Current status of geothermal-electric production in Mexico

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Abstract
Located at the southern section of the North America Plate, Mexico is part of the Pacific Ring of Fire, with important portions of its territory subject to volcanic and seismic events, due to subduction and transforming processes occurring between the plates of Cocos, Pacific, North America and Rivera. In particular, the Cocos Plate’s subduction has produced the Mexican Volcanic Belt (MVB), which is an E-W oriented strip composed of Plio-Quaternary volcanic structures and products that extends in central Mexico from coast to coast and includes some currently active volcanoes. Within the MVB are located three of the five geothermal fields in operation in Mexico, known as Los Humeros with 94 MW of installed capacity, Los Azufres with 247 MW, and Domo San Pedro with 35 MW. The geothermal fluids of all of these three fields are hosted mainly in volcanic rocks. The largest and oldest field in operation is Cerro Prieto, with 570 MW, fluids contained in sedimentary rocks (sandstones intermixed into shales) and located in the northwestern region of the country, near the border to the United States. The smallest field is Las TresVírgenes with only 10 MW and fluids hosted by granitic rocks, located in the Baja California Peninsula. Thus, the geothermal electric installed capacity is 956 MW, all exploiting hydrothermal type geothermal reservoirs, but the still untapped geothermal potential from the same type of resources is estimated at more than 2500 MW.

Keywords: Geothermal-electric capacity, tectonic setting, Mexico, hydrothermal.

1. Introduction
Geothermal energy has been used in Mexico since the Pre-Columbian times, when local tribes in the central and northwestern part of the country took advantage of hot springs for therapeutic, religious and ludic purposes. The Aztec empire, which ruled central Mexico between 1440 and 1521, developed sites with natural hot springs, the most known of which was Oaxtepec, in the central state of Morelos. It is still used as a recreational facility, operated privately and located around 60 km south of Mexico City. There, the Emperor Moctezuma-I constructed a main spa and botanical garden with temples and relaxation rooms for use not only by the royal family but also by soldiers and general people.

For electric purposes, the first geothermal exploration wells were drilled in the decade of 1950s and the first power plant, of 3.5 MW in capacity, started to operate in November 1959 in the Pathé geothermal field located in central Mexico. The plant was operating at a fraction of its capacity for several years, and was finally dismantled in 1973 [17]. It is currently exhibited as a museum piece at the Los Azufres geothermal field.

At the present, there are five geothermal fields in Mexico under commercial operation: Cerro Prieto, Las TresVirgenes, Los Azufres, Los Humeros, and Domo San Pedro, with a combined power capacity of 956 MW. The first four fields were developed and still are operated by the governmental utility Comisión Federal de Electricidad (CFE), who holds the exploitation concession granted by the Mexican Ministry of Energy (Sener), while the Domo San Pedro field is operated by a private company.
The geothermal resources in Mexico are due to its geological location, near the intersection of three main tectonic plates, North America, Pacific and Cocos, and one microplate, the Rivera Microplate (Fig. 1). The subduction of the Cocos Plate beneath the North America Plate has produced the Mexican Volcanic Belt (MVB), also known as the Trans Mexican Volcanic Belt, which is a strip composed of volcanoes and volcanic products of Pliocene-Quaternary age that crosses the country in an approximately E-W direction from coast to coast. The MVB also contains active volcanoes, as the Popocatépetl and the Volcán de Fuego. Three of the mentioned geothermal fields are located inside the MVB, whose origin is ultimately related with the subduction process.

The sliding between the Pacific and the North American plates along the series of transform faults in the northwestern part of the country, has produced the other two geothermal fields in operation (Cerro Prieto and Las Tres Virgenes). This process, which started in the Middle-Late Miocene, has separated the Baja California Peninsula from the mainland Mexico and eventually will convert this peninsula in a new island, including part of the current state of California, at the west of the San Andreas Fault.

Following is a description of each of these geothermal fields.

2. Cerro Prieto geothermal field
This is the oldest and largest field in operation in Mexico, located in the northwestern part of the country (Fig. 1), at around 30 km south of the international border with the United States. The field lies within the alluvial plain of the Mexicali Valley, at an average altitude of 13 meters above the sea level (masl). At its peak in the year 2007, the field had an installed capacity of 740 MW and produced 5592 GWh, at an astounding 88.7% of average capacity factor during the year.

The geothermal field lies within a pull-apart basin between the Cucapah-Cerro Prieto and Imperial faults that are of strike-slip type and belong to the San Andreas fault-system, and then all the region is subject to transtensional stresses. The lithological column in the subsurface of the Cerro Prieto basin is formed by the intrusive basement of Jurassic-Cretaceous age; an argillaceous package resting on the basement composed of gray shales with interbedded sandstones, brown-shales and mudstones; and clastic sediments of Quaternary age deposited mainly by the Colorado River and alluvial fans of the Cucapah Range, composed of gravel, sands and clays [11].

The heat source of the system is a basic intrusive associated to a magnetic anomaly, which seems to be continuously fed by new magmas a consequence of the thinning of the continental crust due to the rifting process occurring between the Cerro Prieto and Imperial faults.

The geothermal fluids are contained in sandstones interbedded into the gray shales that form the lithological unit resting directly on the basement. This package is Middle to Late Tertiary in age with an average thickness of 3000 m. This unit is covered by other shales-sandstones, which in turn are covered by the un-consolidated clastic sediments unit of Quaternary age, with thickness from 400 to 2500 m.

The Cerro Prieto system is a dominated liquid reservoir, and the wells produce a mixture of fluids at surface conditions with approximately 60% water and 40% steam. The liquid fraction has a sodium-chloride chemical type with neutral to alkaline pH. It is a diluted brine with an average of 27,400 mg/kg of total dissolved solids (TDS). The steam fraction contains an average of 1.4% in weight of un-condensable gases [16].

The natural recharge of the reservoir is groundwater from the alluvial regional aquifer and the Colorado River located to the east of the field.
The Cerro Prieto reservoir has been under exploitation for 44 years, since the first power units were installed in 1973. In the last years, the field has experienced problems related to a lower steam production, mainly due to pressure, enthalpy, and temperature drops, which seems to be a result of over-exploiting the geothermal resource. Based on that, the CFE decided in 2011-12 place out of production the first oldest and less efficient four power units of 37.5 MW each. Thus, the current installed capacity in the field is 570 MW, composed of four flash units of 110 MW each (two turbines in tandem of 55 MW each), one low-pressure flash unit of 30 MW and four flash units of 25 MW each.

The power units were fed by 147 production wells during 2017, producing 31 million of metric tons of steam, at an annual average rate of 3,543 tons per hour (t/h). With this production, the electric output of the field was 3,554GWh in the same year, with an average capacity factor of 71.1% in the year. The annual average production rate per well in Cerro Prieto during 2013 was 24 t/h.

There were also 29 injection wells operating in the field to partially dispose 60.6 million tons of separated brine. Most of the brine was disposed in a solar evaporation pond of 15 km².

3. Los Azufres geothermal field

Los Azufres is located within the Mexican Volcanic Belt at the central part of the country (Figure 1), and its average elevation is around 2,850 masl. The field lies in a complex Plio-Pleistocene succession of basalts, andesites, dacites and rhyolites. The heat source of the geothermal system is the magma chamber feeding the San Andrés volcano, the highest peak in the area.

Metamorphic and sedimentary rocks of Late Mesozoic to Oligocene age are underlying the volcanic rocks, and form the pre-volcanic basement that has not been cut by the wells, but is supposed to consist of gently folded shales, sandstones, and conglomerates. The oldest volcanic activity reported in the area began as andesite flows about 18 Ma ago, followed by micro-granular andesites of 5.9 ± 0.6 Ma in age, highly fractured and faulted with layering resembling that of sedimentary rocks in places [6], [8].

The local basement is composed of more than 2700 m thick interstratified lava flows and pyroclastic rocks of andesitic to basaltic composition, with ages between 18 and 1 Ma. The geothermal fluids are found in the middle and lower portions of this local volcanic basement.

Fluidal rhyolites of 1.2 ± 0.4 Ma in age are overlying the andesitic rocks; they include obsidian flows and perlite structures in some sites. The silicic volcanism also includes rhyodacites and dacites with ages up to 0.15 Ma and a thickness of up to 1,000 m. They form domes and short lava flows with glassy structures, and are generally fractured on the surface.

The more recent outcropping rocks include porphyritic andesites, glassy and pumicitic rhyolites, and basalt flows and cinder cones on the western field, product of the youngest volcanic activity in the area [6], [8].

The structures identified in the field and its periphery can be grouped into three main trends of NNW-SSE, NE-SW, and E-W directions. The first trend corresponds to a Miocene deformation with semi-vertical geometry affecting the basement. The two other trends were formed as part of the Mexican Volcanic Belt and present semi-vertical and sub-horizontal geometry, affecting Miocene basement rocks and Quaternary rocks outcropping in the field [15].
The hydrothermal manifestations are hot springs, some with temperatures up to 90°C, fumaroles, steaming soil, mud pools and even small thermal lakes. The thermal features are mostly located along faults or lineaments suggesting a fracture control [18].

Deep geothermal fluids in Los Azufres are of sodium chloride-rich composition with high CO$_2$ contents, and pH around 7.5. The temperatures of the geothermal fluids in the reservoir are commonly between 240 and 280°C, but temperatures as high as 320°C have been recorded some of the deepest wells.

Main non condensable gases in the separated steam are CO$_2$ (94% in volume), with H$_2$S (2.5% in volume) and minor concentrations of H$_2$, CH$_4$, N$_2$ and NH$_3$ (combined 3.5% in volume). In general, production wells have shown a decrease in the temperature of the fluids and an increase in the steam fraction of the reservoir [3].

The first power units in Los Azufres were commissioned in 1982, and currently the installed capacity is 246.6 MW, composed of one 53.6MW and one 50MW condensing, flash power units, four 26.3 MW each flash units, seven 5MW back-pressure and two 1.5MWe binary cycle power units. Four of the backpressure units and the two binary cycle units are out of operation, and then the running capacity is only 226.3 MW. Generation of electricity in 2017 was 1,767GWh, reaching a capacity factor of 89.1%.

45 production wells were in operation in the field along 2017, producing 15.8 million tons of steam, at an annual average rate of 1,803 t/h. The annual mean production per well was 40.1 t/h. The produced steam was accompanied by 6.8 million tons of brine that was fully injected into the reservoir through six injection wells. One additional 25 MW net flash unit is under construction, programmed to be commissioned in 2018. When this occurs, the three last backpressure units currently operating are planned to be placed out of production. Thus the net addition of power will be around 10 MW, and the available steam will be more efficiently used.

4. Los Humeros geothermal field

This geothermal field is located at the eastern end of the Mexican Volcanic Belt, near the limit of this province with the Sierra Madre Oriental province, in state of Puebla, at an average elevation of 2,800 masl. The field has been developed inside the Los Humeros Quaternary volcanic caldera.

The oldest outcropping rocks at the periphery of the field are granites and schists of Paleozoic age, followed by Jurassic and Cretacic limestones. Volcanic activity in the area started in the Miocene, around 15 Ma ago, and continued in the Pliocene between 3.5 and 1.5 Ma. The caldera process began 0.17 Ma ago when a highly differentiated magmatic chamber was emplaced into the Mesozoic calcareous package, which was already partially metamorphized, and produced a huge eruption of pyroclastic rocks that in turn produced the Los Humeros caldera with 15-21 km in diameter. A second caldera collapse occurred 0.07Ma years ago, due to other sudden explosive eruptions; this was the Los Potreros caldera, nested inside Los Humeros caldera with diameter between 7 and 10 km [5], [19].

The last volcanic activities occurred at different ages, the most recent of which was 2800 years ago; they produced rhyolitic domes, abundant cinder cones, andesitic and trachytic flows, including two volcanoes and an explosion crater of 1.7 km in diameter, as well as some phreatic and phreatic-magmatic explosions with deposits of ashes and sand.

The heat source of the current geothermal system is the magmatic chamber that is at its last, hydrothermal stage. The geothermal fluids are contained in a unit composed of thick andesitic lava flows, with some intercalations of horizons of tuffs. This unit is covered by the ignimbrites produced
by the two calderas that act as an aquitard, and overlies the Jurassic-Oligocene (140-31 Ma) basement, composed of limestones, subordinated shales and flint lenses, which were folded and partially metamorphized by the Laramide Orogeny, and then locally metamorphized by Oligocene intrusions. Basement includes also intrusive rocks (granite, granodiorite and tonalite) and metamorphic (marble, skarn, hornfels), and eventually some more recent (Miocene?) diabasic to andesitic dikes.

Two main structural systems have been identified, the oldest NE-SW to E-W and the more recent NW-SE to N-S [7]. Superficial thermal manifestations in Los Humeros are gaseous in the form of fumaroles, heat steam-soils and alteration (kaolin) zones. There seem to be two up-flow areas of the reservoir [9].

The produced fluids are mainly steam with high enthalpy (more than 2000 kJ/kg), yet the well H-1 produces mainly water with enthalpy of 1100-1300 kJ/kg. Water is sodium-chloride to bicarbonate-sulfated with high content of boron, ammonia and arsenic. In general, the water is low-salinity with partial equilibrium at temperatures of 280-310°C.

Fluids of low pH were produced by wells drilled in the area of the field known as Colapso Central, particularly at more than 1,800 m depth. The formation of low pH fluids has been explained as a post-exploitation process related to the migration of deep magmatic volatile species, which is induced by the extraction of fluids. Volatiles such as CO$_2$, H$_2$S, Cl, F, etc., react in their way to the surface with aqueous fluids, producing aqueous corrosive species [9].

The first power units started to operate in 1990, and currently the installed capacity in the field is 93.9 MW composed of three flash units of 26.3 MW each, and eight back-pressure units of 5 MW each. However, five of the latter are out of operation, while the other three remain in stand-by to be used only when the flash units are out of service. Then the running or operative capacity is 93.9 MW. The third 26.3 MW unit started to operate in November 2017.

During 2017, 25 production wells were in operation in Los Humeros, producing 5.97 million of metric tons at an annual mean rate of 682 t/h. Each production well produced an average of 27.3 t/h of steam along the year. The wells also produced 1.16 million tons of brine that was fully injected into the reservoir through three injection wells. With that amount of steam, the power units operating in Los Humeros produced 416GWh, which was one of the highest outcomes of the field, and represent an average capacity factor of 81.6%.

5. Las Tres Virgenes geothermal field
Las Tres Virgenes is located in the middle of the Baja California peninsula (Fig. 1), within a Quaternary volcanic complex, composed of three volcanoes aligned north-south and related to the NW spreading of the Baja California Peninsula. There are two other volcanic complexes in the area, called La Reforma caldera and El Aguajito, being Las Tres Virgenes the most recent.

The geothermal field is at an average altitude of 750 m, with volcanic peaks up to 1,850 masl. It lies inside the Santa Rosalía basin, which is a NW-SE trending Pliocene to Quaternary depression that seems to be the western limit of a deformation zone related to the opening of the California Gulf.

The geothermal system is structurally controlled and is located near the northern edge of the volcanic complex. This, in turn, is emplaced into a system of right strike-slip faults of low and high angle related to a tension zone, and some left strike-slip lateral faults [13].
The oldest lithological unit is a Late Cretaceous (99.1 ± 0.8 Ma) granodioritic intrusion, part of the California Batholith [13]. This is the host rock of the geothermal fluids, and its top is found at depths of 900 to 1000 m in the geothermal wells.

The intrusive rock is overlain by the Upper Miocene-Middle Oligocene volcano-sedimentary sequence known as the Grupo Comondú, consisting of andesites and sandstones with an average thickness of 750 m in the wells. Overlaying the Grupo Comondú, are shallow marine deposits belonging to the Santa Rosalía Basin of Late Miocene to Early Quaternary age, whose rocks are overlain by the more recent volcanic products of the La Reforma, El Aguajito and Las Tres Virgenes centers.

The known geothermal reservoir is liquid dominated (more than three parts of brine and one part of steam) with temperatures ranging from 250°C to 275°C. Geothermal fluids apparently consist of mixtures with different proportions of two primary fluids [2].

There are only two condensing, single flash power units in Las Tres Virgenes of 5 MW each that were installed in 2001. These plants produced 47GWh in 2017, at an average capacity factor of 53.6%. There were only three production wells in operation, producing 0.51 million tons of steam during the year at an average rate of 58.4 t/h, or around 19.5 t/h per well. The steam was accompanied by 1.66 million tons of brine at annual rate of 189.5 t/h, or 63.2 t/h per well. All this volume of brine was injected into the reservoir by two injection wells average capacity factor of 62.3%.

To take advantage of the huge production of hot brine in this field, CFE has planned to install a 2MW binary cycle power unit.

6. Domo San Pedro geothermal field

This field is also located inside the MVB, in its westernmost portion, at the southern Nayarit State. Regionally, the zone is located at the confluence of three physiographic provinces: the Sierra Madre del Sur, the Sierra Madre Occidental (SMO) and the mentioned MVB, which covers all the zone and includes the San Pedro Domes.

There are structural systems of NW-SE, N-S and NE-SW trends. The zone is at the NW portion of the Tepic-Zacoalco Graben of NW-SE orientation, which is currently under a rifting process, and therefore subjected to tensional stress.

By the Pliocene (5 Ma to the present) the volcanism typical of the MVB started in the zone, occurring into an extensional tectonic framework (continental rifting). Part of this volcanic activity was the emplacement of the San Pedro Domes, which are a couple of massive dacitic domes of Quaternary age whose magma chamber seem to be the heat source of the geothermal system. These domes are 0.85-0.79 Ma old, aligned in a general NW-SE trend, and are associated to pyroclastic, pumice and ash flows. They are also probably related to the Las Cuevas hot springs, which are the hottest in the zone (34°C). The volcanic activity in this area finished with the emission of another more recent domes, like the La Atarjea andesitic dome (0.53 Ma), and Los Lobos (0.18 Ma) and Los Ocotes (0.101 Ma) rhyolitic domes.

There are several hot springs and hot-water wells in the zone and its surroundings, whose superficial temperatures are between 18°C and 42°C. All of the samples are of sodium bicarbonate type, excepting a hot spring at 24°C of temperature and sodium chloride composition with boron contents of 1.2 ppm.

At the subsurface, the geothermal fluids are found in Tertiary andesitic rocks and Cretaceous granitic rocks at temperatures around 280°C. The company Grupo Dragón holds currently the exploitation
concession of this field. During 2017, the company operated four production and three injection wells with depths over 2500 meters, producing 1.3 million tons of steam and 1.1 tons of brine.

In 2015 the first two 5MW backpressure, wellhead power plants were installed and put in operation, and the first condensing, single flash power plant of 25.5 MW was commissioned in 2016. Thus, the installed capacity is 35.5 MW. During 2017 only the flash plant was in operation, being the other two as backup, and produced 153.3 GWh. The power produced was consumed by partners of the Grupo Dragón, using a self-supply permit issued by the Mexican Energy Regulatory Commission (CRE: Comisión Regulatoria de Energía) under the former energy regulation.

7. National geothermal potential

As of the beginning of 2018, the total geothermal-electric installed capacity of Mexico was 956 MW in five geothermal fields, which represented around 1.2% of the national electric installed capacity. These fields produced 5,937 GWh of electric energy during 2017, representing ~1.7% of the total production in the country (Table 1).

| Field             | Capacity (MW) | Generation (GWh) | Initial operation | Owner & operator |
|-------------------|---------------|------------------|-------------------|------------------|
|                   | Installed     | Running          |                   |                  |
| Cerro Prieto      | 570.0         | 570.0            | 3,554             | 1973             |
| Los Azufres       | 246.6         | 223.6            | 1,767             | 1982             |
| Los Humeros       | 93.9          | 93.9             | 416               | 1990             |
| Las TresVirgenes  | 10.0          | 10.0             | 47                | 2001             |
| Domo San Pedro    | 35.5          | 25.5             | 153               | 2015             |
| Total             | 956.0         | 923.0            | 5,937             |                  |

Table 1. Geothermal capacity and production in Mexico in 2017

All of those geothermal fields are of hydrothermal, conventional type. According to its national installed capacity, Mexico is currently in the sixth place worldwide, behind the United States (3,789 MW), Philippines (1,870 MW), Indonesia (1,808 MW), Turkey (1,053 MW) and New Zealand (1,005), but it is closely followed by Italy (941 MW).

The unexploited geothermal potential of the country has been estimated using the concept of geothermal reserves and resources defined by the Australian Geothermal Code [1]. Geothermal Reserves can be proven or probable, being the first the economically recoverable part of a Measured Geothermal Resource. Probable Reserves are “the economically recoverable part of an Indicated or in some circumstances, a Measured Geothermal Resource”, which differ from “Proven Reserves because of greater uncertainty, usually in terms of factors that impact the recoverability of thermal energy…” [1].

Geothermal Resources are geothermal plays with “…reasonable prospects for eventual economic extraction, which are known, estimated or interpreted from specific geological evidence and knowledge. Geothermal Resources are sub-divided, in order of increasing geological confidence, into Inferred, Indicated and Measured categories.” Geothermal Play is just an informal qualitative term denoting an accumulation of heat contained in rocks and/or fluids within the Earth’s crust [1].

Based on those general definitions, the geothermal potential of Mexico taking into account only resources of hydrothermal type, can be estimated as presented in Table 2. The 19 zones (14 with probable temperature higher than 180°C and five with 150-180°C) are those reported by Gutiérrez Negrín [10], while the other zones are not yet individualized [14].

| Field / Zone | Geothermal Reserves (MW) | Geothermal Resources (MW) |
|--------------|--------------------------|---------------------------|
Proven | Probable | Measured | Indicated | Inferred
--- | --- | --- | --- | ---
Cerro Prieto | 26 | 52 | 40 | 0 | 0
Los Azufres | 11.6 | 60 | 25 | 25 | 0
Los Humeros | 0 | 26 | 25 | 25 | 0
Las Tres Vírgenes | 2 | 2 | 0 | 0 | 0
Domo San Pedro | 0 | 26 | 25 | 25 | 0
Cerritos Colorados | 26 | 52 | 25 | 25 | 0
Volcán Ceboruco | 0 | 0 | 25 | 25 | 0
14 zones (>180°C) | 0 | 0 | 0 | 600 | 0
5 zones (150-180°C) | 0 | 0 | 0 | 55 | 0
Other zones (>180°C) | 0 | 0 | 0 | 50 | 1044
Other zones (150-180°C) | 0 | 0 | 0 | 0 | 166
**Total** | **66.6** | **218** | **165** | **830** | **1235**

Table 2. Estimated additional geothermal potential in Mexico from hydrothermal geothermal resources (some data taken from [10]).

Regarding the geothermal potential from hot dry rocks, developable with EGS technologies, the proper way to estimate it, is the procedure outlined by Beardsmore et al. [4] in their Protocol that has been reviewed and endorsed by the International Geothermal Association (IGA). One of the projects being developed by the Mexican Center for Innovation in Geothermal Energy (CeMIE-Geo) is following that protocol, and must be finished this year.

However, a preliminary idea about that EGS-potential was presented some years ago [10]. This estimate is based on an old publication of the U.S. Electric Power Research Institute (EPRI), who developed a global estimate of the heat stored down to 3 km depth, country by country. Based on the EPRI assumptions, the stored heat in Mexico for EGS-type resources at temperatures >150°C and down to 3 km depth would be ~56,960 EJ. Making the proper conversions, that heat represents an electric output that could be produced by 5,250 MW of installed capacity. This geothermal potential from EGS-type resources can be considered just as a minor part of the total available thermal energy in Mexico, but offer a general idea on this potential.

The hydrothermal and hot dry rock geothermal potential of Mexico is presented in Fig. 2.

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Fig. 1. Geothermal fields and tectonic framework in Mexico.

Fig. 2. Installed capacity, geothermal reserves and resources and EGS minimum potential estimated in Mexico.