same electricity prices. However, when analyzing the behavior of the MEM from 2016 to 2019, there is a substantial increment in the prices (Figure 2). This can be attributed to the maturation of the market. Since COVID-2019 altered consuming behavior due to lockdown, the prices in 2020 were meager. Nevertheless, after 2021 there is a growing trend. Therefore, the market can experience another "maturation" phase. Thus, from 2022-2027 the same electricity prices (eP) were taken:

- eP (2022) = eP (2016)
- eP (2027) = eP (2021);

for the rest of the years, the last price of the MEM, i.e., eP (2021), was the same, and it was assumed to be constant. This assumption is unrealistic; however, this exercise evaluated the NPV for the entire lifetime. The results of this experiment are in Table 8, and all the NPV values are positive. Thus, the profitability of the power station is very likely to happen during the entire lifetime. Both scenarios show good profitability of the GPS of LH.

[2] https://www.banxico.org.mx/tipcamb/main.do?page=tas&idioma=sp (accessed 6 June 2022)

Table 8 NPV evaluation for the 25 years of lifetime.

NPV MMXN	5%	8%	10%
q1	2,217.94	1,245.44	786.46
q2	3,003.81	1,866.93	1,327.53
q3	4,024.10	2,639.71	1,984.00

Another point to discuss is about the depreciation of the units. According to the operation costs, this part corresponds to 61 % of the total of the costs. Nevertheless, the investment started in 2008. Hence, it is very likely that a significant portion of this investment has already been paid and the depreciation here applied is too big.

Nevertheless, following the proposed analysis, the operational cost will be cheaper once the depreciation is finished. Therefore the GTPS would have less difficulty covering this with the electricity prices in its node. Moreover, the CEL and the Power incentive can help with this.

Merit of order and incentives

Profit maximization occurs when the marginal cost (MC) equals marginal revenue (MR). For the case of renewable power plants, the marginal cost is zero since they do not use any fuel to run. That reduces production costs to fixed costs, and the business might fail to cover this amount. Figure 4 was derivate from the cash input minus the operational costs (eq. (4)). For this case, the dynamic prescribed by the merit of order have a negative outcome when LH cannot cover its operational cost (that happened a lot in 2020). As explained earlier, LH electricity yield will always be dispatched as imposed by eq. (1). However, this does not mean that LH will always earn money. A situation where a power station is running simultaneously, but which operational costs are cheaper than LH but marginal cost is higher is very likely to happen (operational cost ≠ marginal operational cost). For those situations, the Power incentive and the CEL play an essential role. While a monthly cash flow can be negative, the yearly cash flow is positive due to those incentives (Table 4).

As mentioned above, the power incentive is earned when the power station helps cover the demand during the highest peaks of the year. Since the plant capacity factor of a GPS is commonly higher than 70 % (Mines et al. 2015), it will always help to cover the demand, and therefore it always receives the Power incentive. The Power incentive is thought to push the power stations to seek better practices when producing electricity (CENACE 2022c), but a power station that earns it no matter what would remove the pressure to enhance the electricity production process. However, the efficiency estimations on LH show that their values are inside the usual range of of other power stations (DiPippo 2015; Garcia-Gutierrez et al. 2015; González-García et al. 2022).

On the other hand, LH uses a renewable source of energy. Geothermal is considered one (O'Sullivan et al. 2010). Nevertheless, it has an emission factor compared with the average fossil Mexican emission factor (González-García et al. 2022). Although the CEL law only stipulates that if the power station uses a renewable source as a fuel to run, it deserves the CEL per kWhel generated (Diputados 2019b). If the CO_2 footprint is included in this law, LH will lose this incentive. If that happened, the income of the power station would decrease. Therefore, a

reevaluation of the breakeven was carried out, removing the CEL. The breakeven is slightly delayed, and the NPV remains under the same negative values. Therefore, the impact of not receiving the CEL inventive is not that big. So, it can be thought that the merit of order is a dangerous dynamic that sometimes do not to cover the expenses of electricity production. However, the law is designed to benefit renewable or cheap power stations using the incentives mentioned. In turn, the merit of order pushes for better practices when producing electricity by other means, and the CEL generates more income for the renewable power stations increasing the attractiveness of the investment.

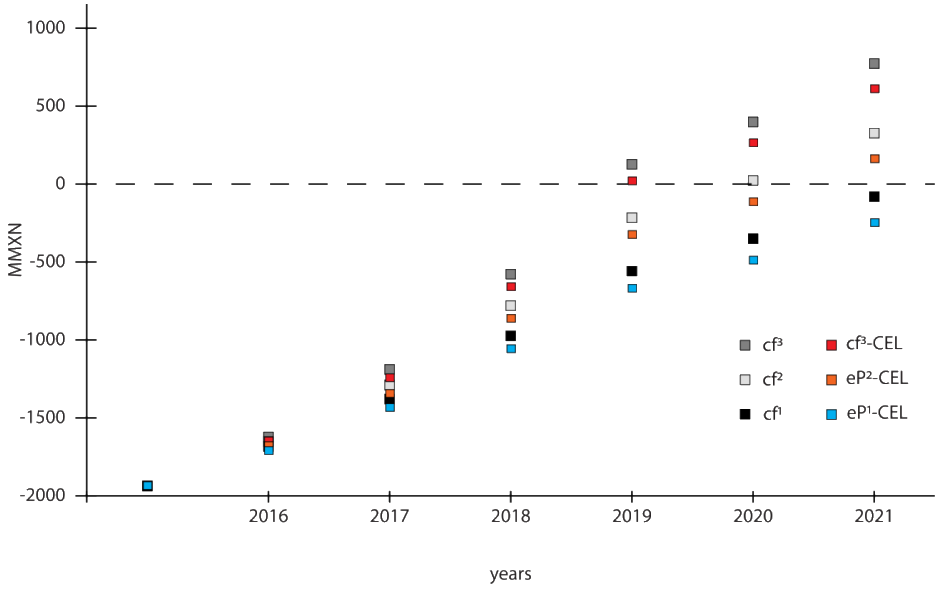

Figure 6 Evaluation of the cumulated cash flow without the CEL incentive.

NPV (MMXN)	5%	8%	10%
q1	-513.44	-639.36	-714.06
q2	-168.52	-325.68	-419.00
q3	206.01	13.54	-100.69

Financial risk

The possibility of losing money at the early stages of geothermal project developments is very high (Sanyal et al. 2016). However, that is not the case when the power station has gone into operational activities. At that point, the system had been proven, and the uncertainty involved with the physical features was known (Ngugi 2014). In that case, any new investment can be planned with a particular low financial risk. After 30 years of the previous operation, a new

development phase for the GPS of LH started, and therefore a considerable investment was made (Table 1). Due to the time this power station has been under operation and monitoring, the financial risk involved in this investment is low.

The wells make the most significant contribution to the risk of geothermal (Sanyal and Morrow 2010). A successful well needs detailed site exploration and evaluation (Ngugi 2007). However, it is always considerable uncertainty (Witter et al. 2019). Nevertheless, the LH investment was made to replace the old conversion technology, and only a few new wells were drilled (SEMARNAT 2006). Thus, the risk of unsuccess new wells was very low.

Moreover, it might be that the upgrading was planned under the known production limits of the geothermal reservoir. If that is the case, the steam demand can be covered at the right moment after the complete installation of the new power plants. Given these circumstances, the investment was done in a known and proven geothermal field.

Outlook

In this work, the profitability of a large geothermal station was evaluated. However, the link of this topic to sustainable exploitation of this resource is still a matter of uncertainty, and it has to be explored. In this sense, the externalities should be capitalized to re-evaluate the power station's profitability and verify that the profitability is still positive.

Conclusion

This work aimed to analyze the financial performance of a big geothermal energy project in Mexico. This work is the first of a kind in Mexico, based on actual operational costs. It was developed under the Mexican energy market (*Mercado Eléctrico Mayorista* MEM) context. The analysis included two scenarios. In the first scenario, the Vesting Contact of the Geothermal Power Station of Los Humeros (GPS of LH) generated a constant cash flow. In contrast, the second scenario took the prices of the Spot Market to simulate the participation of the GTPS of LH in it. Breakeven was reached after 6 and 4 years, respectively. The Net Present value was also evaluated using three different interest rates (5, 8, and 10 %). Not all the combinations were favorable. For the second scenario, almost all of them were negative, indicating a non-profitable project. However, this last evaluation was done for only 5 of the 25 years of lifetime.

For the second scenario, the price reached in the spot market was lower than the operational cost of LH. This situation generated a negative cash flow. Thanks to the incentives, this negative outcome on the merit of order were corrected. The incentives were designed on the laws in which the MEM operates.

The profitability of the actual GTPS is crucial to assure its use for further generations. Good cost-effectiveness provides future maintenance, and all the externalities generated by exploiting this geothermal resource can be reduced. Furthermore, more investment in research over unknown sites can be made with the surplus generated by these power projects.

This work is significant because it shows the behavior of a GPS in a dynamic electricity market. The results displayed here might be interesting for private investors who seek to put their money on infrastructure low-risk projects. Moreover, it is essential to mention that the government might opt to develop different financing structures instead of having all the load on them. Therefore, these projects have the potential to attract private investors to increase the portfolio of investments.

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Ethics declaration

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.

Supplement Materials

The list of contracts to build the expenses reported in Table 1 can be found in the supply material—also the data regarding the vapor cost and the number of workers in Los Humeros.

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