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Situation of Geothermal Energy in Mexico: Country Update

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ABSTRACT

The current situation of geothermal energy in Mexico has not changed much since the last country update report presented in the WGC2020+1. The geothermal-electric installed capacity as of December 2021, was 1001.9 MWe, with the running capacity at 958.9 MWe operating in the five geothermal fields of Cerro Prieto, B.C., Los Azufres, Mich., Los Humeros, Pue., Las Tres Vírgenes, B.C.S, and Domo San Pedro, Nay. There was one additional power plant commissioned in 2019 and some were decommissioned, but the geothermal operating capacity presents only a modest increase of 11.1 MWe over the 947.8 MWe reported three years ago. Cerro Prieto continues to be the largest field in Mexico and the second worldwide, with 570 MWe in operation, and the Domo de San Pedro field is still the only operating field privately owned and handled in the country. One additional field, located at the central state of Guanajuato, has been under exploration by another private company, including exploration drilling, with promising results so far, and the exploitation concession granted by the energy ministry. The other known geothermal field, Cerritos Colorados in the State of Jalisco, with a probable reserve of 75 MWe and granted to the Comisión Federal de Electricidad, remains in stand-by. Geothermal heating and cooling (or direct) uses are sub-utilized in Mexico, with an estimated 153.7 MW of thermal power operating in hot pools and spas, one agricultural application and some geothermal heat pumps installed in 2018 as part of small demonstration projects. Geothermal roadmaps published in 2017-2018 expect 1670 MWe of geothermal power by 2030 from conventional, hydrothermal resources, and 3800 MWt of heating and cooling applications from geothermal energy by the same year, but currently these expectations look overestimated.

INTRODUCTION

Compared to 2018, according to data reported in the WGC2020+1, the situation of geothermal energy in Mexico is practically the same, both for electric power and for heating and cooling (H&C, or direct uses) developments. Thus, three years ago there were 1005.8 and 947.8 MWe for installed and operating capacity in the country, respectively (Gutiérrez-Negrín *et al.*, 2020), and now there are 1001.9 and 958.9 MWe, respectively (Table 1). In fact, today there is a new power plant that was commissioned in 2019 in the Los Azufres field, but some backpressure units were decommissioned. The total capacity of geothermal H&C in 2018 was reported to be 156.1 MWt (Gutiérrez Negrín *et al.*, 2020), and now it is estimated at 153.7 MWt. Being the status the same, the differences are due to adjustments in the nameplate capacity, since no new H&C projects have been commissioned in the last three years.

Table 1. Geothermal installed capacity and electric generation in Mexico in 2021 (prepared with data from CFE, 2022, and Geodesa, 2022, personal communications).

Geothermal field	Capacity (MWe)		Electric generation in 2021 (GWh)	
	Installed	Running	Gross	Net
Cerro Prieto, BC	570.0	570.0	2510.6	2363.4
Los Azufres, Mich.	275.1	257.1	1370.6	1300.1
Los Humeros, Pue.	120.7	95.7	479.7	447.6
Las Tres Vírgenes, BCS	10.0	10.0	43.1	36.8
Domo de San Pedro, Nay.	26.1	26.1	107.6	99.4
Total	**1001.9**	**958.9**	**4511.6**	**4247.3**

The gross electric energy produced in the fields, however, shows a relevant decrease of 16% in 2021 compared to 2018, with 863.5 GWh less, because of two important power units were out of operation in 2021: unit 1 of Cerro Prieto III, with 110 MWe of nameplate capacity, and unit 17 of Los Azufres, with 53.4 MWe of nameplate capacity (CFE, 2022, personal communication). Thus, the total gross electricity generation in the country was 4511.6 GWh, with 4247.3 GWh effectively delivered to the grid, after discounting electricity consumed in the auxiliary equipment of the units (Table 1).

It is convenient to mention that geothermal development for power in Mexico has been carried out by the federal government, through the former geothermal energy commission (Comisión de Energía Geotérmica, CEG) since the fifties, when the CEG installed the first power unit of 3.5 MWe in the geothermal field of Pathé, and through the federal utility Comisión Federal de Electricidad (CFE) since the sixties. That’s why four of the five geothermal fields currently in operation in the country, and their respective power units, are owned and handled by the CFE, who holds the exploitation concessions awarded by the energy department, and only Domo de San Pedro field is owned by a private company (Geodesa, SA de CV, a subsidiary of the Mexican energy company Grupo Dragón, SA de CV). In fact, CFE also holds the exploitation concession of another geothermal field, named Cerritos Colorados in the western state of Jalisco, where several wells indicate a probable reserve of 75 MWe. Activities in this field were stopped in the eighties due to environmental and societal issues, but it’s expected to be continued eventually (Fig. 1).

GEOTHERMAL FIELDS IN OPERATION

As mentioned before, there are currently five geothermal fields in operation in Mexico, whose location is presented in Figure 1. Most of them, including the Cerritos Colorados field, are located inside the Mexican Volcanic Belt (red dashed line in the insert of Fig. 1), which is a roughly E-W oriented physiographic province in central Mexico composed of volcanoes and volcanic products of Plio-Quaternary age, including some of the most active stratovolcanoes in the country.

Cerro Prieto is the largest and oldest field in operation in Mexico. This field is located in north-western Mexico (Fig. 1), near to the international border with USA, at ~8 meters above the sea level (masl), and within a pull-apart basin formed between two strike-slip faults that form part of the southern extension of the San Andreas system. The tectonic regime is featured by transtensional stresses, and the heat source is supposed to be a basic magmatic intrusion that raised due to the thinning of the continental crust in the basin. The geothermal reservoir is of hydrothermal, two-phase, liquid-dominant type, with fluids contained in Tertiary sandstones interbedded into shales, with an average thickness of 2400 meters (Gutiérrez-Negrín, 2015), even though the deepest well is 4032 m. Wells produce a mixture of fluids at surface conditions with around 64% liquid and 36% steam. Liquid phase presents the typical sodium-chloride composition and neutral to alkaline pH. It is a diluted brine with an average of 27,400 mg/kg of total dissolved solids (TDS), varying from 20,000 mg/kg in the sector CP-I to 33,000 mg/kg in the area of CP-II. The steam fraction contains an average of 1.4% in weight of non-condensable gases, ranging from 1% in CP-I to 1.8% in CP-III, being CO_2 the main component (89% of total gases) (Portugal *et al.*, 2005).

Units 1 and 2 of the sector Cerro Prieto I (CP-I), of 37.5 MWe in capacity each, were the first power plants commissioned in the field in April 1973. These plants, altogether with units 3 and 4 of the same capacity, were de-commissioned in 2011 and 2012, and finally dismantled and removed in 2016. As a result, the installed capacity in this field decreased in 150 MWe, and reduced to the current 570 MWe. It is composed of four condensing, flash units of 110 MWe each, located in the sectors known as CP-II and CP-III, one condensing, low-pressure unit of 30 MWe in CP-I, and four condensing flash units of 25 MWe each in CP-IV.

During 2021 there were 129 production and 28 injection wells in operation in all the field (CFE, 2022, personal communication). There are no data available for 2021, but in 2020 the wells produced around 24 million tons of steam, at an annual average production of 21.7 m^3/h per well. As reported in Table 1, in 2021 the gross electricity generation in Cerro Prieto was 2510.6 GWh, and the net generation was 2363.4 GWh (CFE, 2022, personal communication). Unit 1 of CP-III, with 110 MWe in capacity, was out of operation during 2021, but unit 3 of CP-IV, with 25 MWe of net capacity, generated 213.9 GWh along the year (CFE, 2022, personal communication). It means a capacity factor of 97.7% that is the highest of the field (and the country), and is also a remarkable achievement for a plant with 21 years in operation. The unit 5 of CP-I, which is the only one working with low-pressure steam, produced 231 GWh, reaching a good capacity factor of 88.1%, despite its 39 years of operation.

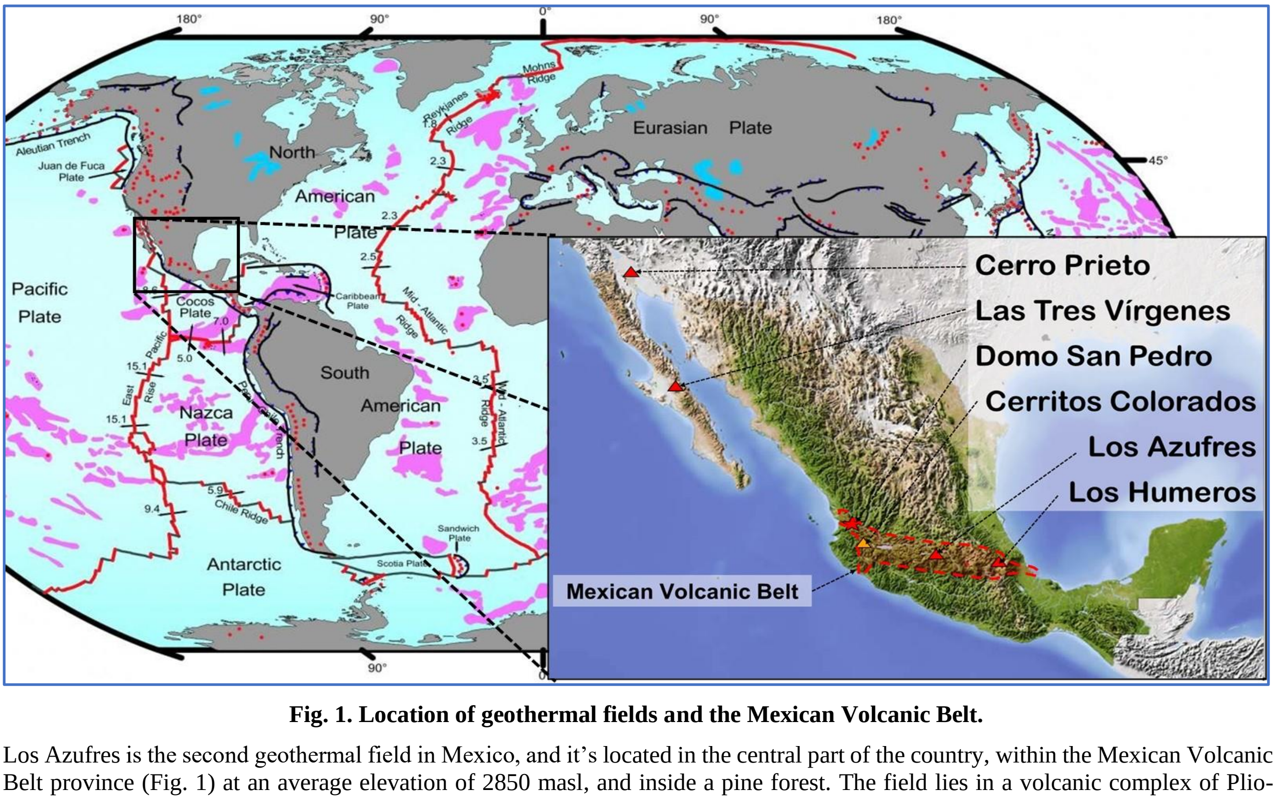

Fig. 1. Location of geothermal fields and the Mexican Volcanic Belt.

Los Azufres is the second geothermal field in Mexico, and it's located in the central part of the country, within the Mexican Volcanic Belt province (Fig. 1) at an average elevation of 2850 masl, and inside a pine forest. The field lies in a volcanic complex of Plio-Pleistocene age, that includes andesites, basalts, dacites and rhyolites produced by three main volcanic cycles. The geothermal reservoir is of hydrothermal, two-phase, vapor-dominant type, whose fluids are contained in the middle and lower portions of a 2700 m thick package of interstratified lava flows and pyroclastics of andesitic to basaltic composition, with ages between 18 and 1 Ma. This package is overlain by more recent rhyolites, which include obsidian flows and perlite structures in some sites. The magma chamber feeding the San Andrés volcano, the highest peak in the area, is deemed as the heat source of the geothermal system (Gutérrez-Negrín, 2015). The deepest well in the field is 3544 m deep.

Geothermal fluids in Los Azufres are sodium chloride-rich waters with high CO_2 contents, and pH around 7.5. Main non-condensable gases in the separated steam are CO_2 (94% in volume), with H_2S (2.5% in volume) and minor concentrations of H_2, CH_4, N_2 and NH_3

(combined 3.5% in volume). Production wells present a decrease in the temperature of the fluids and an increase in the steam fraction of the reservoir (Barragán-Reyes *et al.*, 2012), and currently the wells produce a mixture of fluids with around 71% of steam and 29% of liquid at surface conditions.

The first power units in Los Azufres were commissioned in 1982 and the latest unit (Unit 18) was commissioned on late 2019. The current installed capacity is 275.1 MWe, composed of seven condensing, flash units (one of 53.4, one of 50, three of 26.6, one of 26.8 and one of 27.2 MWe), seven back-pressure units each of 5 MWe, and two binary cycle units of 1.45 MWe each. Three out of the seven back-pressure and the two binary cycle units are out of operation, and therefore the running capacity is 257.2 MWe (Table 1). In 2021 there were 50 production wells and 6 injection wells in operation in this field (CFE, 2022, personal communication). In 2020 the wells produced around 16.4 million tons of steam, at an annual average production of 37.5 m^3/h per well. In 2021 the gross electricity generation in Los Azufres was 1370.6 GWh, and the generation delivered to the grid was 1300.1 GWh, as reported in Table 1. The unit 18, which was commissioned in 2019 and is the most recent unit in the field with 27.2 MWe in capacity, produced 219 GWh during 2021, operating at the best capacity factor in this field (91.9%) (CFE, 2022, personal communication). The unit 17, of 53.4 MWe in capacity, was out of operation most part of the year.

Fig. 2. View of a back-pressure unit in Los Humeros (Courtesy of CFE).

Los Humeros geothermal field is the third largest one in Mexico, and it is also located in the central part of the country, at the eastern portion of the Mexican Volcanic Belt province (Fig. 1) at an average altitude of 2800 masl. The field is inside the ~70 ka old Los Potreros volcanic caldera, with 5-8 km in diameter, which in turn is nested within the older (~165 ka) and larger (18-20 km in diameter) Los Humeros caldera (Gutiérrez-Negrín *et al.*, 2020). The more recent volcanic activity, not related to the caldera process, took place between 10-3 ka ago, composed of two extreme volcanic sequences: one of basic composition (SiO_2<55%) between 7-4 ka, and other acidic (SiO_2>65%) with ages of 10-3 ka. The current heat source seems to be a differentiated magma chamber, stratified into several smaller chambers located at different depths that probably share the same feeding source at more depth (Carrasco-Núñez *et al.*, 2020).

Los Humeros geothermal reservoir is of hydrothermal, two-phase, vapor-dominant type, with fluids hosted in Pliocenic hornblende andesites lying over a complex basement composed of rocks of sedimentary (limestones), metamorphic (marble, skarn, hornfels), and intrusive (granite, and aplitic and basic dikes) origin. Fluids produced in Los Humeros are a mixing with more than 85% of high-enthalpy steam and 15% liquid of sodium-chloride to bicarbonate-sulfated type with high content of boron, ammonia and arsenic with partial equilibrium at 280-310°C (Barragán *et al.*, 2008).

The first power plants at Los Humeros were two backpressure units of 5 MWe in capacity each, commissioned in 1991 (see Fig. 2). The present installed capacity is 120.7 MWe (Table 1), which is the sum of three condensing, flash units, two of 26.8 MWe each, and one of 27.1 MWe, and eight back-pressure units, of 5 MWe each. The running capacity is 95.7 MWe, due to five out of the back-pressure units are out of operation, even though all are still placed in the field and technically ready to operate again. In 2021 there were 29 production wells and three injection wells in operation in the field, the deepest of which is 3280 m deep. Those wells produced around 5.8 million tons of steam in 2020 (no data for 2021) at an annual average of 22.7 m^3/h per well. Total electricity generation in 2021 was 479.7 GWh gross, and the 447.6 GWh net, as reported in Table 1 (CFE, 2022, personal communication). The best capacity factor in the field during 2021 was 78.4%, corresponding to unit 10, of 26.8 MWe in capacity, which generated 184 GWh.

Las Tres Vírgenes geothermal field is located at the middle of the Baja peninsula in the state of Baja California Sur (Fig. 1), and is the field with the lowest capacity of only 10 MWe (Table 1). The field lies in an extensional tectonic regime related to the opening of the Gulf of California producing a structural system that includes right strike-slip faults of low and high angle and some left strike-slip lateral faults. Las Tres Vírgenes is a Quaternary volcanic complex composed of three volcanoes aligned N-S, developed at the western limit of a regional deformation zone. The geothermal reservoir is of hydrothermal, two-phase, liquid dominant type, with more than 75% of liquid phase and 25% of steam at surface conditions. Fluids are contained in the oldest lithological unit, which is a Late Cretaceous (99.1 ± 0.8 Ma) granodioritic intrusion, part of the California Batholith (Macías and Jiménez, 2012), whose top is found at depths of 900 to 1000 m in the wells. The heat source of the system is related to the magma chamber of the La Virgen volcano, which is the youngest and most southern of the volcanic complex.

Two condensing, flash type power units with a capacity of 5 MWe each, have been in operation in the field since 2001. Gross electricity generation in 2021 was 43.1 GWh in 2021, being 36.8 GWh the electricity delivered to the grid as reported in Table 1 (CFE, 2022, personal communication). Unit 2 generated 23 GWh along the year, reaching a capacity factor of only 52.5%. However, the two power units of Las Tres Vírgenes provided 24.5% of the electrical demand of the Mulegé isolated system (SIM: Sistema Interconectado Mulegé) in 2021, which is a small electric network independent of the national grid: the system demand was 150 GWh in 2021 (Sener, 2022), and Las Tres Vírgenes contributed 36.8 GWh. Only three production and one injection wells were in operation during 2021, being 2505 m the depth of the deepest well. Around 0.6 million tons of steam were produced in 2020, at an annual average production of 22 m^3/h per well.

The Domo San Pedro geothermal field is located in the western portion of the Mexican Volcanic Belt in central Mexico (Fig. 1), and it's the only field not operated by the CFE but by a private company. The field is related to a couple of massive dacitic domes of Quaternary age (~0.1 million years) whose magma chamber appears to be the heat source of the geothermal system, which is of hydrothermal, two-phase, liquid-dominant type. Besides the mentioned dacitic domes, there are cones, pyroclastic rocks and other volcanic structures of Plio-Quaternary age, all emplaced in the northwestern edge of the Tepic Graben. This graben is deemed as a regional structure of pre-rifting type, and therefore the field is in an extensional tectonic regime. The geothermal fluids are hosted by Tertiary andesitic and Cretaceous granitic rocks (Gutiérrez-Negrín, 2015).

The field has an installed capacity of 26.1 MWe as presented in Table 1, with a single condensing flash power plant of that nameplate capacity, commissioned in 2016. Originally two backpressure units, each of 5 MWe, were installed in this field in 2015, to test the reservoir, but both were decommissioned since April 2016, when the new unit started to operate, and now have been dismantled. The gross electric output of the field in 2021 was 107.6 GWh, and the net generation was 99.4 GWh as presented in Table 1 (Geodesa, 2022, personal communication), all of which is sent to the grid to supply the electric demand of other companies of the same corporative group scattered in the country. Geodesa holds the exploitation concession of this field, as well as the self-supply electric generation permit.

Main data on geothermal-electric generation in Mexico in 2021, compared with similar data in the last years are presented in Table 2; data for previous years are taken from Gutiérrez-Negrín *et al.* (2015, 2020). According to that, and considering the total running capacity in the country and the gross electricity output in 2021, the national average capacity factor is 53.7%, which is the lowest in the last 26 years, which is the same situation of the combined steam production. The annual average steam specific consumption is the highest, but comparable to that for 2003 (Table 2). Thus, data for 2021 are atypical and difficult to contrast with previous years, which seems to be a consequence of the economic downturn due to the Covid 19 pandemic, at least partially.

Table 2. Data on geothermal-electric production in Mexico in the last years.

Data	1995	1999	2003	2008	2013	2018	2021
Geothermal fields in operation (number)	3	3	4	4	4	5	5
Installed capacity (MWe)	753	755	953	958	1107	1006	1002
Running capacity (MWe)	753	755	953	958	839	948	959
Gross electricity output (GWh)	5682	5619	6282	7047	6070	5375	4512
Annual average capacity factor (%)	86.1	85.9	74.5	84.0	82.5	66.6	53.7
Steam produced (million m^3)*	55.0	56.3	67.5	65.9	55.7	50.9	48.7
Annual average steam specific consumption (m^3/MWh)	9.7	10.0	10.7	9.35	9.27	8.47	10.8
Average production wells (number)	173	164	197	229	223	225	209
Average steam produced per well (m^3/h)*	36.3	39.2	39.1	32.8	28.5	25.8	26.1

**Data for 2021 corresponds to 2020, and corresponding data for 2018 and 2020 from Domo San Pedro field are estimated.*

GEOTHERMAL ENERGY IN THE ELECTRICITY PORTFOLIO

In 2021, geothermal installed capacity was 1.16% of the total electric installed capacity in Mexico, which was 86,153 MWe, while the geothermal-electric generation delivered to the grid represented 1.31% of the total generation that was 323,527 GWh. That means that geothermal energy is a tiny component of the national electricity mix, even though it is relevant in isolated local grids, like the Baja California electric grid (SIBC: Sistema Interconectado de Baja California), where the Cerro Prieto power plants deliver their generation. Excluding self-supplying, co-generation and some export-imports from California, USA, the Baja California electric system is composed of 1526 MWe of combined cycle plants, 459 MWe of turbo-gas plants, 320 MWe of conventional thermal-electric plants, 570 MWe of geothermal plants, and 5 MWe of PV solar plants (Sener, 2022). Thus, the Cerro Prieto plants comprise 19.8% of the 2880 MWe of this system. Regarding generation, electricity produced in this system in 2021 was 11,869.1 GWh (SIE, 2022), out of which 2363.4 GWh were delivered by the geothermal units of Cerro Prieto (Table 1), representing almost the same share (19.9%) of the installed capacity. This means that a fifth of the electricity used in this isolated system that includes large urban centers like Tijuana and Mexicali is produced by geothermal energy –excluding again self-supplying, co-generation and some imports from California. Another locally relevant contribution of geothermal in Mexico, is the Las Tres Vírgenes field, which contributed 24.5% of the electricity supply in the Mulegé isolated system, as mentioned before.

The electricity portfolio in Mexico by December 2021 is presented in Fig. 3. Almost two thirds of the installed capacity of 86,153 MWe was composed of power plants based on fossil fuels, totaling 55,341 MWe. Most of the plants consuming fossil fuels are of combined cycle type with 33,640 MWe, and then are conventional thermal plants (including fluidized bed combustion) with 11,793 MWe, coal-electric plants with 5463 MWe, turbo-gas plants with 3744 MWe, and internal-combustion plants with 701 MWe (Sener, 2022).

Hydroelectric power plants are the more abundant technology of renewable energy, with a combined capacity of 12,614 MWe, equivalent to 14.6% of the national total. Then are wind and solar plants, with 6978 and 5955 MWe, equivalent to 8.1% and 6.9%, respectively, of the total; all the wind plants are onshore and all the solar plants are of photovoltaic type. Then come geothermal power plants with 959 MWe of running capacity (Table 1), and finally bioenergy plants that include biomass, sugar cane bagasse, and biogas, with a combined capacity of 378 MWe or 0.4% of the total. Besides renewable energy power plants, there are a couple of nuclear plants with 1608 MWe in capacity (1.9% of the total), and several scattered plants of efficient co-generation with 2304 MWe (2.7%) (Sener, 2022), that use residual steam of agro-industrial processes to generate electric energy in a similar way to CHP (Combined Heat and Power) plants. Nuclear and efficient-cogeneration are considered as clean energies, since they don't emit GHG to the atmosphere, even though they are not renewable.

Thus, in general terms the electricity portfolio of Mexico is composed of 64.2% of fossil fuels plants and 35.8% of clean energy power plants, as presented in the left graph of Fig. 3.

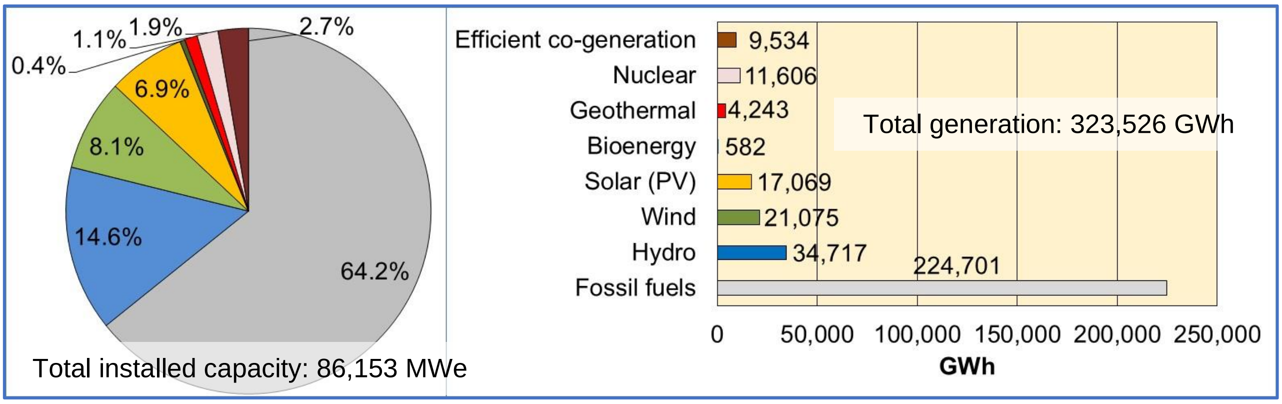

Fig. 3. Mexico's electricity capacity share (left) and generation in GWh (right) in 2021 by energy source (prepared with data from Sener, 2022).

Geothermal fields in operation, on the other side, delivered 4243 GWh to the electric grid during 2021, as presented in Table 1, which contributed with 1.3% to the national generation that was 323,526 GWh (Sener, 2022). Power plants fueled by fossil fuels, mainly natural gas, coal and oil-fuel, generated 224,701 GWh (Fig. 3), representing 69.5% of the total, with 182,898 GWh produced by combined-cycle plants, 22,196 GWh by conventional thermal plants, 9175 GWh by turbo-gas plants, 8704 by coal-electric plants and 1728 GWh generated by internal-combustion plants (Sener, 2022). Generation of power plants using clean energies is presented in GWh in the right graph of Figure 2, with hydro plants contributing 10.7% of the total, wind 6.5%, solar 5.3%, nuclear 3.6%, efficient co-generation 2.9%, bioenergy 0.2%, and geothermal 1.3% as mentioned.

According to those data, net electricity generated by clean energies in the country in 2021 was 98,825 GWh, equivalent to 30.5% of the total. To contextualize that figure, it is important to mention that Mexico is a signatory country of the Paris Accord, which was incorporated as part of its national legislation when it was published in the official federal gazette (DOF: Diario Oficial de la Federación) on November 2016. In consequence, the country has defined some national partial goals in order to comply the Paris Accord objectives, which were included in two federal acts: LTE (energetic transition law) and LGCC (general law of climate change). Being the energy sector one of the main contributors to atmospheric GHG, one of the main partial goals for electricity is that 30% of the national electricity generation be produced by clean energies in 2021 (set in LTE) and 35% in 2024 (set in LTE and LGCC). Therefore, the goal for 2021 was accomplished.

On May 2023 the Sener released the most recent version of the electric industry outlook annual report, with data for 2022. Geothermal net electricity generation in the five fields in operation was 4413 GWh, around 4% more than in 2021 (see Table 1), and the whole net electricity generation in the country was 340,713 GWh, and so the share or geothermal was approximate the same than in 2021 (1.3%). And the clean energy share of the total was 31.2%, a little bit below the national goal for this year that was 32% (Sener, 2023).

A specific aspect of the electric sector in Mexico is that CFE still keeps and operates 51.3% of the installed capacity in the country (44,181 MWe), but generated only 39.6% of the electric energy in 2021 (128,175 GWh), because many of its plants weren't dispatched by the system operator (CENACE) due to legal restrictions. The remaining capacity is operated by private companies under several legal figures: self-supply, independent producers, private generators, small-production, and co-generation (47.6%), and by the oil national company PEMEX (1.1%). Most of the electric generation in 2021 was provided by private companies (59.7%), with the Pemex plants generating 0.7% for its own uses (See Fig. 4).

Figure 4 also presents the relation between fossil-fueled and clean energy power plants of CFE, PEMEX and private generators, regarding their respective capacity in MWh (left graph) and, more importantly, considering the effective generation in 2021 (right graph). It's clear that 38% of the electricity generated by the CFE plants was produced from clean sources, despite the lower dispatch, while only 25.5% of the electric energy produced by privately operated power plants (PIE + Other privates) was generated using clean sources. That debunks the extended, but wrong, belief that in Mexico CFE uses dirty power plants and private companies use clean sources to generate electricity.

GEOTHERMAL HEATING & COOLING

There are no changes between the figures presented in the previous report (Gutiérrez-Negrín *et al.*, 2020), but some specific data were revised and adjusted for the current report. As it has been highlighted before, the potential for geothermal H&C uses in Mexico is huge. Several years ago, a group of researchers of the former electrical research institute (IIE, which is now INEEL), compiled and analyzed data collected by CFE about hot springs and other superficial manifestations in the country. Their compilation resulted at

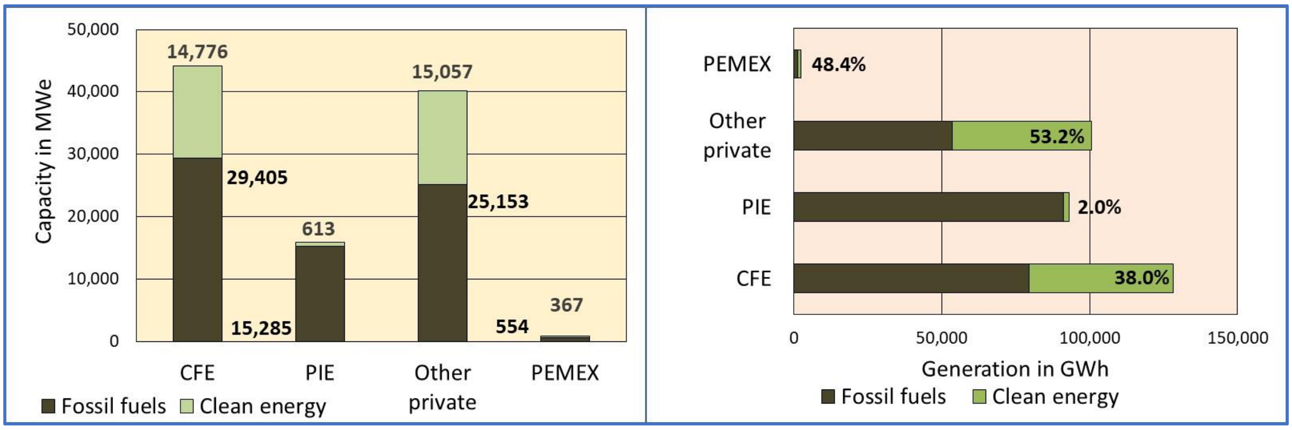

Fig. 4. Share of fossil and clean sources of electricity capacity (left) and generation (right) in Mexico in 2021, by type of operator (prepared with data from Sener, 2022).

more than 1600 individual thermal manifestations scattered in the national territory, and particularly in the central part corresponding to the MVB province. They grouped those manifestations into more than 900 geothermal systems located in 26 of the 32 current states of the country, all of which were later sub-grouped into four superficial temperature categories: <62°C, 62-100°C, 100-149°C and >149°C. They found also that around 5% of those systems present <62°C of temperature, around a half in the rank between 62 and 100°C, 40% between 100 and 149°C, and the remaining 5% with the highest temperature rank (>149°C). One of the main conclusions of their analyses was that if only 0.1% of the energy of such geothermal resources could be recovered, that would represent more than 40,000 MWt of installed capacity for H&C applications (Iglesias *et al.*, 2015). This can be deemed as the geothermal H&C potential in Mexico.

Besides the general H&C geothermal potential in the country, Sener published in 2018 a geothermal roadmap for direct uses that was prepared with the collaboration of several researchers, private developers, experts and CFE's technical staff. This roadmap expects Mexico will have 3800 MWt in operation by 2030, out of which 2400 MWt would be installations using the separated brine in the geothermal fields in operation expected by that year (applications in cascade), around 1000 MWt in applications installed outside the geothermal fields, and 400 MWt in geothermal heat pumps (GHP). Those goals are probably over-estimated, since imply a 25-fold growth in the next seven years, but are less than a tenth of the total potential.

In the country report of WGC2020+1 it was informed that the Mexican Center for Innovation in Geothermal Energy (CeMIE-Geo) was a national R+D+I project funded by the federal government. In the period 2014-2019, CeMIE-Geo carried out seven specific projects related to geothermal H&C, which included installing demonstration ground-source heat pumps (GHP), greenhouses air-conditioned by GHP, a pilot poly-generation plant with cascade-use, and design and construction of a food dehydrator based on geothermal heat (García-Gutiérrez *et al.*, 2019).

The main H&C use in Mexico is still composed of bathing and swimming facilities with recreational and/or therapeutic purposes, which are reported in third row of Table 3, where are also reported data for other applications.

Table 3. Summary of heating and cooling projects in Mexico.

Geothermal application	Total installed capacity (MWt)	Total energy (TJ/year)		Number of installations	Notes
		Produced	*Used*		
Agriculture and food processing	0.562	16.36	16.360	2	*Several different installations in each one of 18 reported states
Industrial process heat	0	0	0	0	
Health, recreation and tourism	152.922	4099.55	4099.55	Unknown*	
Heat and cooling for buildings	0.213	3.63	3.63	4	
Other uses	0	0	0	0	
Total	**153.398**	**4119.53**	**4119.53**		

Note: Excluding GHP, in all the remaining cases the following formulas were used for: (1) Capacity = Max. flow rate (kg/s) [inlet temp. (°C) - outlet temp. (°C)] x 0.004184; (2) Energy = Energy use (TJ/year) = Ave. flow rate (kg/s) x [inlet temp. (°C) - outlet temp. (°C)] x 0.1319. Installed capacity of GHP is included in first and fourth rows, with no data about its annual energy produced and used.

Agriculture and food processing applications include almost only the project Geodry-Domo San Pedro, which is a commercial fruit-dehydrator using part of the residual brine separated at the Domo San Pedro, State of Nayarit, geothermal field. The project is operated by the private company Deshidratador Geotérmico de Alimentos de Nayarit, SAPI de CV, a small spin-off company derived from Project 27 of CeMIE-Geo. This company designed and built a fruit dehydrator of 0.527 MWt in capacity, which uses around 6 kg/s of residual brine at 166°C of inlet temperature and 145°C of outlet temperature (Aviña, 2022, personal communication), and produce 16.2 TJ/year of energy. Dehydrator can process daily up to one ton of pulp (mainly mango and pineapple, but also cucumber and jackfruit has been processed) and produce around 200 kg of dry product in a dehydration process that takes 15-17 hours depending of the fruit. The project started commercial operations in November 2018, and currently employs 15 local and mostly female workers, including the supervisor (Pérez-González *et al.*, 2020). The remaining 0.035 MWt of the installed capacity reported in the first row of Table 3, is the capacity of a small GHP demonstration project to control the temperature in a greenhouse located in the Polytechnical University of Baja California in Mexicali, which was also one of the original CeMIE-Geo projects. There are four GHP units with no data about energy production in 2021, but it was around 0.136 TJ/year in previous years.

Data reported in the third row of Table 3 correspond to several baths, ponds, pools and spas in 18 of the 32 states of the country, using hot springs and a small number of shallow wells producing hot water, with temperatures ranging from 32°C up to 73°C. All of these installations were developed and are operated by private investors, but a minor part of them is operated by state or municipal governments, through tourism offices or associated to local owners. Thus, the estimated capacity of this application (152.9 MWt) represents 99.7% of the total H&C capacity in Mexico, but most of the data is probably outdated.

Data presented in the fourth row of Table 3 is from the only space heating using geothermal fluids that operates in the country, and from three small GHP demonstration projects. The first is located in the Los Azufres geothermal field, State of Michoacán, and is operated by the CFE to heat the administrative offices and lodging facilities in that field. It was originally designed and built in 1997 and was expanded between 2008 and 2014, and provides heat to the offices, laboratories, lodging cabins and other facilities of the CFE in the field, besides all of the hot water supply. The system uses 1.25 kg/s of separated brine before reinjection, to heat the ground water used in the heating system through a heat exchanger (Ávila Apolinar *et al.*, 2017), with water coming at 110°C and leaving the system at 88°C. The GHP projects are ground-coupled demonstration installations, located in the Los Humeros village, State of Puebla, with two GHP units of 0.021 MWt total to heat a small school and health clinic; in the Polytechnical University of Baja California with three GHP units of 0.042 MWt in total to cool laboratory facilities; and two units of 0.035 MWt total in the Michoacán University to heat laboratory installations. There are no available data about energy use and production of these small projects.

OTHER GEOTHERMAL DEVELOPMENTS

As mentioned in previous reports, there is a geothermal energy act in Mexico that is currently in force. According to that law, the Geothermal Direction of the Sener has awarded seven exploitation concessions and 24 exploration permits as of December 2021. Five of the concessions were granted to CFE for Cerro Prieto, Los Azufres, Los Humeros, Las Tres Vírgenes and Cerritos Colorados, one more was granted to Geodesa (subsidiary of Grupo Dragón) for the Domo San Pedro field, and more recently another concession of exploitation was granted by Sener to the private company Energías Alternas Estudios y Proyectos (ENAL) for the geothermal field of Celaya, Guanajuato. In this zone, ENAL has been developing a first project of 25 MWe with an investment estimated at 77 US$ million, which includes drilling three exploration-production wells. One prototype small power plant of 500 kW is currently installed in the zone to test the reservoir (Espíndola, 2022, personal communication).

CFE also holds 13 of the exploration permits awarded by SENER, and has carried out complementary geological and geophysical surveys in only a few of those geothermal zones during the last years, due to the lockdowns derived from the Covid19 pandemic. CFE designed and located a new exploration well in one of the granted zones, but it has not drilled so far. All of the remaining 11 exploration permits were granted to private companies, some of which developed sporadic geological, geophysical and geochemical surveys in their respective zones, due to the same pandemic restrictions. Among those companies, ENAL has completed the exploration activities in one of its three additional granted zones, and is preparing to drill the first deep exploration well (Espíndola, 2022, personal communication).

There have not been new grants for exploration during 2020 and 2021, because the Sener offices suspended almost all administrative procedures since the beginning of 2020, which were resumed in the first months of 2022.

As it happens in all the world, the main issue for developing geothermal-electric projects in Mexico is closely related to the high risk, large time of development (compared to other renewable projects) and difficult financing access. Therefore, it was good news to learn about the launching of the former Geothermal Financing Mexican Program (PGM) that was a risk-transfer and financing program supported by the Inter-American Development Bank (IDB) and the Mexican development bank Nafin, structured under the global loan modality. As informed in the WGC2020+1 country-update report, PGM consisted of two main legs: risk-mitigation, and financing adapted to the different phases of project exploration and execution, with a third minor leg of technical assistance. The program's total amount is US$108.6 million and aimed to finance up to 300 MW of geothermal capacity over ten years (Gutiérrez-Negrín *et al.*, 2020).

Sener appointed the geothermal division of the INEEL (Instituto Nacional de Electricidad y Energías Limpias) national institute, as the technical executor of the PGM. Thus, INEEL carried out diverse activities in 2020 and 2021, but eventually Sener decided to update and modify the Call for Proposals, the bidding procedures and other relevant parts of the program, including its name, which is now PFTRG (Program for Geothermal Financing and Risk Transfer). A new call for proposals was launched in the second quarter of 2022, and a new international tender for selecting the drilling companies has been announced in the last quarter of 2022 (Aragón, A., 2022, personal communication), and it is expected to finish in the first semester of 2023.

On the other hand, and related to the same subject, since 2020 there is an additional financing fund available for geothermal projects in Mexico, the Geothermal Development Facility for Latin America (GDF-Latam), which was originally aimed to geothermal projects in other Latin American countries excluding Mexico. GDF-Latam is financed by the German Federal Ministry for Economic Cooperation Development (BMZ) and the EU, through the Latin America Investment Facility (EU-LAIF), with €50 million. Four projects submitted by CFE and three private companies were awarded for surface exploration studies in the fifth (2020) and for confirmation drilling in the sixth (2021) rounds, and the seven round is currently in progress (see https://gdflac.com/results/).

The Mexico's potential is larger than the potential of the geothermal zones granted for exploration. For conventional geothermal resources, of hydrothermal type, that potential is estimated at around 2500 MWe (Gutiérrez-Negrín *et al.*, 2020) based on a previous estimate made by adapting the concepts of geothermal reserves and resources proposed in the Australian Geothermal Reporting Code; that total comprises only hydrothermal resources of temperature ≥150°C (Gutiérrez-Negrín, 2012). A more defined prognosis is presented in the geothermal roadmap published by Sener in 2017, which expects the commissioning of 750 MWe additional by 2030, to reach around 1670 MWe in that year (Sener, 2017). This objective reflects the vision of the geothermal experts that participated in the elaboration of the roadmap in 2017, and yet is barely a third of the mentioned potential of 2500 MWe. However, to reach that additional capacity in 2030, it would be necessary to commission an average of 100 MWe in each of the next seven years, which certainly looks not much probable.

Finally, the Mexican territory has also a very high potential for hot dry rock resources, able to be developed with EGS technologies in the long term. A group of researchers coordinated by INEEL assessed the EGS potential in Mexico by following the protocol published by Beardsmore *et al.* (2010) and endorsed by the International Geothermal Association (IGA). They concluded the country's technical potential for EGS is about 2300 GWe, and that with a recovery factor of 2%, at depths between 3 and 7 km, it would be possible to install around 47,000 MWe (Hernández-Ochoa *et al.*, 2020).

CONCLUSIONS

Regarding the total capacity and generation of heat and power, the status of geothermal energy in Mexico is practically the same than reported three years ago. However, a new geothermal power plant was commissioned, and other smaller and older were decommissioned in that period, and an additional geothermal concession was granted to exploit a new geothermal field in the central part of the country.

Of course, the main reason for the small growth of geothermal projects, is the slowing of the Mexico's economic growth due to the restrictions adopted in 2020-2021 to fight the Covid 19 pandemic. But besides that, there has not been as much private investment as expected when the geothermal energy act was passed in 2014, which could change with the reactivation of economy and the new financing and de-risking programs.

Potential for future projects and geothermal fields is still high in Mexico, with around 2500 MWe of additional power for conventional resources, and more twenty times more for unconventional resources of EGS type. Potential for geothermal H&C projects is also high, with 3500 MWt able to be developed in the next ten years.

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