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Geothermal resources in Latin-America and their exploration using electromagnetic methods

Octavio Castillo-Reyes[1,2*], Rosa María Prol-Ledesma[3], Fernando Corbo-Camargo[4] and Otilio Rojas[2]

*Correspondence: octavio.castillo@upc.edu; octavio.castillo@bsc.es

[1] Department of Computer Architecture, Universitat Politècnica de Catalunya-BarcelonaTech (UPC), Jordi Girona 1-3, 08034 Barcelona, Spain
[2] Barcelona Supercomputing Center (BSC), Plaça Eusebi Güell 1-3, 08034 Barcelona, Spain
[3] Instituto de Geofísica, Universidad Nacional Autónoma de México (UNAM), Ciudad Universitaria, Delegación Coyoacán, 04510 Ciudad de México, México
[4] Instituto de Geociencias, Universidad Nacional Autónoma de México (UNAM), Boulevard 9, Juriquilla, 76230 Querétaro, México

Abstract

The global priority for sustainable societies drives the transition to green energy, with geothermal power as a promising alternative. Latin-American countries benefit from the active volcanism along the Pacific Rim, which fuels their significant geothermal potential. Geothermal electricity production in the region is steadily growing and currently represents approximately 11% of global output (16 GW). This paper provides details on the installed capacity of electrical generation in the most geothermally significant Latin-American countries, as well as the estimated potential production from existing prospects in the region. We also discuss the multiple challenges that limit the widespread development and exploitation of this valuable resource in Latin-America. As México stands as the top electricity producer in the region and ranks sixth worldwide, we offer an overview of its geothermal potential, the use of electromagnetic imaging technologies to enhance Mexican geothermal resource exploration, and the challenges and limitations associated with traditional exploration techniques. Additionally, we present recent case studies on the combined use of these technologies in México, highlighting best practices and lessons learned. The paper identifies open questions and outlines future research directions, particularly in México, to unlock the geothermal potential of the entire region.

Keywords: Geothermal resources, Latin-America region, Electromagnetic imaging, Software-based solutions

Introduction

Everyday life demands reliable and affordable energy services, such as heating and cooling, electricity supply, and transport. The availability of energy is one of the most critical aspects to the development of any society since it enables the smooth functioning of all economic sectors, from business and industry to agriculture. Energy is also closely linked to human health, education, and social welfare, as it provides access to clean water, sanitation, and healthcare (Khan et al. 2021).

The energy demand to support human activities and economic growth has been rapidly increasing over the past few decades. This energy demand is driven by several factors, including global population growth, urbanization, and economic and technological development. By 2050, the demand for energy could double or even triple with respect to 2022 consumption, as the global population rises and developing countries expand their economies (Perez and Perez 2022). According to the data from the United Nations (UN), it is projected that the world population will increase from 7.2 billion to more than 9 billion in 2050 (Cohen et al. 2001). This increase coupled with continued demand for the same, limited natural resources will cause a significant increase in energy consumption. This rapid rise in energy demand poses significant challenges, including energy security and environmental sustainability. This vision was enshrined into diverse and several legislation such as the *2030 Agenda for Sustainable Development and its Sustainable Development Goals* [SDGs (SDG 2019)], the *Paris Agreement on Climate Change* [PACC (United-Nations 2015)], and the *European Green Deal* [EGD (Fetting 2020)]. These strategic plans include a dedicated and stand-alone goal on energy transition, which aims to ensure access to affordable, reliable, sustainable, and modern energy by 2050.

Energy transition refers to the shift from traditional energy sources, such as fossil fuels, to renewable and sustainable energy sources. The energy transition is driven by the need to reduce greenhouse gas emissions (GHG) to zero or near-zero levels, while also ensuring energy security and affordability (Steg et al. 2015). This transition pursues changes in the way energy is produced, distributed, and consumed, as well as changes in policy and regulation. Making the energy sector climate neutral is a critical aspect of the energy transition. Achieving this goal requires a significant increase in the use of renewable and sustainable energy sources such as biomass (Field et al. 2008), geothermal resources (Barbier 2002; IRENA and IGA 2023), sunlight (Kabir et al. 2018), water (Kaygusuz 2004), and wind (Blanco 2009). These renewable and sustainable sources are naturally replenished and do not run out.

Geothermal energy is a key player to address one of the most fundamental challenges facing a high-tech society: securing the future supply of energy needed to sustain our twenty-first century infrastructure and contribute to the transition from fossil and nuclear energy to renewables (Lund and Boyd 2016). As a virtually unlimited renewable energy source, geothermal is versatile and reliable and does not depend on weather patterns. As such, geothermal energy is a serious and viable contender to help lever the energy sector into a carbon-neutral system by 2050. Geothermal energy is derived from the thermal energy generated and stored in the Earth's interior. Current technology allows exploitation of geothermal energy as the hot reservoir water transports the heat to the surface though boreholes that profit the reservoir rocks permeability that is related to either primary or secondary porosity; however, intense effort is performed to make economically profitable exploitation of the denominated Enhanced Geothermal Systems (EGS) that do not have enough permeability to be exploited with the conventional technology. Positive results have been obtained in the FORGE project, but their commercial utilization is still ahead (Jones et al. 2024). Geothermal energy is a commercially proven and renewable energy that can be used for heat and power generation (IGA and IFC 2014). This source is one of the most promising alternatives for switching from conventional to renewable energy sources as geothermal plants have continuous source of energy (IRENA 2023). It is becoming popular worldwide due to its low emissions and the capacity factor that has increased to a global weighted average capacity factor for newly commissioned geothermal projects of 85% in the 2022 projects, within a narrow range of approximately 80–90% (IRENA 2023). It is important to remark that only nuclear plants have a higher average capacity of 92%. Also, the manageable nature of geothermal energy production makes it relevant for improving the grid stability of the renewable mix. Furthermore, unlike some other renewable energy resources, the use of geothermal energy does not rely on rare Earth minerals avoiding the risk of new global dependencies. The feasibility of exploiting geothermal energy resources in the world has been analyzed recently by IRENA and IGA (2023). Today, 30 countries utilize geothermal energy for electricity production (IEA 2022). The top 10 countries represent around 93% of the total installed geothermal power generation capacity of 16,355 MW. These top 10 countries are (Geoenergy 2023): United States (3900 MW), Indonesia (2418 MW), Philippines (1952 MW), Turkey (1691 MW), New Zealand (1042 MW), Kenya (985 MW), **México** (976 MW), Italy (916 MW), Iceland (754 MW), and Japan (576 MW).

Latin-America's geothermal capacity amounts to approximately 1.7 GW, contributing around 11% to the global installed capacity. However, the region's growth rate has been lower than the global average, ranging from 1.5 to 2.0% per year (IRENA and IGA 2023). The majority of geothermal projects in Latin-America make use of high-temperature volcano-hosted hydrothermal resources. To further advance the sector, Latin-American countries are actively enhancing their enabling frameworks and regulations to attract investments in geothermal electricity generation as well as heating and cooling applications (Mahlknecht et al. 2020). In terms of geothermal energy utilization in Latin-America, the focus has primarily been on electricity generation rather than heating and cooling (IRENA and IGA 2023). **México** stands out as a leader in geothermal electricity production, boasting an installed capacity of 963 MW. Central American countries like El Salvador, Nicaragua, and Costa Rica also rely significantly on geothermal power to meet their electricity demand. On the other hand, South America has seen limited progress in geothermal electricity generation, Chile producing 48 MW and small-scale pilot projects in Argentina and Colombia.

México, ranked sixth among the top 10 list geothermal-electricity-producing countries globally, has significant potential for geothermal energy due to its location on the Ring of Fire, a volcanic belt that extends around the Pacific Ocean. The country has a large number of active volcanoes and thermal springs, which indicate the presence of geothermal resources. The transition to green energy resources and sustainable societies is a global priority, and **México's** untapped geothermal potential could play a vital role in achieving these goals. Despite its potential, the exploitation of geothermal energy in **México** is still in early stages. To advance a stronger and more integrated sustainable geothermal energy system, the European Commission, via its Low Carbon Energy Observatory, has identified the following scientific-technical challenges (Bruhn et al. 2022):

i. Ensure a reliable pre-drilling assessment of geothermal resources (reduces seismicity risk).

ii. Improve performance (competitive production and cost) and reliability (with reduced operational and maintenance costs) of geothermal systems (shallow and deep resources) that allow their widespread and cost-effective exploitation.
iii. Extend geothermal uses to complex and untested geological conditions.
iv. Reduce the environmental impact of geothermal plants.
v. Increase citizen engagement by having a complete understanding of the environmental and social impact of geothermal energy.

Geophysical imaging technologies could be applied to face the mentioned challenges greatly. In recent years, electromagnetic (EM) imaging has gained traction for enhancing geothermal resource exploration by providing resistivity maps of the subsurface. EM imaging is a non-invasive geophysical technique that uses natural or induced EM fields to image the subsurface. These images can be used to detect and map the subsurface structures and properties that are associated with geothermal systems, such as faults, fractures, and fluid pathways. EM imaging can also be used to monitor the changes in subsurface properties and fluid content during the operation of geothermal fields. Furthermore, EM imaging tools can be used to increase measurement precision and apply faster analysis of acquired data to achieve feasible models of geothermal reservoirs. Such accurate models are critical to reducing the average cost for exploration while increasing the drilling success rate. In addition, such EM images would lessen any potential environmental impact.

The contribution of this paper is threefold. First, we present an overview of the main exploration projects and feasibility evaluations for geothermal energy sources in Latin-America, and provide details on the electricity generation. Then, we focus on geothermal exploration studies developed in this region based on EM methods, and comment on the current challenges encountered for full exploitation of this energy source. Second, we provide an updated review of geothermal power production in the region, emphasizing the role of geophysical exploration, particularly EM imaging, in these developments. By examining both historical and recent exploration projects, we highlight how the integration of EM imaging techniques has enhanced the efficiency and effectiveness of geothermal resource identification and utilization. We offer a comprehensive overview of the current state of geothermal resource exploration in **México** and discuss the potential of EM imaging for improving exploration and monitoring efforts. Additionally, we present case studies showcasing recent advancements in the use of EM imaging technologies in **México**, illustrating their impact and benefits. Finally, we identify research questions that need to be addressed to optimize the use of EM imaging tools in geothermal exploration in **México**. This analysis highlights the importance of disruptive technologies to advance geothermal energy development in **México** and promote sustainable energy transition. The rest of the paper is structured as follows. "Electromagnetic imaging for Earth subsurface exploration" section covers the principles, techniques, and applications of EM imaging in Earth subsurface exploration. "Geothermal energy in Latin-America: a regional perspective" section discusses the current state of geothermal energy in Latin-America from a regional perspective. "Geothermal energy in México: a case study" section provides an overview of geothermal potential in México. A summary of case studies on EM imaging for geothermal resources in **México** is also presented. A discussion of lessons learned and open research questions is presented in "Discussion" section. Finally, "Conclusions" section provides summary remarks and conclusions.

Electromagnetic imaging for Earth subsurface exploration

EM imaging is a powerful geophysical technique for probing the Earth's subsurface. This method involves the measurement and analysis of EM fields that are either naturally occurring or artificially generated. The subsurface properties of the Earth, such as electrical conductivity and permittivity, can be inferred from the behavior of these fields (Zhdanov 2009).

The use of EM imaging methods, particularly the Magnetotelluric (MT) technique (Vozoff 1991), has revolutionized Earth's subsurface exploration. This is largely due to the method's non-invasive nature and its ability to provide detailed information about the subsurface (Osseyran and Giles 2015). By applying the MT technique, it is possible to delineate geological structures, identify changes in subsurface materials, and map the distribution of minerals or fluids (Börner 2010). This technique is particularly useful in identifying hidden and valuable resources and minerals that are difficult to locate with traditional exploration methods, such as seismic techniques. Additionally, subsurface models produced by the MT method can reduce the time and cost required for drilling exploratory wells, thereby minimizing the environmental impact of exploration activities. Given these advantages, the MT method has been utilized in a wide range of applications, including mineral exploration (Sheard et al. 2005; Queralt et al. 2007; Yang and Oldenburg 2012), hydrocarbon exploration (Newman and Alumbaugh 1997; Eidesmo et al. 2002; Avdeev 2005; Constable 2006; Srnka et al. 2006; Orange et al. 2009; Börner 2010; Constable 2010; Castillo-Reyes et al. 2018; Werthmüller et al. 2021), environmental site characterization (Tezkan et al. 1996; Zacher et al. 1996; Pellerin and Alumbaugh 1997; Eigenberg et al. 1998; Tezkan 1999; Doll et al. 2000; Auken et al. 2006; Zhang et al. 2011; Di et al. 2014; Deidda et al. 2022), CO_2 storage characterization (Chen et al. 2007; Girard et al. 2011; Vilamajó et al. 2013; Zhdanov et al. 2013; Park et al. 2017; Tveit et al. 2020), geothermal reservoir imaging and characterization (Caldwell et al. 2004; Spichak and Manzella 2009; Piña-Varas et al. 2015; Kana et al. 2015; Coppo et al. 2016; Darnet et al. 2018; Castillo-Reyes et al. 2021), crustal conductivity studies (Hördt et al. 1992; Ledo et al. 2002; Campanyà et al. 2012; Castillo-Reyes et al. 2022), and water prospecting (Palacky et al. 1981; McNeill 1990; Palacky 1993; Nobes 1996; Chang et al. 2019), among others.

In an EM imaging context, the nature of the energy source defines whether an EM method is passive or active. In a magnetotelluric [MT; (Vozoff 1991)] method, the energy sources are subsurface electrical currents arising from variations in the Earth's magnetic field, known as telluric currents. Thunderstorms and interactions between solar winds and the ionosphere generate this natural source field (Chave and Jones 2012). The exploration depth of this method depends on the electrical resistivity of the medium and the sampling frequency. For example, at a frequency of 10^{-5} Hz, the exploration depth can reach up to 200 km, allowing for the study of the lithosphere and the upper part of the mantle. The audio-magnetotelluric (AMT) method (Hoover and Long 1976) operates at a higher frequency range (10 kHz to 1 Hz), suitable for exploring shallower depths. Consequently, both methods are complementary for subsurface surveys targeting depths between the surface and 5 km. Modern MT equipment now features broad-spectrum sensors, utilizing a frequency range from 10 kHz to $10^{-}5$ Hz, effectively combining the capabilities of both AMT and MT methods. Thus, MT allows mapping hydrocarbons or geothermal reservoirs. For AMT/MT surveys, measurement devices of the magnetic and electric field components are three buried induction coil magnetometers and four porous pot electrodes, respectively. Data from these sensors are recorded by a digital data acquisition station. Records from multiple stations are processed and combined to produce 2D or 3D cross-sections of electrical resistivity with depth.

As previously mentioned, the MT method is a technique that measures natural EM signals propagating within the Earth. This makes it a versatile and practical method, as it does not require long cable lengths or powerful energy sources to supply the ground, unlike other EM geophysical methods such as time domain EM surveys [TDEM; (Pellerin et al. 1996; Cumming et al. 2000)] or controlled source EM surveys [CSEM; (Constable 2010)]. These latter methods are also used in various types of exploration but generally do not exceed depths of a few kilometers. Additionally, the TDEM method is widely used in the study of geothermal fields to address the static correction problem that MT measurements may encounter (Cumming and Mackie 2010).

Resistivity images, derived from EM measurements, serve as powerful and versatile tools for subsurface exploration and reservoir characterization. These images provide detailed, non-invasive information about the subsurface, revolutionizing the field of geophysics and finding application across a broad spectrum of industries. The potential of this technology is immense, and its continued evolution and improvement are inevitable. Advancements in sensor technology, data processing, numerical modeling, and computational simulation will enhance the accuracy, reliability, and efficiency of resistivity images obtained through EM methods, particularly MT methods. As we continue to push the boundaries of what is possible, we can anticipate the discovery of new applications and insights into the Earth's subsurface. The knowledge gained from EM imaging facilitates informed decision-making, contributing to a sustainable and prosperous future. In the following sections, we will examine the current and future exploitation of geothermal energy resources in **Mexico**.

Our study specifically emphasizes the potential of EM imaging in enhancing geothermal conceptual models and exploration strategies. While economic considerations and logistical challenges are crucial in practical applications, they are outside the scope of this work due to the substantial variability among exploration projects influenced by factors like investment types and geological complexities. Our research integrates insights from diverse literature examples to underscore how EM methods can transform geothermal exploration across Latin-America. For comprehensive reviews of costs, logistical difficulties, and data quality in geothermal exploration using EM techniques, readers are referred to (Wright et al. 1985; Akar and Young 2015; Khankishiyev et al. 2024).

Geothermal energy in Latin-America: a regional perspective

Geothermal resources in Latin-America

Latin-America, located within the Pacific Rim's Ring of Fire, benefits from volcanic activity that serves as a heat source for numerous geothermal systems. Countries like **México**, Guatemala, El Salvador, Nicaragua, Colombia, Ecuador, and Chile exhibit geothermal activity associated with recent volcanism. Geothermal electricity production started in the 1970s in **México** and El Salvador, the 1980s in Nicaragua, and the 1990s in Guatemala. Table 1 presents data on electricity production from geothermal energy in Latin-America.

Since the 1970s, following the first global oil crisis that prompted the exploration of alternative energy sources, geothermal electricity generation has steadily grown in Latin-America. The region currently boasts approximately 1.7 GW of geothermal capacity, accounting for 11% of the global installed capacity (around 16 GW). However, the average growth rate in the region over the past 20 years, ranging from 1.5 to 2.0% per year, has been lower than the global trend of 3% (IRENA and IGA 2023).

Geothermal power plants operate in 17 fields across nine countries in Latin-America, primarily in Central America and **México**. Some fields, such as Cerro Prieto and Los Azufres in **México**, Ahuachapán in El Salvador, and Momotombo in Nicaragua, have been in operation for over 40 years. The majority of the installed capacity utilizes high-temperature volcano-hosted hydrothermal resources. Several Latin-American countries, including Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Ecuador, El Salvador, Guatemala, **México**, and Nicaragua, have undergone evaluations of their geothermal potential. While some evaluations are recent and were presented at the World Geothermal Congress, many of them are outdated. Some countries have limited evaluations, such as Honduras with an installed capacity of 35 MW, Panamá, and the southern part of Venezuela. Regional evaluations also extend to Caribbean islands, where the interest in developing geothermal energy as part of energy transition programs is growing.

Latin-America, an emerging market for geothermal heating and cooling, is actively enhancing its regulatory frameworks and establishing new regulations to encourage investments in both electricity generation and heating and cooling (IRENA and IGA

Table 1 Latin-American countries that are actually producing geothermal electricity [after Huttrer (2020)]

Country	2015		2020		2020 increase	Forecast for
	Installed (MW)	Energy (GWh/year)	Installed (MW)	Energy (GWh/year)	Since 2015	2025 (MW)
Argentina	0	0	0	0	0	30
Chile	0	0	48	400	48	81
Costa Rica	207	1511	262	1559	55	262
El Salvador	204	1442	204	1442	0	284
Guatemala	52	237	52	237	0	95
Honduras	0	0	35	297	35	35
México	869	3961	963	4389	94	1061
Nicaragua	159	492	159	492	0	159

2023). Notably, countries like Chile is spearheading these efforts. In terms of geothermal electricity generation, **México** and Central-America has made significant progress compared to South America and the Caribbean. **México** stands out as one of the top ten geothermal-electricity-producing countries globally, with an installed capacity of 963 MW. Central American countries, despite their smaller electricity markets, have a substantial portion of their national electricity demand met by a few hundred MW of geothermal installed capacity. For example, El Salvador relies on geothermal power for 24.9% of its electricity, Nicaragua for 20.8%, and Costa Rica for 14.6%, as reported by Rojas (2022). On the other hand, South America has seen limited geothermal electricity generation, with the first large-scale operation (48 MW) in Chile's Cerro Pabellón geothermal field (recently expanded to 81 MW) and Colombia producing 72,000 kWh at the Maracas oil field with a plant of 100 kW installed capacity (Franco et al. 2021). Below, we present additional details on the most geothermally significant countries in Latin-America.

Argentina

Exploration efforts in Argentina have been focused on the direct use of geothermal resources. Nineteen projects have been studied, and prefeasibility studies have been completed for eleven of them. Reconnaissance studies have been conducted for one project, while seven areas have reached the development and production stage. The areas currently in the development stage are: La Paz, Maria Grande, Villaguay, Gualeguaychu, Concordia, Uritorco, and Cerro San Martin. The total installed capacity for the utilization of geothermal energy is 150 MWt. Recently, there has been a growing interest in high-enthalpy systems, and there are seven projects in the western part of the country. The Copahue geothermal field previously had an installed capacity of 0.67 MW, but has since been shut down (Pesce 2005). However, there are plans to reactivate this field, and the geothermal potential of Argentina has been estimated to be at least 1000 MW (Agostina et al. 2020).

Bolivia

Since 1984, prefeasibility evaluations were performed in two high temperature (240 and 250 °C) projects in Bolivia, where more than 70 geothermal areas have been identified. International calls have been published to develop the Laguna Colorada geothermal prospect that has an estimated potential of 240 MWe (Villarroel 2020), however, no further actions have been taken.

Brazil

Studies on the geothermal potential of Brazil have shown that most resources correspond to low-enthalpy systems, and high-enthalpy geothermal systems are restricted to the Atlantic islands of Fernando de Noronha and Trindade. The total capacity of the low-enthalpy systems in Brazil is estimated to be 362 MWt (Hamza et al. 2005). However, a new heat flow map has proven the possibility of some areas hosting high-temperature geothermal systems that may be explored in the future (Pereira et al. 2022).

Chile

The Chilean Andes are the location of Quaternary volcanic activity, and more than 300 geothermal areas have been discovered with an estimated potential of 16,000 MWe (Lahsen et al. 2005). In Chile, geothermal resources have traditionally been used for recreational and touristic purposes. The current utilization of geothermal energy accounts for 8.27 MWt. However, electricity production has recently commenced with the assignment of permits in the Apacheta and Tolhuaca geothermal fields, which have an installed capacity of 48 MWe (Lahsen et al. 2005). The recent changes in the geothermal law have encouraged widespread exploration for geothermal resources. Explored areas in northern Chile include Puchuldiza and El Tatio, while areas in central Chile include Calbozos, Nevados de Chillán, and Cordón Caulle. Further growth in electricity production from geothermal energy is foreseen as the gas price increases, natural gas reserves are exhausted, and uncertainties in gas imports persist. A strong impulse for geothermal exploration was promoted by the creation of the Andean Geothermal Center of Excellence (CEGA), where geothermal research is thriving, including lithium extraction from geothermal water (Goldberg et al. 2021).

Colombia

Geothermal energy in Colombia is primarily utilized directly, and exploration of geothermal resources is mostly in the reconnaissance stage (Alfaro et al. 2000), such as in the Azufral volcano, Paipa geothermal area, San Diego, Paramillo de Santa Rosa, and Cerro Machín. However, in Paipa, social problems halted shallow well drilling, but surface exploration continues. There are plans to install 70 MWe (Alfaro et al. 2000). Inventories of hot springs have been conducted in several areas, including Cerro Bravo-Cerro Machin and Cundinamarca. Geothermal studies and a geothermal map of the country have been reported by Alfaro et al. (2000). Additionally, the exploitation of geothermal energy from oil fields has commenced with an electricity production of 70kWe by Parex Resources in the Llanos Orientales sedimentary basin (Omar et al. 2021).

Costa Rica

The total installed capacity is 252 MWe in the Pailas and Dr. Alfredo Mainieri Protti geothermal fields, with 97.5 MWe and 154.5 MWe, respectively. This amount of electricity represents 16% of the total energy produced in the country. Furthermore, there are plans to drill 20 wells to develop the Borinquen I geothermal field, which will fuel the first of two 55 MWe plants. Additionally, there are numerous geothermal prospects to further increase geothermal electricity production in the country (Sánchez-Rivera et al. 2021). An estimation of the geothermal power potential of Costa Rica is about 1000 MWe, even though the presence of national parks in target areas limits their exploitation Olave and Vargas-Payera (2020).

Ecuador

Geothermal exploration has been carried out since the 1970s in Ecuador, and the geothermal potential has been estimated at 500 MWe for the Tufiño-Chiles, Chachimbiro, and Chalupas fields (Beate and Salgado 2005). Other geothermal areas with potential for exploitation include Chalpatan, Cuicocha, Cayambe, Pululahua, San Vicente, Guagua Pichincha, Portovelo, Alcedo, Tungurahua, Guapan, and Salinas. The theoretical geothermal potential of continental Ecuador is above 2000 MW following the methodology developed by Stefansson (2005), which accounts for the number of active volcanoes in the region Jara-Alvear et al. (2023). However, despite the abundant geothermal resources, only one exploration well has been drilled in Chachimbiro, where up to 50 MWe could be installed (Beate et al. 2020). The direct utilization of geothermal energy has an installed capacity of only 5 MWt (Beate and Salgado 2005).

Guatemala

Electricity is produced in Guatemala at the Zunil and Amatitlan geothermal fields. Production started in 1998 in Amatitlan and has continued since. Presently, the total installed capacity in both fields is 52 MWe. Additionally, the installed capacity of direct utilization of geothermal energy is 10 MWt (Manzo 2005). Future plans include the development of new fields: San Marcos, Tecuamburro and Moyuta (Asturias 2008). The accessible exploitation basis of geothermal potential energy in Guatemala is estimated to be 1000 MWe.

El Salvador

There are geothermal fields producing electricity in El Salvador: Ahuachapán, Berlín, and Chinameca, with a total installed capacity of 204 MWe. However, there are plans to increase it to 300 MWe (Herrera et al. 2010). A significant part of the total energy produced (25%), comes from geothermal energy. The increase of reinjection in Ahuachapán is expected to help increase production in this field, as well as the installation of binary plants (Rodríguez and Herrera 2005). The Berlín geothermal field is being exploited in association with ENEL, which has scheduled an increase in production and the future use of binary plants. An estimation from the U.S. Department of Energy projects El Salvador’s geothermal power potential over 2210 MWe Battocletti et al. (1999).

Nicaragua

Nicaragua has a large potential for electricity production from geothermal energy. Its reserves were estimated to be more than 1000 MWe (Zúñiga Mayorga 2005). Geothermal areas are distributed throughout the country, associated with intense volcanic activity. Electricity production began in 1983 in the Momotombo geothermal field, with an initial installed capacity of 35 MWe (Zúñiga Mayorga 2005). Subsequently, production increased with the addition of the San Jacinto field, resulting in a current installed capacity of 159 MWe. In the future, three more areas show potential for electricity production: El Hoyo-Monte Galan with an estimated capacity of 200 MWe, Managua-Chiltepe with 150 MWe, and Masaya-Granada-Nandaime with 200 MWe.

Table 2 EM exploration of geothermal fields in Latin-America

Country	Field	MT soundings	References
Bolivia	Laguna Colorada, Sol de Mañana	70	Quiroga et al. (2023)
Ecuador	Cachimbiro	70	Beate et al. (2020)
	Chacana	130	
	Tufiño-Chiles	100	
Perú	Urbinas volcano	15	Gonzales et al. (2014)
Colombia	Paipa	88	Alfaro-Valero et al. (2020)
	Nevado de Ruíz	105	Rojas Sarmiento (2014)
	Nevado de Ruíz	43	González-Garcia et al. (2015)
Argentina	Tuzgle volcano, Puna	10	Sainato and Pomposiello (1997)
	Tocomar	30	Ahumada et al. (2022)
	Tucuman and Santiago del Estero provinces	11	Baldis et al. (1983)
	Domuyo geothermal area	103	Silva-Fragoso et al. (2021)
	Tucuman basin	41	Guevara et al. (2020)
	Socompa volcanic zone	34	Guevara et al. (2018)
Chile	Villarica volcano	31	Pavez et al. (2020)
	Lazcar volcano	18	Díaz et al. (2012)
	Juncalito geothermal prospect	19	García and Díaz (2016)
	Tolhuaca goethermal system	–	Pavez et al. (2022)
	San Pedro-Linzor volcanic chain	45	Mancini et al. (2019)
Salvador	Ahuachapán geothermal field	172	Santos (2010)
	Berlin geothermal field	107	
	San Vicente geothermal field	58	

Exploring geothermal resources with MT methods in Latin-America

With Latin-America's abundant geothermal potential, applying EM methods presents opportunities for harnessing clean and renewable energy sources and driving the region towards a greener future. In pursuit of prospecting new geothermal fields, EM exploration has been conducted in several Latin-American countries. While a considerable portion of this exploration has been carried out by private companies, whose information remains confidential, valuable insights can be obtained from publicly available data. By examining country-specific research and industry projects, Table 2 provides comprehensive information on academic endeavors and private enterprises that have chosen to share their data.

Current challenges of geothermal energy in Latin-America

Geothermal energy has emerged as a promising renewable energy source in Latin-America, offering significant potential for sustainable power generation. However, several challenges impede the widespread development and utilization of this valuable resource in the region. Understanding and addressing these challenges is crucial to unlocking the full potential of geothermal energy in Latin-America and ensuring its long-term sustainability.

One of the primary challenges is the high upfront costs associated with geothermal exploration and development. Geothermal projects require significant investments in drilling, resource assessment, and infrastructure development (Guerrero-Lemus et al. 2017). These costs can pose a barrier, particularly for countries with limited financial resources or uncertain investment climates. Access to adequate funding mechanisms and financial incentives is essential to attract private investors and support the development of geothermal projects. Another critical challenge is the technical complexity of geothermal resource assessment and exploration. Unlike other renewable energy sources such as wind or solar, geothermal resources are not visible on the surface, making it necessary to employ advanced exploration techniques such as seismic surveys and geochemical analysis. The lack of expertise and technical capacity in these specialized fields can hinder the accurate assessment of geothermal resources and increase exploration risks. Collaboration among research institutions, industry stakeholders, and governments is vital to fostering knowledge transfer, capacity building, and the development of advanced exploration technologies.

Geothermal projects also face regulatory and legal challenges that vary across countries in Latin-America. Inconsistent and cumbersome permitting processes, unclear regulatory frameworks, and bureaucratic obstacles can delay project development and increase costs (Guimarães 2020). Streamlining and harmonizing regulatory procedures, providing clear guidelines, and establishing a supportive policy environment can encourage investment and expedite the deployment of geothermal projects.

Environmental considerations are of utmost importance in geothermal development. While geothermal energy is considered clean and sustainable, there are potential environmental impacts associated with drilling, fluid extraction, and waste disposal (Olave and Vargas-Payera 2020). Proper environmental impact assessments and mitigation measures are crucial to minimize any adverse effects on ecosystems, water resources, and local communities. Developing robust environmental regulations, monitoring protocols, and community engagement strategies can ensure responsible and sustainable geothermal development. Additionally, geothermal projects often face social and community acceptance challenges (Payera 2018). Local communities may have concerns about the potential impacts on their livelihoods, cultural heritage, and land rights. Engaging in transparent and inclusive dialogue with affected communities, addressing their concerns, and providing equitable benefit-sharing mechanisms can help build trust and ensure the social acceptance of geothermal projects.

The integration of geothermal energy into the existing energy grid is another challenge. The intermittent nature of some renewable energy sources, including geothermal, requires careful planning and coordination with the grid infrastructure. Developing smart grid systems, energy storage solutions, and fostering the deployment of geothermal power plants in strategic locations can enhance the integration of geothermal energy into the grid and support the stability and reliability of the overall energy system.

Geothermal energy in México: a case study

Development of geothermal exploitation in México

México has a complex geologic and tectonic setting that creates favorable conditions for the occurrence of geothermal systems, and over 2000 superficial manifestations of hydrothermal activity have been reported (see Fig. 1). Despite this potential, geophysical studies have been conducted in only a few areas (< 20). The exploitation of **México's** geothermal resources began in the early 1960s, and the country has remained on the

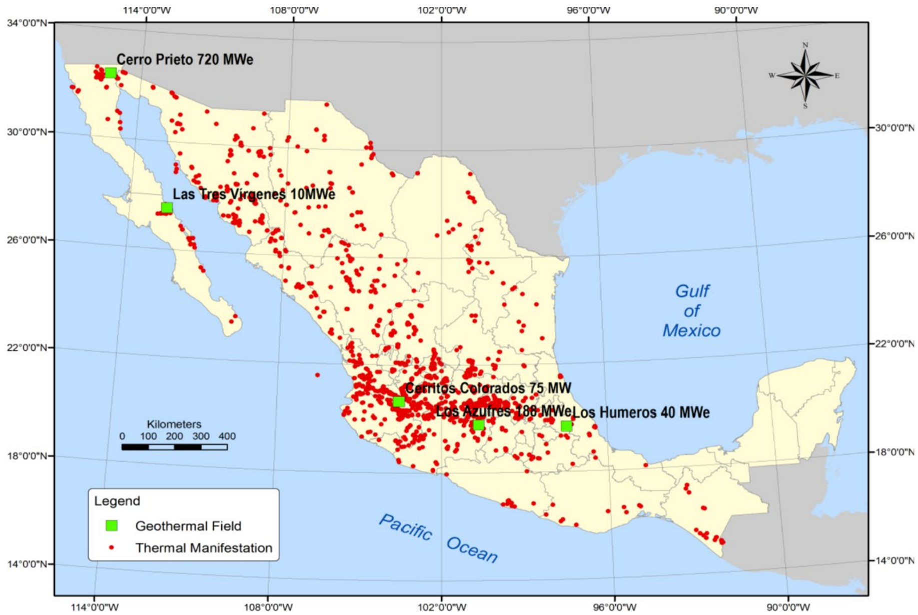

Fig. 1 Location of the reported hydrothermal manifestations and the geothermal fields (Iglesias et al. 2015)

Table 3 Historic evolution of top 10 list geothermal energy installed capacity in MW. After data from Quijano-León and Gutiérrez-Negrín (2003); Magaly et al. (2014); Gutiérrez-Negrín et al. (2020); IEA (2022)

Country	1979	1987	1995	2000	2005	2010	2013	2015	2017	2019	2020	2022
United States	502	2212	2817	2228	2534	3098	3389	3450	3567	3653	3714	3722
Indonesia	–	87	310	590	797	1197	1341	1340	1699	1948	2133	2276
Philippines	4	894	1227	1909	1930	1904	1848	1870	1868	1868	1918	1918
Turkey	0.5	15	20.4	20.4	20.4	82	166.6	624	1005	1347	1688	1170
New Zealand	203	263	286	437	435	762	842	1005	980	1005	1005	1037
México	75	655	753	755	953	958	775	869	926	951	963	963
Italy	421	504	632	785	791	843	875	916	944	944	944	944
Kenya	–	15	45	45	127	167	248.5	600	676	763	861	861
Iceland	64	39	50	170	202	575	664	665	665	755	755	754
Japan	165	215	215	414	547	535	537	519	542	549	603	603

list of the top ten countries with the highest production of electricity from geothermal energy (Geoenergy 2020). However, geothermal electricity production has stalled in the last two decades (see Table 3), and there is a need for a strong boost of clean energy growth to promote geothermal exploitation and comply with the country's commitments to the UN plans for 2030.

One of the major challenges for geothermal exploration in **México** is that presently only the government electricity company, Federal Electricity Commission (FEC; Comisión Federal de Electricidad-CFE), is authorized to develop geothermal exploration. It uses geological surveys to provide site information for exploration and exploitation wells. The common practice for well siting by FEC is to conduct geological surveys, and only after production has started, EM surveys are performed.

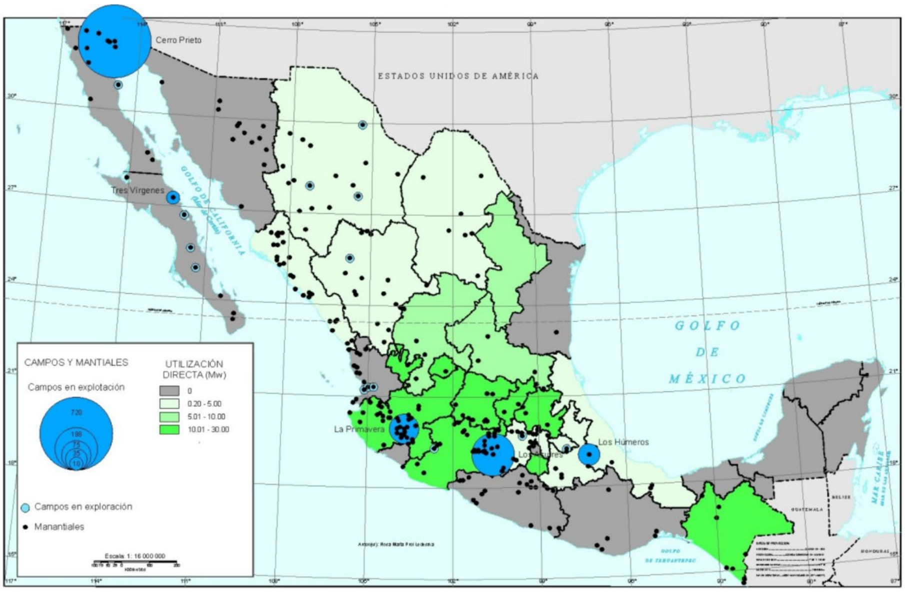

Fig. 2 Geothermal areas and direct use in **México** (Prol-Ledesma and Torres-Vera 2007)

Table 4 Production of each presently active geothermal field in **México** with data from Gutiérrez-Negrín et al. (2020)

Field	Capacity (MW)		Wells in operation		Owner
	Installed	In operation	Production	Injection	operator
Cerro Prieto, Baja California	570	570	129	28	CFE
Los Azufres, Michoacán	275.1	257.2	49	6	
Los Humeros, Puebla	120.7	95.7	29	3	
Las Tres Vírgenes, Baja California Sur	10	10	3	1	
Domo San Pedro, Nayarit	26.1	26.1	3	1	Grupo Dragón
Total	1001.9	959	213	39	

This approach has resulted in a lack of integration of geophysical information for the exploration and exploitation of geothermal fields in **México**. Geothermal exploration in **México** has a long history dating back to 1951, when the Geothermal Energy Commission (GEC) conducted the first geothermal exploration studies. Currently, there are five fully operational geothermal fields in **México** (see Fig. 2), four operated by the FEC (Cerro Prieto, Los Azufres, Los Humeros and Las Tres Vírgenes) and one (Domo San Pedro) operated by a private company Grupo Dragón. Table 4 displays the production of each field along with the corresponding number of drilled wells. The first geothermal well was drilled without any geophysical survey based on the main faults location in the Pathe geothermal prospect (de Septien Anda et al. 1961). However, the GEC was canceled and the responsibility for geothermal development was transferred to the FEC, who has been in charge of geothermal development since then. The Pathe geothermal field began electricity production with a capacity of 3.5 MW in 1959, and was the first geothermal plant to produce electricity in America. It continued operating until 1973.

The Cerro Prieto geothermal field was the second geothermal prospect to be explored in **México**. The field is currently the third largest in the world and started production in 1973, with two geothermal plants installed and producing 35 MW each (Quijano-León and Gutiérrez-Negrín 2003). The current installed/operational capacity of the Cerro Prieto geothermal field is 570 MW, and the production has been declining steadily from 868 MW in 2010. Despite being one of the largest geothermal fields in operation, exploitation at Cerro Prieto has been based on the results of geological-structural surveys rather than geophysics. The first resistivity surveys were conducted in 1978 (Díaz and Arellano 1979; Razo Montiel et al. 2018), five years after production started, and the first MT profiles were reported in 1980–1981 (Gamble et al. 1980, 1981). The most recent MT studies correspond to academic works that have apparently not been considered in planning the exploitation of the field (Oliver-Ocaño et al. 2019; Bravo Osuna 2019).

After the successful production at Cerro Prieto geothermal field, the CFE developed four more geothermal prospects: Los Azufres, Los Humeros, La Primavera, and Las Tres Vírgenes. Los Azufres was the first of these fields to start production in 1982, with an installed capacity of 275.1 MW and an operational capacity of 257.2 MW. The field underwent a magnetotelluric (MT) survey when it was already producing electricity in 1991 (Copley and Orange 1991). Similarly to Cerro Prieto, this survey helped to optimize the location of the production wells.

The Los Humeros geothermal field started production in 1990, and extensive geological and geochemical studies were performed. However, it was only in 2018 that the first electromagnetic surveys were conducted. The field has an installed capacity of 120.7 MW, with an operational capacity of 95.7 MW.

Las Tres Vírgenes is the most recent geothermal field to be commissioned by the CFE in the Baja California Peninsula. The field was commissioned in 2002 and has an installed capacity of only 10 MW, with an annual average plant capacity factor of 49.2%. This production is low, especially considering that the Peninsula is disconnected from the national electrical grid. Extensive geophysical studies have been conducted in this field, including electrical surveys since 1984 (Razo Montiel 1984) and several electromagnetic surveys reported in the last 20 years (Romo et al. 2000).

In addition to the CFE's projects, the Grupo Dragón explored and started production at the Domo San Pedro geothermal field in 2016, with an installed/operational capacity of 26.1 MW. Besides the five geothermal fields currently in production, there is another field, Cerritos Colorados (previously known as La Primavera), which has the potential to generate 75 MW of electricity. Despite having nine successfully drilled wells and being ready to begin production since 1988, this field was halted due to opposition from social organizations who disagreed with the drilling practices employed by FCE. Recent research projects have been conducted to study the field, including electrical resistivity tomography (Bolós et al. 2019) and thermal modeling of the La Primavera Caldera(Espinoza-Ojeda et al. 2021).

Estimation of México's geothermal resources

Low and medium enthalpy resources

Geothermal energy has gained increasing attention worldwide as a renewable and sustainable alternative to traditional fossil fuels. In **México**, hydrothermal manifestations are the primary sources of geothermal energy, and they mainly correspond to low-to-medium enthalpy systems. Despite the lack of direct utilization projects and minimal use of binary plants, the available geothermal resources in **México** have been evaluated since the 1970s.

The first resource report in the 1980s was a rough estimation of two large areas with constant thickness and temperature (Mercado 1977). One area was the Mexican Volcanic Belt province, which had a length of 900 km, a width of 4 km, and an average temperature of 125 °C, resulting in a potential of 31,498 MW. The other area included the Mexicali Valley, Laguna Salada, and the Altar Desert, covering a total area of 2000 km^2,

Table 5 Results of the evaluation of the low–medium enthalpy resources in **México** (Iglesias and Torres 2009)

State	**Num. geothermal manifestations**			**Num. localities included in the study**	**Reserves (kJ)**			**Average temperature (°C)**	
	Total	**Included in the study**			**Minimum confidence interval (90%)**	**Maximum confidence interval (90%)**	**Mean of the distribution**	**Media**	**Standard deviation**
		Num	**%**						
Aguascalientes	49	18	36.7	7	2.36E15	5.58E15	3.80E15	119.41	22.25
Chiapas	14	3	21.4	3	4.57E14	1.04E15	7.3E14	139.01	26.49
Chihuahua	53	13	24.5	11	2.17E15	3.34E15	2.73E15	104.72	22.00
Colima	3	1	33.3	1	6.03E13	3.63E14	1.93E14	114.79	76.65
Durango	55	5	9.1	5	6.48E14	1.40E15	9.95E14	85.20	12.94
Edo. México	6	5	83.3	3	5.30E14	1.23E15	8.65E14	129.81	8.52
Guanajuato	172	75	43.6	47	1.08E16	1.35E16	1.21E16	114.92	17.64
Guerrero	10	1	10	1	6.00E13	3.80E14	1.92E14	78.05	92.38
Hidalgo	76	43	56.6	28	8.69E15	1.19E16	1.03E16	112.50	16.75
Jalisco	391	66	16.9	41	124E16	171E16	1.46E16	113.44	21.83
Michoacán	72	27	38	24	5.72E15	8.45E15	6.98E15	119.15	25.29
Morelos	2	1	50	1	6.50E13	3.20E14	1.74E14	95.80	64.37
Nayarit	56	19	33.9	13	3.70E15	5.92E15	4.75E15	110.57	17.22
Oaxaca	12	5	41.7	4	5.67E14	1.21E15	8.63E14	112.93	13.18
Puebla	17	7	41.2	6	9.20E14	1.67E15	1.28E15	106.68	15.97
Querétaro	172	63	36.6	54	1.23E16	1.55E16	1.38E16	107.22	16.64
San Luis Potosí	20	7	35	6	1.25E15	2.55E15	1.86E15	108.72	46.64
Sonora	77	9	11.7	8	1.21E15	2.45E15	1.77E15	87.16	13.19
Veracruz	10	2	20	2	2.74E14	8.00E14	5.03E14	108.11	13.86
Zacatecas	44	12	27.3	11	2.26E15	4.05E15	3.08E15	107.48	17.66
Total	1310	382	29.16	276					

a thickness of 1.5 km, and an average temperature of 135 °C, with a total geothermal resource of 45,815 MW.

A more detailed evaluation was conducted by Iglesias et al. (2002) for the hydrothermal systems with a temperature of less than 200 °C. This study estimated the thermal energy of 297 geothermal areas located in 20 different states. Subsequently, a more recent study (Iglesias and Torres 2009) evaluated only 276 areas, which was only 29% of the 1310 that had been previously reported (Rodríguez et al. 1993). The thermal energy associated with these geothermal areas was calculated to be between 21.4–23.9E9 (see Table 5).

The most recent hydrothermal areas database includes 2332 geothermal manifestations (Iglesias et al. 2015), which represents a significant increase of 72% from the 2009 database. Therefore, this evaluation should be considered as a minimum value for low-to-medium enthalpy geothermal resources. The reserves average value is 8.15E16 kJ, which is equivalent to approximately 21.4E15 m^3 natural gas or approximately 1.9E9 Arabian Light oil barrels. It is worth mentioning that the present installed capacity for direct utilization of geothermal energy is 156 MW (Gutiérrez-Negrín et al. 2021). Therefore, there is enough capacity to increase utilization of the known resources improving the local economies.

High-enthalpy resources

Following the start of production in Cerro Prieto, the geothermal resources of **México** were estimated for the first time in 1982 (Mercado et al. 1982). At that time, only 130 hydrothermal areas had been discovered, and reconnaissance exploration had been conducted in nine areas, yielding an estimation of 4000 MW. A year later, another estimation using geochemical methods reported a potential of 13,110 MW (Mercado 1977).

Table 6 Evaluation of the geothermal resources in **México**, published by different institutions/authors since the start of geothermal exploitation in the country (Alonso 1976, 1985; Mercado et al. 1985; Iglesias et al. 2002; Iglesias and Torres 2009; Ordaz Méndez et al. 2011; Le Bert et al. 2011; Gutiérrez-Negrín 2012; Arango-Galván et al. 2015)

Author	Reserves			Total (MW)	Remarks
	Proved	Probable	Possible		
Alonso (1976)	–	–	–	4000	
Mercado (1977)	–	–	–	13,100	
Alonso (1985)	1340	4600	6000	11,940	
Mercado et al. (1985)	–	–	–	45,815	Hydrothermal manifestations with temperature in the range 125–135 °C
Iglesias et al. (2002)	–	–	–	2.26E10	276 geothermal areas with temperature between 60–180 °C
Iglesias and Torres (2009)	–	–	–	33.8E10	918 zones with temperature ≤ 200 °C
Ordaz Méndez et al. (2011)	186	2077	7423	9686	1380 geothermal manifestations and geothermal fields
Le Bert et al. (2011)	–	–	–	751	Volumetric evaluation of 20 geothermal areas (with and without geophysical data)
Gutiérrez-Negrín (2012)	75	655	1210	2310	Based on Ordaz Méndez et al. (2011) and Le Bert et al. (2011)
Arango-Galván et al. (2015)	–	–	–	> 400	Only for Baja California Peninsula

As exploration works continued, the results were used to calculate proved, probable, and possible reserves of 1340 MW, 4600 MW, and 6000 MW, respectively, totaling 11,940 MW (Alonso 1985). A more recent evaluation of high-enthalpy geothermal resources was carried out by FCE, which included volumetric evaluation of 1300 geothermal areas. The results indicated probable reserves of 2077 MW and possible reserves of 7423 MW (Ordaz Méndez et al. 2011). The proved reserves (186 MW) considered the increasing installed capacity projects in operational geothermal fields. The total reserves calculated were 10,450 MW, which is more than ten times the current installed capacity, which has remained unchanged for almost 20 years. Recently, Prol-Ledesma et al. (2016) compiled all the evaluations, which are shown in Table 6.

EM imaging for geothermal exploration in México

In recent years, various exploration projects and studies utilizing MT measurements have been conducted in different geothermal areas of **México**. These projects have been supported by organizations such as the CeMie-Geo and the GEMex Project, which have played a significant role in advancing geothermal research in the country.

Under the CeMie-Geo project titled *"Passive seismic and magnetotelluric exploration in the geothermal fields of Volcán Ceboruco and La Caldera de la Primavera,"* the Ceboruco volcano was extensively studied. A total of 25 sites were analyzed using broadband MT data, providing valuable insights into the volcano's characteristics and geological features (Fuentes-Arreazola et al. 2021; Hering et al. 2022).

Similarly, within the scope of the CeMie-Geo project *"Innovative application of modern techniques for geothermal exploration by the integration of geological, geochemical, and geophysical methods, study case of Los Humeros volcanic field,"* the resistivity structure resulting from 2D and 3D inversions of 78 broadband MT soundings was analyzed to understand the physical properties of the Humeros geothermal field (Arzate et al. 2018; Corbo-Camargo et al. 2020). Furthermore, as part of the GEMex Project, an additional 122 MT broadband soundings were acquired in the same volcanic complex of Los Humeros (Held et al. 2020; Ruiz-Aguilar et al. 2020). In the Acoculco caldera, 68 MT measurements were conducted as part of the GEMex Project (Ordaz Méndez et al. 2011).

Academic research projects have also made significant contributions to geothermal studies in both high and low-enthalpy areas. For example, the project *"Unconventional geothermal energy in **México**: an interdisciplinary study in the southeastern part of the Sierra Madre Occidental"* focused on low-enthalpy areas, specifically the Juchipila and Santiago Papasquiaro grabens located in Zacatecas and Durango states, respectively. Using 61 MT sites in the Juchipila graben and 34 MT sites in the Santiago Papasquiaro graben, researchers successfully characterized the grabens and identified the contact between sedimentary fill and the underlying basal layer (Billarent-Cedillo et al. 2021; Ávila Vargas 2019)

In another study, the Independencia basin was investigated using electrical and electromagnetic measurements, including vertical electrical sounding (VES), time domain electromagnetic (TDEM), and audio magnetotelluric (AMT) techniques. With a total of 27 AMT, 32 TDEM, and 78 VES soundings, the geometry of the basin, the depth of the basement, and low resistivity zones associated with hydrothermal alteration were identified (Castro 2018; Castro et al. 2021).

In high-enthalpy, the ongoing project *"Geothermal evaluation and determination of the magmatic source in the San Pedro-Ceboruco graben" (IA103221)*, funded by PAPIIT, generate an electrical resistivity model that reflects the subsoil structures and indicates the possible fluid circulation zones of geothermal interest and the geological units in the Graben of San Pedro—Ceboruco. Identifying the San Pedro dome as an active geothermal station as mentioned above. Also, the project *"Mid-to-Deep-crustal Electromagnetic Investigation of Tepic-Zacoalco Rift (DEMITZ)-Exploring Magmatic Systems and Anisotropy in Western México"*, funded by Deutsche Forschungsgemeinschaft (Germany), using the magnetotelluric method to characterize conductivity anomalies in the crust and upper mantle with special interest on anisotropic features in the Tepic Zacoalco Rift. In total, 57 broadband MT soundings and 17 low-frequency soundings (LMT) have been acquired in both projects (Pers. Comm. Dr. Fernando Corbo Camargo). Moreover, the Colima volcano has been studied, in which under the financing of the Consejo Nacional de Humanidades Ciencias y Tecnología (CONAHCYT, Project 221487) a 3D model of electrical resistivities was obtained that was related to velocities due to an Ambient seismic noise Tomography (Arzate et al. 2023). For this study, 21 MT stations were acquired.

Furthermore, due to the energy reform and the government's commitment to clean energy, several geothermal exploration tenders have been opened to private companies. For instance, Reykjavík Geothermal undertook an exploration project between the Ceboruco and Tepetiltic volcanoes, and the company decided to share its MT data with the academic community, enabling the creation of a 3D resistivity model for the area, which was presented at the 25th EM Induction Workshop (Castro et al. 2022).

These research initiatives, supported by various funding sources and collaborations, have significantly contributed to the understanding of **México's** geothermal resources and have the potential to drive further developments in the field.

Current challenges of geothermal energy in México

México has been a pioneer in geothermal resource exploitation in the Americas, yet the lack of proper regulations to encourage public participation in geothermal resource exploitation has hindered geothermal electricity production since 2005, as illustrated in Table 3. Currently, only FCE has been granted exploration and exploitation rights for geothermal prospects, and it has been more than 20 years since the last geothermal plant was commissioned by FCE. Private companies were granted permission to explore ten electricity generation prospects between 2014 and 2018, but they were not granted permission to renew the advanced exploration phase and these projects can now be considered cancelled.

There are no current projects for low–medium enthalpy areas, except for one research project for direct use in fruit and vegetable dehydration. Although low-enthalpy areas are mostly utilized for balneology, mainly swimming pools, there is a significant opportunity for profit with the abundant resources if appropriate information about these resources is disseminated. These resources could be used for sophisticated balneological purposes, climatization, agricultural, and industrial applications.

In 2014, the government-funded research centers on clean energy and related subjects, particularly the Mexican Innovation Center in Geothermal Energy (CeMIE-Geo), generated important results applicable to the exploration and exploitation of México's geothermal resources, including a detailed national inventory and exploration of specific prospects (Arango-Galván et al. 2015; Prol-Ledesma et al. 2018; Prol-Ledesma and Morán-Zenteno 2019). However, this research center has been neglected by the current administration, and funding for geothermal research and application projects has been scarce.

Discussion

As we explore the literature on geothermal resources in Latin America and their exploration using EM methods, it becomes evident that several research questions, challenges, opportunities, and future directions merit further investigation. Our revision aims to delve deeper into these aspects, aiming to provide a more comprehensive analysis. Such progress could address in the following aspects:

i. Advocate for the inclusion of geophysics in the initial exploration phase before drilling wells: This would involve conducting geophysical surveys, such as EM surveys, to provide data on the subsurface properties and characteristics of the target area. This approach would enable a better understanding of the geothermal resource potential, reduce drilling costs and risks, and increase the overall success rate of geothermal development.

ii. Integrate EM imaging solutions with other exploration techniques: Investigating the most effective ways to integrate EM imaging data with other exploration data (e.g., seismic methods, gravity techniques) to improve the accuracy and reliability of geothermal resource exploration is required.

iii. Study inter-dependencies across survey parameters: This could involve a detailed analysis of how survey parameters, such as source frequency, antenna spacing, and orientation, affect the quality of EM imaging data. By understanding how survey parameters influence the imaging results, it is possible to improve the quality of the data, which can lead to more informed decision-making in the management and monitoring of geothermal fields.

iv. Study the cost-effectiveness and environmental impacts of EM imaging for geothermal resource exploration: One could explore the role of EM imaging in achieving sustainable energy resources and assess the trade-offs between cost, environmental impact, and energy production. Additionally, one could investigate the potential of EM imaging for identifying and mitigating environmental risks associated with geothermal exploitation (e.g., subsidence, induced seismicity, and geothermal fluid leakage).

v. Increase the maturity of AI-based EM imaging solutions in the exascale computing era: One could explore the potential of AI techniques for enhancing the accuracy, resolution, and speed of EM imaging for geothermal resource exploration. This could involve developing new AI-based algorithms for processing and interpreting EM imaging data, as well as integrating EM imaging data with other exploration data using AI techniques. It is imperative to consider the exascale computing era (Shalf et al. 2011) in this context.

vi. Encourage collaboration between the government and private sector to enable the use of more advanced and integrated exploration techniques: The private sector could play a significant role in bringing in advanced exploration technology and techniques that can complement the existing geological surveys conducted by the FEC. Such collaboration would enable the government to tap into the expertise and knowledge of the private sector, leading to the development of more efficient and effective geothermal projects.

vii. Promote research and development efforts in geothermal exploration and exploitation in Latin-America: This could involve investing in research and development of advanced geophysical techniques and promoting the education and training of geoscientists in the country. This approach would enable the development of local expertise, leading to a more comprehensive understanding of the geothermal resources in Latin-America and more effective and efficient geothermal projects.

viii. Identify the unresolved questions that currently hinder the successful application of EM imaging for geothermal resource exploration in Latin-America: This could include a detailed assessment of the strengths and limitations of EM imaging technology in the context of geothermal resource exploration. Furthermore, there is a need for evaluating the challenges pertaining to data acquisition, processing, and interpretation, along with the limitations of the existing EM inversion algorithms. Additionally, future directions for research could include a comprehensive evaluation of the cost-effectiveness and environmental impacts of EM imaging, with an emphasis on developing sustainable energy resources.

ix. Create a centralized platform for geothermal research and collaboration, uniting diverse institutions (government and private) involved in the field: This platform would serve as a hub for sharing information, data, and research findings related to geothermal exploration in México. By promoting collaboration and information exchange, duplication of research efforts can be minimized, and resources can be allocated more efficiently. The centralized platform would facilitate coordination among research institutions, allowing them to identify ongoing studies and areas of focus. It could include a database or repository of previous studies, exploration data, and geological surveys conducted by different entities. This would provide researchers with a comprehensive overview of the existing knowledge and findings, helping them avoid redundancy and focus on areas that require further investigation.

Exploring the aforementioned research questions can significantly advance our comprehension of the potential of EM imaging in geothermal resource exploration and promote the progress of sustainable energy resources.

Conclusions

This paper details the installed generation capacity of electricity of most geothermally significant countries in Latin-America, and comments on the estimated potential production of existing prospects. Main geothermal developments have taken place in **México**, Costa Rica, Salvador, Nicaragua, Guatemala, Chile and Honduras, with a production capacity by 2020 of 963, 252, 204, 159, 52, 48, 35 MWe, respectively. This production capacity along with geothermal electricity generation of other Latin-American countries, allows the region to produce approximately 1.7 GW, contributing around 11% to the installed capacity worldwide. On the other hand, countries with large geothermal reserves for practical electricity production are **México**, Costa Rica, Salvador, Ecuador, Argentina, Nicaragua, Guatemala, and Chile with estimations above 10.45, 1.0, 2.21, 2.0, 1.0, 1.0, 1.0 and 16 GWe, respectively. In addition, evaluations of geothermal reserves have taken place in Bolivia, Brazil, and Colombia. Thus, geothermal energy has emerged as a promising renewable energy source in Latin-America, offering significant potential for sustainable power generation, with an important contribution to a more sustainable energy future.

In this region, **México** is the top electricity producer from geothermal sources, so we develop an extensive analysis of EM imaging technologies for geothermal exploration in this country. This analysis starts with the general current state of MT imaging technology, including advantages and limitations, applications in geothermal energy, and future directions for exploration of geothermal resources in **México**. We identify the need for further research in areas such as the integration of EM imaging with other exploration techniques, the study of survey parameters and inversion algorithms, the monitoring and management of geothermal fields, the evaluation of cost-effectiveness and environmental impacts, and the exploration of AI tecniques in the exascale computing era for enhancing EM imaging. Our findings suggest that EM imaging has the potential to significantly improve the accuracy and reliability of geothermal resource exploration in **México**. Its non-invasive nature and ability to provide detailed information about subsurface properties make it a powerful and versatile tool for subsurface characterization.

We are confident that this literature review paper offers significant value, not only for geothermal resource exploration in **México** but also for the global community, especially the expanding exploration efforts in Latin-America. By addressing the research questions and challenges identified in this paper, not only can the EM and geothermal communities in **México** advance their understanding of the potential of EM imaging, but also contribute to the global development of sustainable energy resources. The insights gained from this literature review paper can inform and guide future research efforts and investment in EM imaging for geothermal resource exploration worldwide. We hope that this revision encourages the EM and geothermal international communities to continue exploring the vast potential of this powerful and versatile technology for the benefit of society and the environment.

In summary, we hope that this paper not only encourages the EM and geothermal communities in Latin-America, especially in **México**, but also inspires researchers and practitioners worldwide to further explore the potential of EM imaging and its integration with other exploration techniques. By working collaboratively and addressing the open research questions and challenges, we can unlock the full potential of EM imaging for geothermal resource exploration and contribute to the development of sustainable energy resources globally

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Author contributions
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Declarations

Competing interests
Authors declare that they have no competing interests.

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