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Non-Conventional Geothermal Resources in Mexico: Northern Mexico as a Case Study

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1 INTRODUCTION

The presence of geothermal resources extends throughout México due to abundant tectonic-volcanic activity, which generates earthquakes and volcanic eruptions and is a source of the great wealth of geothermal resources in many regions of the country (Aryanfar et al., 2023; Castillo-Reyes et al., 2024). The geographical position of México is well-suited to low- and medium-enthalpy geothermal energy. The country has more than 4,000 thermal manifestations across the territory, as well as five existing geothermal fields (Cerro Prieto, Los Azufres, Los Humeros, Tres Vírgenes, and Domo de San Pedro). Of the known manifestations, there is sufficient data to estimate the potential of 2376, which comprises 927 geothermal systems located throughout 26 of the country's 32 states (Iglesias et al., 2015, 2016). This potential has mostly been proposed for exploitation as direct use. However, the direct use in México is low (Lund et al., 2022). Although México ranks sixth among countries with almost 1000 MW of installed geothermal capacity as of 2024, efforts to further develop this industry are supported by legislative and regulatory reforms (Gutierrez-Negrin, 2024).

Due to the high energy demand in México, it is crucial to exploit the full potential of renewable natural resources, both for their positive environmental impact and for the long-term benefits of providing energy and generating economic savings. A national problem of great importance is the production, consumption, savings, and use of energy, not only in electricity but also across all productive human activities that involve energy use in any form (Aryanfar et al., 2023; Solano-Olivares et al., 2024). The energy sector in México is undergoing changes aimed at reducing carbon emissions, diversifying the energy mix, and attracting international investment (Aryanfar et al., 2023; Castillo-Reyes et al., 2024). Geothermal energy is an inexhaustible and very abundant natural resource in México, which should be increased in use and exploitation to meet society's energy needs and support its productive activities. Even so, it has not been possible to exploit it to the fullest and sustainably, leaving considerable numbers of zones across the national territory with significant energy potential unexploited (Espinoza-Ojeda et al., 2023). To develop and make the most of renewable energy resources, there must be a balance between advancing science and technology and the various uses and exploitations of these resources, while also considering their positive environmental impact (Solano-Olivares et al., 2024).

Many low- to medium-enthalpy geothermal resources are in communities far from urban centers and/or with difficult access, and they lack electricity service. Therefore, bringing electricity to these communities is very important. For many years, governments have used diesel generators to power communities far from the electrical grid or in difficult-to-access areas. This solution has the lowest initial investment cost. Still, it uses a finite resource that, due to its nature, is increasingly scarce on the planet and therefore increasingly expensive, thereby raising the operation and maintenance costs of a project of this type (Cota Soto et al., 2016).

Currently, geothermal resources in México have not been fully exploited, particularly in rural areas with low socio-economic development. Low- to medium-enthalpy resources are abundant throughout Mexico and can be used directly in towns, cities, and municipalities. Hence, this work analyzes the potential direct uses of geothermal energy across localities with heat sources, aiming to identify diverse applications that meet the population's energy needs and available resources. Additionally, this research aims to evaluate the geothermal potential of abandoned hydrocarbon wellbores, either for electricity generation or direct use. This will involve analyzing the coaxial borehole heat exchanger (BHE) model installed in the wellbores, which uses the natural heat from the surrounding formation and transfers it to a working fluid flowing through the BHE.

2 METHODS & RESULTS

In accordance with the general objectives of this study, which consists mainly of the analysis of Mexican geothermal resources to propose a catalog of direct uses, the following tasks were applied:

2.1 Thermal data

Continental geothermal gradients, heat-flow values, formation temperatures, and corrected bottom-hole temperatures were provided by Espinoza-Ojeda et al. (2023). To propose Geothermal Direct Uses, it is necessary to know the subsurface temperatures. To do this, it is highly recommended to know the geothermal gradient, heat flow, or formation temperature, which are estimated from geophysical wellbore logs (direct subsurface measurements). As conditions for the use of available data, the exploitation of a conventional geothermal site is considered up to 3000 meters of depth, and according to the geothermal gradient, temperatures between 20 and 200 °C, since the resource will be considered for Direct Uses. For abandoned hydrocarbon wellbores, the database contains thermal geophysical parameters, coordinates, formation geology, and the thermophysical properties of the wellbore's mechanical design. Internal materials include the wellbore casing steel, a thermally insulated pipe/tube, the working fluid, and the reservoir rock.

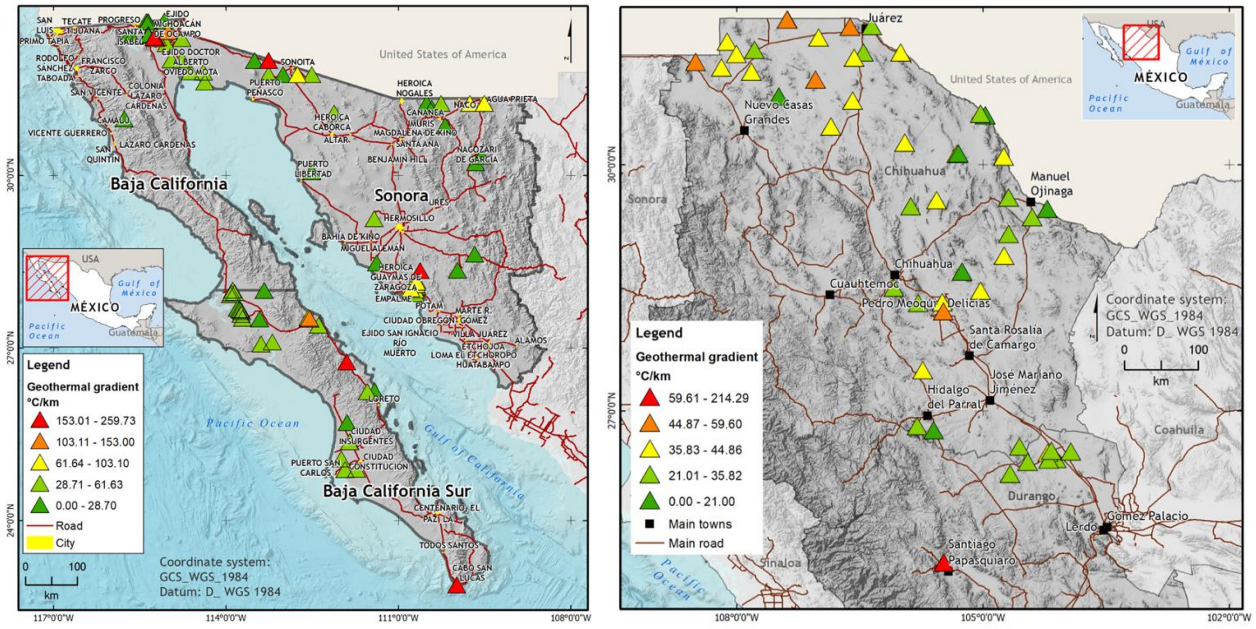


Figure 1. Geothermal gradient sites: (Left) Baja California Peninsula and Sonora; (Right) Chihuahua and Durango.

2.2 Study zone

The study areas were selected by analyzing heat flow and geothermal gradient maps; this will provide a perspective of the possible uses available in the area. Ninety-two sites are in the Mexican states of Baja California, Baja California Sur, and Sonora (see Figure 1: Left). Subsequently, the populations closest to the geothermal resource will be identified, establishing a 10 km limit as the maximum distance between the geothermal site and the area of interest to be considered an “exploitable” or “non-exploitable” geothermal resource. Fifty abandoned hydrocarbon wellbores are primarily located in Chihuahua and northern Durango (Figure 1: Right).

2.3 Socioeconomic analysis

Once the geothermal sites were located, the socioeconomic characteristics of the nearest city/town/village were studied. Other reliable sources of information about the study area were used, integrating data such as the type of population, the number of inhabitants, the main economic activities, the industrial development, the annual environmental temperature, the annual precipitation, the environmentally sensitive parameters, and the distance between the geothermal point and the population, among others. All these factors will influence the viability of using geothermal resources and their potential applications.

2.4 Resource classification

The possible geothermal direct uses were classified according to the maximum formation temperature, socioeconomic characteristics, and weather of the study area, using the temperature ranges established by the Lindal Diagram (Figure 2) as a reference.

2.5 Resource maps

Thematic maps showing geothermal resource sites and potential direct uses (Figure 3: Left). They were developed using a Geographical Information System to better describe and interpret data.

2.6 Geothermal potential of hydrocarbon wellbores

A numerical-analytical model was applied to simulate heat and fluid transport within the wellbore. This model comprises the following processes: (a) heat transfer between the wellbore-formation interface, (b) heat transfer in the heat exchanger placed inside the wellbore, (c) the injected fluid flow as heat transport inside the heat exchanger, and (d) calculating the extracted fluid temperature based on the injected fluid temperature, fluid flow velocity, and heat transfer from the formation-wellbore interface. Based on these processes, the steady-state energy balance for the annular fluid at the bottom of the system can be expressed as follows:

$$Q_{in} + Q_{formation} + Q_{tubing} + Q_{out} = 0 \quad (1)$$

where,

$$Q_{in} = \dot{m} c_{P_C}^{j-1} T_C^{j-1} \quad (2)$$

$$Q_{formation} = h_C^j A_C \left(T_R^j - T_C^j\right) \quad (3)$$

$$Q_{tubing} = u_t^j A_t \left(T_H^j - T_C^j\right) \quad (4)$$

$$Q_{out} = \dot{m} c_{P_C}^j T_C^j \quad (5)$$

where, $\dot{m}$ is the mass flow (kg/s), cpc is the specific heat at constant pressure under flow conditions of the cold stream on the annulus side (J/kg°C), hc is the convective heat transfer coefficient under flow conditions of the cold stream on the annulus side (W/m2 °C), Ac is the casing area (m2), At is the tubing area (m2), TR is the formation (rock) temperature (°C), TC is the temperature of the cold stream on the annulus side (°C), and TH is the temperature of the hot stream inside the tube (°C). Finally, the Organic Rankine Cycle (ORC) system model was used to estimate the thermal potential and the work required to operate the system (Figure 3: Right).

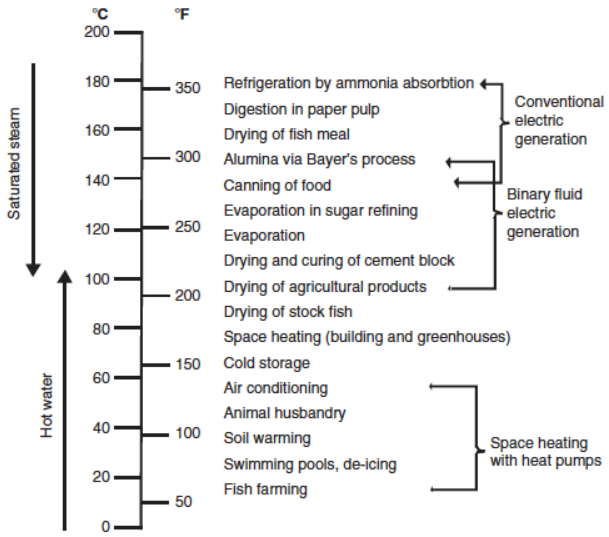


Figure 2. Lindal Diagram (taken from Sayigh, 2012).

Figure 3 (Left) shows a map of locations where GDU may be used, based on subsurface temperatures suitable for drying fruits and vegetables. Figure 3 (Right) presents a map of net heat output (Qnet) across the studied region for a mass flow of 6 kg/s, providing a spatial overview of the geothermal potential at the analyzed sites. This visualization highlights the variability in thermal output across wells and serves as a valuable tool for site selection and project planning.

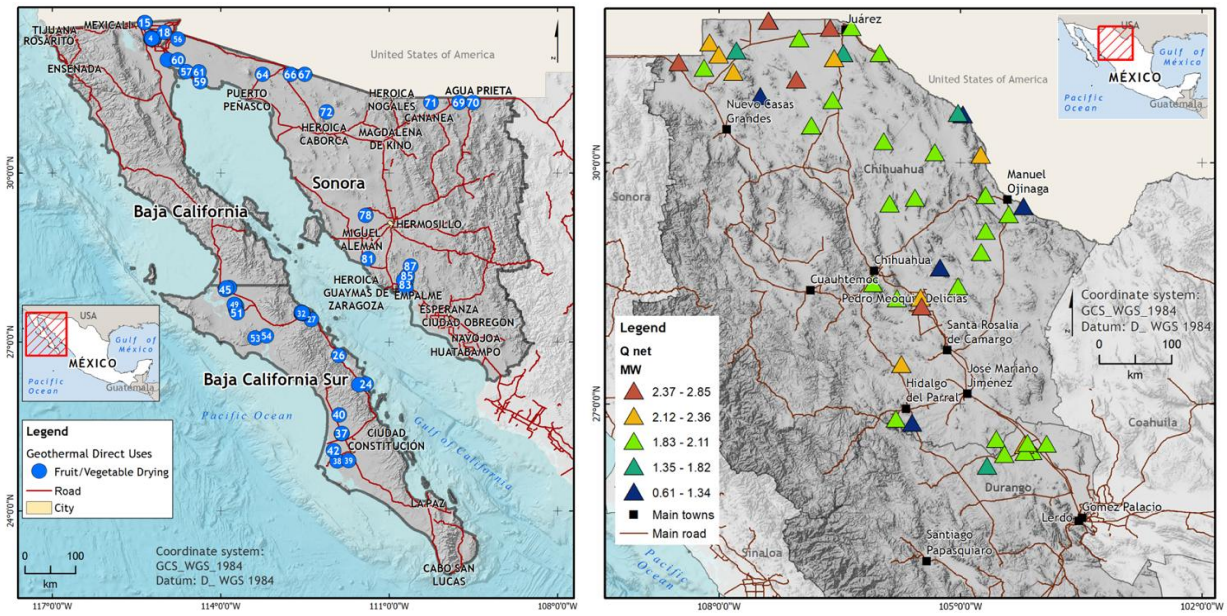


Figure 3. (Left) Location of the Geothermal Direct Use (GDU): Fruit/Vegetable Drying. (Right) Map of sites with net heat production for a mass flow rate of 6 kg/s.

3 DISCUSSION & CONCLUSION

This study analyzed low- and medium-enthalpy geothermal resources on the Baja California Peninsula and in Sonora. In summary, a catalog of geothermal direct uses is presented to guide project development. A significant advantage is that there are no legal problems with the direct uses proposed for its development, exploiting low and medium enthalpy geothermal resources (Aragón-Aguilar et al., 2013, 2019); In addition, it has been shown that the applications of geothermal direct use through thermal springs, wellbores and reservoirs are very wide in the world, they are not expensive and they are very environmentally friendly (Islam et al., 2022; Lund et al., 2022; Benavides et al., 2023).

In addition, this study provides a detailed techno-scientific evaluation of the geothermal potential of abandoned hydrocarbon wellbores in México, applying an analytical-numerical model of a coaxial borehole heat exchanger (BHE). In this work, the reader will find a great abundance of geothermal resources in northern Mexico. Despite their large territories and diverse geographical characteristics, they share similar environmental and socioeconomic parameters.

Despite traditional GDU, balneology, and leisure centers, heat pumps, space heating/cooling, and greenhouse heating, among others, are positioned as the most widely used, owing to the geothermal potential of low- and medium-enthalpy resources. The heat pump and space heating/cooling could play an essential role in most areas with extreme climates. Other uses in agriculture and livestock, hot water for domestic use, cold storage, pasteurization, production of drinking water by distillation, fruit and vegetable drying, aquaculture, and pisciculture (fish farming) are also considered essential applications.

In high enthalpy sites, according to the current technology developed, cascade systems can be applied through the direct use of the residual heat from an electric power production process, or from a combined cooling, heat, and power (CCHP) system, or from an Organic Rankine Cycle (ORC) cogeneration system (Aviña Jimenez et al., 2016; Rubio-Maya et al., 2016; Roumi et al., 2017). Geothermal cascade systems are widely used in many countries and have enabled secondary processes such as refrigeration, desalination, dehydration, defrosting, greenhouse climate control, and paper recycling.

The thermal energy production of non-conventional geothermal systems (hydrocarbon areas) in México was studied and calculated. Under the assumption that no reservoir fluids would be present, formation temperatures would be between ~45 and ~200 °C at an approximate depth of 3000 m.

Based on the results, existing abandoned or disused hydrocarbon wellbores in México present a significant opportunity to produce geothermal energy using coaxial BHE technology. Furthermore, by analyzing different

conditions for estimating thermal energy, we will gain a general understanding of the various applications that operate under these conditions.

Finally, the analytical approach and the associated simplified model proposed in this work could serve as a useful methodological tool for preliminarily assessing the feasibility of converting selected abandoned hydrocarbon wellbores to geothermal use using a coaxial BHE. This work is a prelude to further exploration of various aspects of coaxial BHE design in Mexican hydrocarbon wellbores, with the aim of maximizing energy production and optimizing operations.

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