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Geothermal Country Update Ecuador 2020-2023

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ABSTRACT

Ecuador's massive geothermal potential remains largely under-explored and barely harnessed. Government policies, according to the Master Plan for Electricity, aim to develop renewable energy resources, including geothermal, to substantially reduce the use of fossil fuels. The current electric energy mix is dominated by hydro (58.5%), fossil fuels (39.2%) and other (2.3%) with a total installed generation capacity of 8734.41 MWe (MEM 2022). The gross energy production was 32571 GWh/yr in 2021, where 26089.4 GWh (80%) are from renewables, 6123,3 GWh (18.8%) are from fossil fuels and 358.3 GWh/yr (1.1%) are from interconnexion with neighboring countries (ARCERNNR 2022). The theoretical geothermal exploration potential of Ecuador is given by six geothermal plays: 1. Galápagos Rift, 2. Galápagos Hot Spot, 3. Northern Andes, 4. Southern Andes, 5. Coastal Fore-arc basin, and 6. Oriente Foreland basin. Chachimbiro, located in play #3, is the first priority prospect among eleven proposed in the Geothermal Plan launched by the government in 2010. It has completed the prefeasibility stage, and a successful deep exploration well. The wellhead is located at 3460 masl presenting BHT of 235°C. It was drilled with the help of non-reimbursable funding and technical cooperation of JICA to CELEC EP, the institution in charge of high temperature geothermal resources. A follow up 2nd stage at Chachimbiro, to be funded by a government-to-government loan through JICA, is envisioned for drilling 5 additional appraisal wells and for the installation of a 5MWe wellhead unit, both to be tendered by CELEC under JICA regulations; positive results would aim for a 50 MWe power plant. At time being, Chachimbiro is on hold until the approval of the loan by Ecuador´s authorities. Three high temperature prospects, all in play #3, namely Chacana-Jamanco, Chacana-Cachiyacu and Tufiño-Chiles, and one low temperature prospect, Chalpatán, are almost ready for deep exploratory drilling; a brandnew near-neutral alk-chloride bicarbonate boiling spring at 87ºC surfaced in 2020 about 7 km S of Chiles volcano, due to recent shallow seismic activity pulses. It seems to be related to the deep water-dominated reservoir of the Tufiño-Chiles Geothermal system. The other six prospects are Chalupas, Chimborazo and Chacana-Oyacachi (all in play #3), Guapán and Baños de Cuenca, both in play #4 and Alcedo (in play #2), which are awaiting government funding to complete prefeasibility studies.

Utilization of geothermal energy is still restricted to direct uses in swimming pools (5.16 MWt and 102.4 TJ/yr for annual utilization). Nevertheless, the IIGE, which is in charge of the development of low temperature geothermal resources, has started the operation of the first greenhouse powered by GSHP with a horizontal ground loop. The IIGE also launched the study for the use of low to medium temperature geothermal resources in the country's energy mix, including the Geothermal Resource Map, which was done with the technical support of CEGA in the framework of the government-to-government agreement with Chile. IIGE's main near-future developments include i) the study for a geothermal desalination plant in Galápagos, ii) studies for a hybrid solar/geothermal grain dryer, and iii) analysis for geothermal heating using PCR (phase change materials) for urban and rural buildings, among others.

Preliminary studies targeting prospective reconditioning of Oil and Gas wells for geothermal production and direct uses in the Oriente Basin (Play # 6) have been undertaken and look very promising. First thoughts about candidate sites for interesting prospects for deep geothermal resources at the brittle/ductile transition are being considered by academia and industry, with emphasis in Play # 3. An important new action is the set-up of the Geothermal Round Table, which is due in January 2023 with MERNNR (Ministry of Energy and Non-Renewable Resources) as leader, it is funded by the IDB (Interamerican Development Bank, ca. 10 MUSD), and will determine the updated road map of the future harnessing of geothermal resources in Ecuador for the next decade and its inclusion into the energy matrix.

Finally, 2021 saw the birth of The Ecuadorian Geothermal Association (AGE), which has joined efforts with similar entities of Mexico, Colombia, Perú, Chile, the IGA, and GGA for pushing forward the development of geothermal resources in the region, and aims at becoming the memory and official voice of geothermal in the country. Along with this effort, Ecuador also counts now with its WING (Women in Geothermal) branch, with worldwide contacts in the geothermal industry.

1. INTRODUCTION

This paper is a follow up of the country update for the previous interval (Beate et al., 2020). It summarizes geothermal activities in Ecuador for the period 2020-2023. Nevertheless, the history of exploration before 2020 and the detailed description of explored and under-explored areas or prospects has been only thinly included in this summary, since no substantial changes have occurred in this last period regarding exploration, mainly because of priorities hit during the Covid19 pandemic; in this case, the reader is kindly referred to the previous country updates (Beate and Salgado, 2010, Beate and Urquizo, 2015 and Beate et al., 2020) and to the references therein.

Ecuador is a democratic republic, located on the equatorial pacific margin of Western South America; it has 18 million inhabitants (INEC, 2019) living in a territory of 256,370 km^2 (IGM, 2019); the official language is Spanish and the GNP was 108 398 MUSD for the year 2018 (BCE, 2019).

Since the approval of our last Constitution in 2008, the governmental aim has steered towards a stronger participation of the state in exploration and development of the country's energy and mineral resources. It is the aim of the government to change the energy matrix towards the substitution of the fossil fuels for power generation with indigenous, clean, renewable energy resources, mainly hydro, but also including wind, solar, geothermal and biomass.

The leading agencies for geothermal energy are MERNNR (Ministry for Energy and Non-Renewable Resources), CELEC EP (Public Corporation for Electricity Generation and Transmission), IIGE (Institute for Geological and Energy Research) and MAE (Ministry of the Environment, which includes Water issues).

Public funding has been allocated for geothermal exploration to both high and low temperature resources. In accordance to the Constitution, which dictates that the State will be responsible to provide and regulate public services such as electricity, energy concessions can be granted by exception through private finance initiatives (i.e., public auctions), private investment or joint ventures with public companies where the State of Ecuador owns at least 51 % interest, but final adjustments for geothermal regulations are still pending.

The following pages include a short overview of Ecuador's geological setting, a listing of geothermal resources and potential, together with the state of geothermal utilization and a discussion of the actual and future development.

2. OVERVIEW OF ECUADOR´S GEOLOGICAL SETTING

Mainland Ecuador, located at the pacific equatorial margin of western South America, consists of three geographically and geomorphologically distinct regions: the coastal plains or Costa to the W, the Andes high mountain chain or Sierra in the center and the upper Amazon basin or Oriente flatlands to the East. A fourth region comprises the Galapagos Archipelago, roughly located about 1000 km W of mainland Ecuador, in the Pacific Ocean (Fig.1).

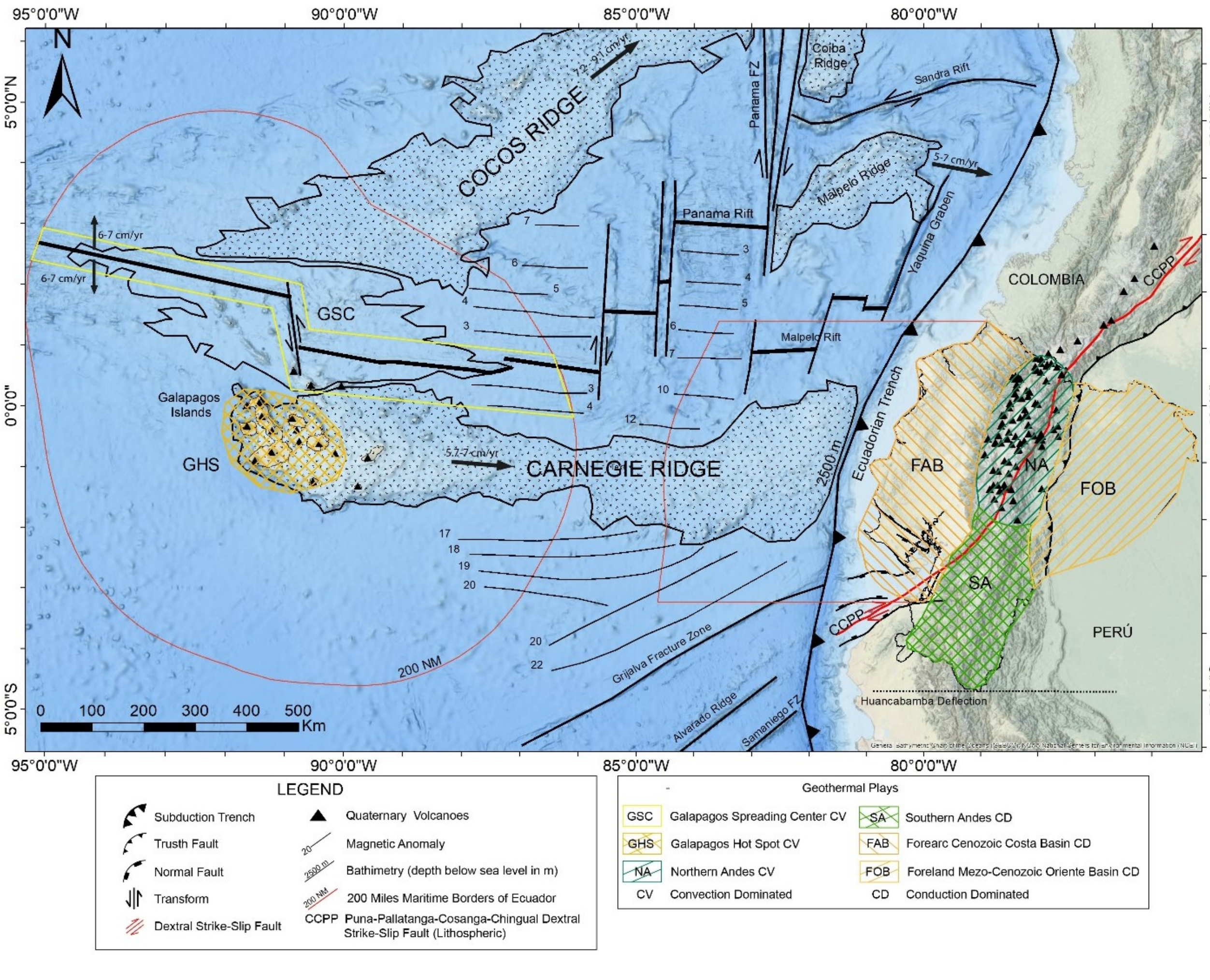

Figure 1. Geodynamic setting of Ecuador and its Geothermal Plays. Redrawn after The Global Multi-Resolution Topography (GMRT) Synthesis (Ryan, W.B.F. et al., 2009) and Maritime limits of Ecuador-IOA (2011) and modified from Bernard and Andrade (2011), Spikings et al., (2001) and Gutscher et al., (1999).

The Andes are the backbone of the country. They consist of two parallel NNE striking mountain chains: a) the Eastern Cordillera or Cordillera Real, which are sub-linear NNE striking belts of juxtaposed metamorphic rocks of mainly Paleozoic age, intruded by both, S and I – type batholiths of early – mid Mesozoic age (Spikings et al., 2015); and, b) the Western Cordillera or Cordillera Occidental, which core consists of oceanic lithosphere with a Mid-Cretaceous basaltic plateau on top, accreted towards the continent in late Cretaceous; further Paleocene volcanics and volcaniclastic material was added in now folded and faulted sequences; these rocks are intruded by Neogene I-type granitoids (Litherland et al., 1993; Vallejo, 2007). Both cordilleras have been tectonically uplifted (Horton & Folguera, 2019) and are capped by mid- to late Tertiary volcanics. Between the two Cordilleras, the Interandean Valley developed; it is laterally bonded by active faults, mainly thrust faults, and consists of thick late Tertiary to Recent volcaniclastic and epiclastic sedimentary sequences. Covering both Cordilleras and the Interandean Valley in the Northern half of the Sierra, a broad, well developed, cal-alkaline volcanic arc extends northwards into Colombia (Barberi et al., 1988; Hall & Beate, 1991). This continental arc is of Quaternary age and consists of more than 80 volcanoes, of which at least 20 have been active in the Holocene (Hall et al., 2008) and two are currently in eruption. The Southern half of the Sierra shows extensive, Oligo-Miocene explosive volcanism, but now extinct, due to the flattening of the slab since late Miocene (Gutscher et al., 2000).

The Costa is the flat region west of the Andes; it comprises a late Cretaceous to Cenozoic forearc basin underlain by cold early Cretaceous, oceanic crust; no active volcanism is present in this region (Litherland et al., 1993).

The Oriente is an extensive sedimentary basin, which overlies a cratonic basement (Baldock, 1982). Older rocks include Jurassic batholiths and a Cretaceous carbonate platform, covered by Tertiary epiclastic sediments (Vallejo et al., 2022). Along the cordilleran foothills, large thrust faults cut the sequence with a NS strike. Quaternary alkaline volcanoes are present along the western margin of the basin in a back arc setting (Hall et al., 2008). Mid-to Late Cretaceous intraplate basaltic volcanism affected the central part of the basin (Barragan & Baby, 2014)

The Galapagos Archipelago, together with the aseismic submarine Carnegie ridge, represents the Galapagos Hot Spot (GHS) trace above the Nazca Plate. The islands consist of about fifteen Quaternary basaltic shield volcanoes, increasing in age towards the East. Just N of the Islands, the Galapagos spreading center (GSC) follows a EW strike and it is off set by the 91ºW transform (Fig. 1).

Geodynamic processes are controlled since late Oligocene by the nearly orthogonal convergence between Nazca and South American plates, which has generated regional uplift and crustal faulting and deformation, as well as extensive volcanism (Lonsdale, 1978). The western and northern part of the country constitute the North Andean Block, which moves in a NE direction along the dextral strike slip CCPP fault (Yepes et al., 2016; Vaca et al., 2019).

3. GEOTHERMAL RESOURCES AND POTENTIAL

Six geothermal plays (GTP), following Ecuador´s tectonic setting, together with its geology and geothermal manifestations, are proposed after IGA-IFC (2014) and summarized (from W to E), in order to update the known prospects (what, where, characteristics of resource and potential of prospects) and to assist on the assessment of exploration potential and targeting on high and low temperature geothermal resources (Fig. 1 and Table 1).

Table1. General Characteristics of the Geothermal Plays of Ecuador.

Geothermal Play	Dominant heat transfer mechanism	Tectonic setting	Volcanic activity		Status of geothermal exploration	Geothermal potential (theoretical)	Remarks
			Style	Age			
Galapagos Spreading Center	Convection	Rift	Basaltic	Quaternary	Unexplored	High	Protected area
Galapagos Hot Spot	Convection	Hot spot	Basaltic	Quaternary	Early reconnaissance	High	Protected area
Northern Andes Highlands	Convection	Continental arc	Andesitic, dacitic-rhyolitic	Quaternary	Reconnaissance to prefeasibility	High	Half dozen projects in prefeasibility stage (First deep exploration drilling @Chachimbiro)
Southern Andes Highlands	Conduction	Continental arc	Rhyolitic, andesitic	Tertiary	Early reconnaissance	Moderate	Early prefeasibility stage in Baños de Cuenca prospect
Costa Forearc Basin	Conduction	Forearc basin	-	-	Early reconnaissance	Low	Initial observation for direct uses
Oriente Foreland Basin	Conduction	Foreland basin	Basaltic	Cretaceous	Early reconnaissance	Moderate to high	Potential use of many out of service deep oil wells

<u>Geothermal Play 1: Galápagos Spreading Center (GSC).</u> This convection-dominated play is located to the N of the Galapagos Archipelago and consists of the submarine crest of the active Galapagos Spreading Center (GSC) and the 91ºW Transform, and the small-to moderate size, basaltic, northern islands of Genovesa, Marchena, Pinta, Wolf and Darwin (Fig.1). The oceanic rift has been active since Late Oligocene and very high heat flow values are reported since the dawn of plate tectonics (Williams et al., 1974). Intense submarine hydrothermal activity, including black smokers, has been described in literature. The rift is cut by the seismically active 91ºW transform and separated for more than 100km, where the southern part of the rift is quite close to Pinta Island (about 30 km). Due to rift-transform interaction (Harpp et al., 2002), several ridges do connect the northern islands with rift activity, enhancing volcanism in this area; many historical and sub-historical lava flows are commonplace. Genovesa is on top of such a ridge and its

central caldera shows signs of past hydrothermal activity (Beate, 1978); on the other hand, ridge-parallel NE fractures cross the island and show very recent associated basaltic lava flows (Harpp et al., 2003). This play has not been explored yet for geothermal energy, despite the high heat flow scenario. On the other hand, it is part of the Galapagos protected area, which renders any geothermal development as utopic under present technological and environmental constraints.

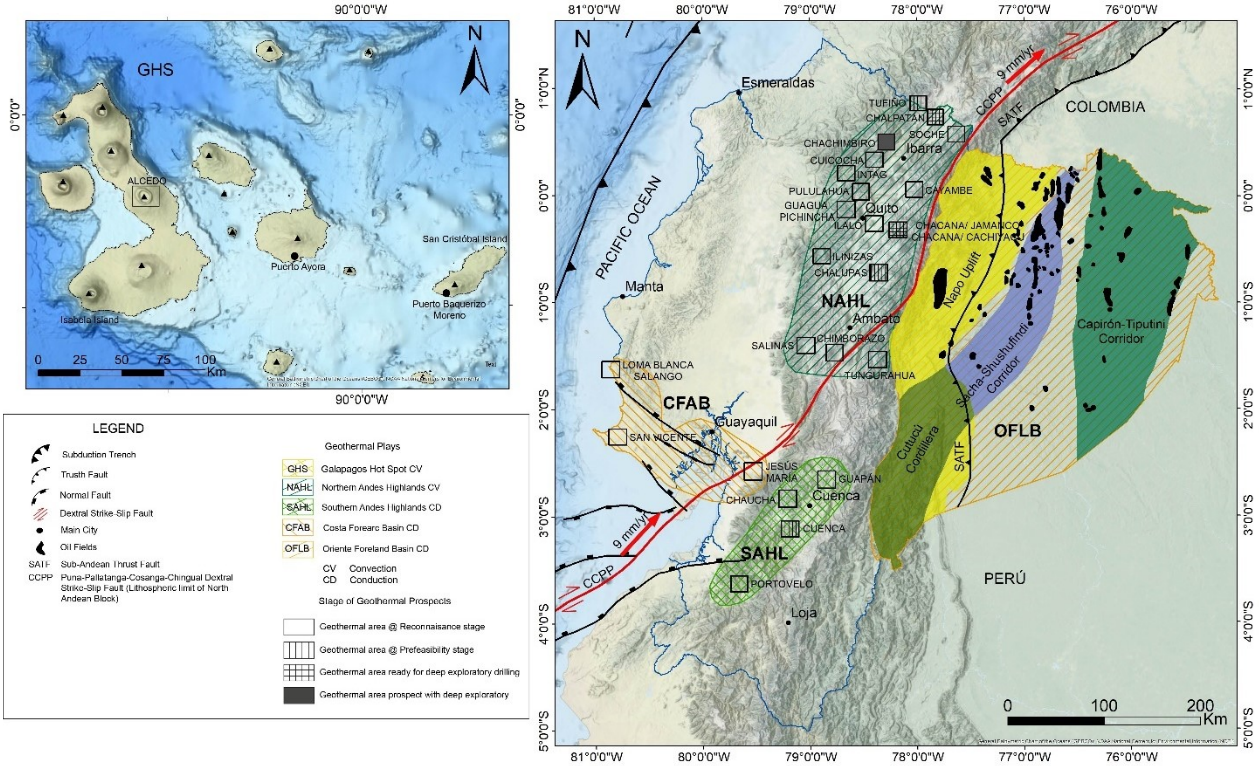

Figure 2. Geothermal Plays showing location and exploration stage of Geothermal Prospects in mainland Ecuador. Modified from Vaca et al., (2019); Beate and Urquizo (2015) and Baby et al., (2013).

Geothermal Play 2: Galapagos Hot Spot (GHS). This convection-dominated play comprises the central part of the Galapagos Platform, which has been constructed by the Galapagos Hot Spot (GHS) on top of the East- drifting lithospheric Nazca Plate. The majority of the 15 islands are constructed by basaltic shield volcanoes with central calderas of Quaternary age (Harpp and Geist, 2018). Most of the recent and current volcanic activity is located in the bigger western islands, which are closest to the hot spot up-flow. The central and eastern islands show a general eastwards increase in age due to the drift of the Nazca plate, nevertheless, many of these islands also show signs of recent volcanic activity. This is due to plume-rift-asthenosphere interactions along time. This play has not yet been explored for geothermal resources, despite the high theoretical potential due to massive volcanism and high regional heat flow, mainly for strict environmental and conservation policies, since Galapagos is a National Park.

Only one geothermal prospect is known until now from volcanological studies. It is located on Isabela Island inside the summital collapse caldera of Alcedo shield volcano. It shows extensive hydrothermal alteration, numerous explosion craters (at least seven), strong geothermal fumaroles discharging vapor at 97°C (locally superheated at 130ºC) and a heat source related to a primary basaltic origin but also to shallow rhyolitic intrusions associated with explosive silicic volcanism of recent age (c.a. 120 ka, Geist, 1994) like obsidian flows and rhyolitic Plinian tephra. The area is situated on the SSW structural rim of the caldera, which might indicate good permeability at depth exploratory wells, were a shallow high-temperature water-dominated geothermal system is present. Empirical gas geothermometry indicates temperatures of 260 to 320°C for this intra-caldera reservoir, which is probably capable of producing up to 150 MWe (Goff et al., 2000). This project has the capacity to decarbonize the Islands energy matrix (Icaza Alvarez et al., 2022; Jara-Alvear et al., 2021).

This spectacular geothermal prospect is located inside the Galápagos National Park, and any intend to explore and exploit it must obey strict environmental regulations, if a geothermal permit is granted at all. Other limitations are the lack of any road infrastructure, few distant power users without transmission line and scarce or no water for drilling. If power is tapped, it would imply the construction of submarine transmission lines to the load centers located tens of km away in Isabela, Santa Cruz and San Cristóbal islands.

The Ministry of Energy and Mines is planning a cooperation with JICA to carry out geothermal exploration in Isabela, one of the Galapagos Islands (GTPlay#2). There is a plan to work as a team with CELEC EP, IIGE and Elecgalapagos to carry out geological, geochemical and geophysical studies to determine the potential of geothermal energy on the island. JICA will provide experts to analyze the data obtained and perform conceptual models to estimate the potential. The MEM plans to sign the agreement at the end of 2022.

Geothermal Play 3: Costa Forearc Basin (CFAB). This conductive-dominated play comprises the geographic Costa region and represents the fore-arc basin, which mainly consists of Tertiary shallow marine sediments overlying a cold basaltic oceanic crust of mid-K age (Baldock, 1982; Litherland et al., 1993). Given that the northern part of this play has no geothermal manifestations and sediment cover is rather shallow, we recommend the southern part of the play for GT exploration purposes. Several warm springs are located along the coastal front (i.e., Salango-Agua Blanca) and the southern part is dominated by the Ancón oil field (Salinas warm springs at San Vicente, a methane-rich mud volcano) and the Gulf of Guayaquil gas field, where production drilling has reached deep levels of the basin sequence (86ºC BHT at 4899 m, Barba, 2017). Geothermal gradients are about low average for this kind of geological setting, showing a range from 17 to 24 ºC/km (Barba, 2017), due to the presence of a cold mid-cretaceous oceanic basement. Nevertheless, the availability of out-of-service deep reaching production wells, indicates the presence of an already-drilled low-temperature GT resource which awaits to be assessed and, eventually, tapped for direct uses. On the other hand, this area is cut by the dextral strike-slip CCPP fault, which enters the Gulf of Guayaquil from the ocean in a NE direction and represents the border of the North Andean block, whose trace can be followed all though Ecuador and Colombia up to Venezuela (Yepes et al., 2016). This main structure is active and apparently controls the location of the hot springs of Jesus Maria (55ºC), at the Andean foothills, at the E border of this play. Low temperature geothermal resources for direct use are the main target in this conduction dominated play.

Geothermal Play 4: North Andean Highlands (NAHL). This convection-dominated play comprises the northern half of the Andes Cordillera; it is characterized by the presence of extensive active Quaternary volcanism and hosts the most explored geothermal sites in the country.

Chachimbiro is the first priority prospect, of 11 prospects in the Geothermal Plan launched earlier by the government (Beate, 2010).

The Chachimbiro Project is the most advanced project. The first well was drilled in 2017 and reached 235°C. The project is executed by the national utility CELEC EP and has an ODA loan with JICA approved since 2019 for the first stage. The first stage involves 5 production diameter wells, a wellhead power plant and the engineering for the next stage. CELEC EP did all the paperwork to obtain the sovereign guarantee and permission from the Ministry of Economy and Finance (MEF) to start the loan, but in the first quarter of 2021, the Ministry replied that it cannot issue the Sovereign Guarantee until CELEC includes in its liabilities the two hydroelectric plants debts: Coca Codo Sinclair and Sopladora (2300MUSD) paid by the MEF so far. CELEC is not yet receiving the funds to cover this debt and this decision requires an increase in tariffs or electricity subsidies. For now, the government has not found a final solution and the Chachimbiro Project remains on hold.

The Chacana Project is under analysis to start a process to make a joint venture with CELEC EP to develop it. The associativity regulation for CELEC EP is under development, but this project will be one of the first to be carried out in this modality. The Chacana Project has two prospects: Jamanco and Cachiyacu. This is the closest project to Quito (40km) and is very well connected by highways and transmission lines.

No changes have occurred in this period 2020 – 2023 for the other prospects. Three high temperature prospects in this play, namely Chacana-Jamanco, Chacana-Cachiyacu and Tufiño-Chiles, and one low temperature prospect, Chalpatán, are almost ready for deep exploratory drilling. The other six prospects are Chalupas, Chimborazo, Chacana-Oyacachi, Baños de Cuenca, Guapán and Alcedo, where the latter three correspond to plays 5 and 2 (Alcedo), respectively. These prospects are awaiting government funding to complete prefeasibility stage studies and site deep exploration wells to tap geothermal energy for electricity generation and direct use.

Geothermal Play 5: South Andean Highlands (SAHL). This conductive-geothermal play is located in the southern half of the Andes Cordillera and is characterized by extinct mid-late Tertiary volcanism; the last eruption in this area happened 3.6 Ma ago (Beate, 2001) in the Quimsacocha caldera. Many hot to warm springs are scattered in the area (De Grys, 1970), although Baños de Cuenca (75ºC) and Guapán (50ºC), together with Portovelo (55ºC) represent the hottest ones. IIGE´s early pre-feasibility study points to deep temperatures of 100 to 140 ºC for Baños de Cuenca, being the most likely heat source the normal geothermal gradient, although a recent gravity survey by Asimbaya (2020) suggests a heat source to the E. An MT survey by IIGE is planned for the near future in the Baños de Cuenca area.

Geothermal Play 6: Oriente Foreland Basin (OFLB). This conductive dominated play comprises the eastern Oriente Foreland basin, which is a thick sequence of Mesozoic to Tertiary age sediments, including a carbonate platform and continental siliciclastic units (Baldock, 1982; Vallejo et a., 2021). These rocks host many oil fields, from which Ecuador has drawn an important part of its cash for the last half century through oil exports. The oil industry has drilled in this time about 2000 production wells covering a great deal of the basin and an average GTG of 22 ºC/km on 100 wells has been obtained by Burgos (2004) and Barba et al. (2021). A recent study by Angulo (2019) shows BHT distribution and preliminary values for geothermal gradients for most of the oil production areas (fig. 3). Results indicate low GT gradients for the Central Corridor (av. 16.75ºC/km), but rather anomalous high gradients for the areas located on each side of the Corridor: av. 57.11ºC/km in the W area and av. 56.9 ºC/km for the area to the E, reaching a maximum value of 88ºC/km. Unofficial reports indicate about 200 000 barrels of 85ºC hot water per day in one of the eastern oil fields (ITT). The western part is called the Napo-Cutucú uplift and shows the older rocks of the sequence, including the large outcropping Pungarayacu tar field as well as active alkalic back-arc volcanoes (i.e., Sumaco). It is possible, that deeper fluids are reaching shallower levels following paths along fractures and faults. The eastern part is called the Capirón-Tiputini oil play and shows a closer vertical distance to the hotter (?) basement. The existence of high GT gradient anomalies and a thorough knowledge of geology and structure of the Oriente basin, together with the straightforward availability of many out-of-service deep production wells in this geothermal play at sites with anomalous GTG, opens up the opportunity to readily consider the assessment and development of low – medium temperature resources for direct uses or even for electricity generation. The first step of using the energy that is currently discarded (by hot water dumping and reinjection) to supply all the thermal needs of the Oil and Gas industry (See discussion section) in this play is a straightforward task (Choi et al., 2017). Further development of thermoelectric downhole power generators or centralized binary power plants require more investigation and investment but can help drastically offsetting the carbon footprint in the region (Wang et al., 2018).

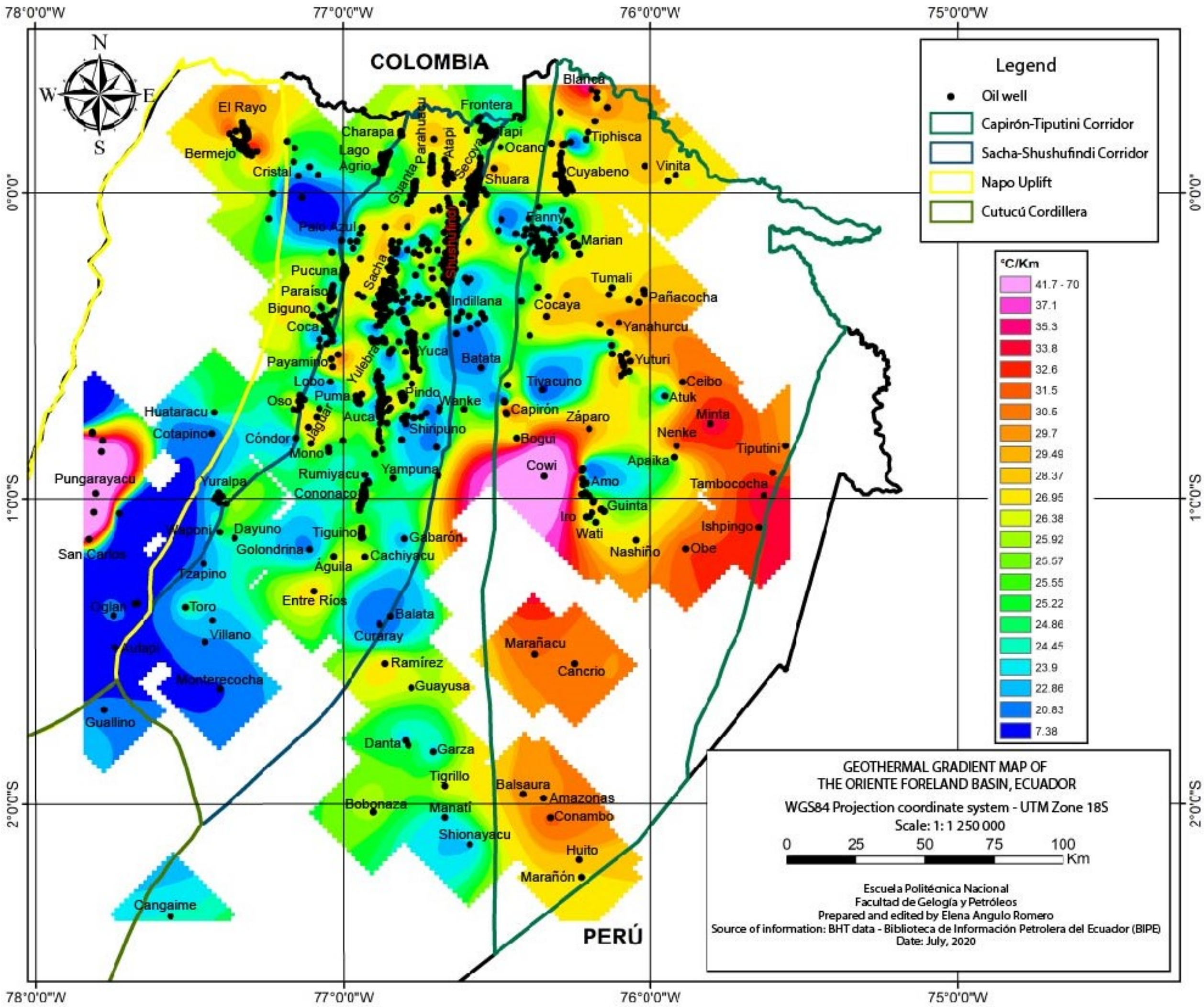

Figure 3. Geothermal Gradient Map of the Oriente Foreland Basin using Bottom-Hole temperatures data. Modified from Angulo and Beate (2019).

4. GEOTHERMAL UTILIZATION

Until 2019, utilization of geothermal resources in Ecuador was restricted to direct uses only, that is, for bathing resorts, balneology and swimming pools. A summary of many, but not all, hot and warm springs used for swimming pools is shown in Standard Table 3, giving a total installed capacity of 5.157 MWt and an annual energy output of 102.401 TJ/yr, which remains unchanged since the last update.

4.1. Direct Uses

In 2021, the Institute for Geological and Energy Research (IIGE) with technical support from the Andean Geothermal Center for Excellence released the first map with the identification and characterization of the usable geothermal potential in Ecuador for direct use purposes (fig.4). It was elaborated using available geo-chemical data and a mathematical model to estimate deep earth temperatures in the provinces that have a geothermal resource nearby.

As a result, attention was regained in the Chalpatán geothermal prospect in which the development of a geo-industrial complex in the area would greatly benefit farmers from the utilization of low and medium grade geothermal heat in activities such as horticulture, aquaculture, cereal and dairy farming, and livestock rearing (Lloret, 2021). The proposal is still on hold pending funds to advance to an exploratory phase which includes drilling two wells at a depth of approximately 1500 m to study the lithostratigraphy and the characteristics of the materials from the edge of the caldera.

4.2. Ground Source Heat Pumps (GSHPs)

IIGE has started the construction of a hybrid renewable energy system that uses GSHPs and solar energy for quinoa drying. A water-water heat pump will extract energy from a horizontal ground loop that will act as backup system to a solar collector array. Hot water will be fed into a fan coil heat exchanger in order to accelerate the drying of quinoa grains. The project is part of a second phase pilot program, located next to the geothermal greenhouse which is in operation since 2021 (IIGE, 2021). Other R&D activities related to the use of ground source heat pumps include: 1) the study on the design of low temperature geothermal systems for heat removal in buildings with humid and tropical climates and 2), the implementation of HVAC energy saving strategies for public buildings in the Galapagos Islands. The first has received funds from the Cooperative Joint Commission between the governments of Ecuador and

Chile with results expected to be ready in the last quarter of 2023. The second has been submitted for international cooperation fund allocation and is currently waiting for final approval.

Finally, interest from a private resort located within the Chacana caldera has been manifested in order to use hot springs to heat a small building complex that will host their guests. Prefeasibility studies are being prepared.

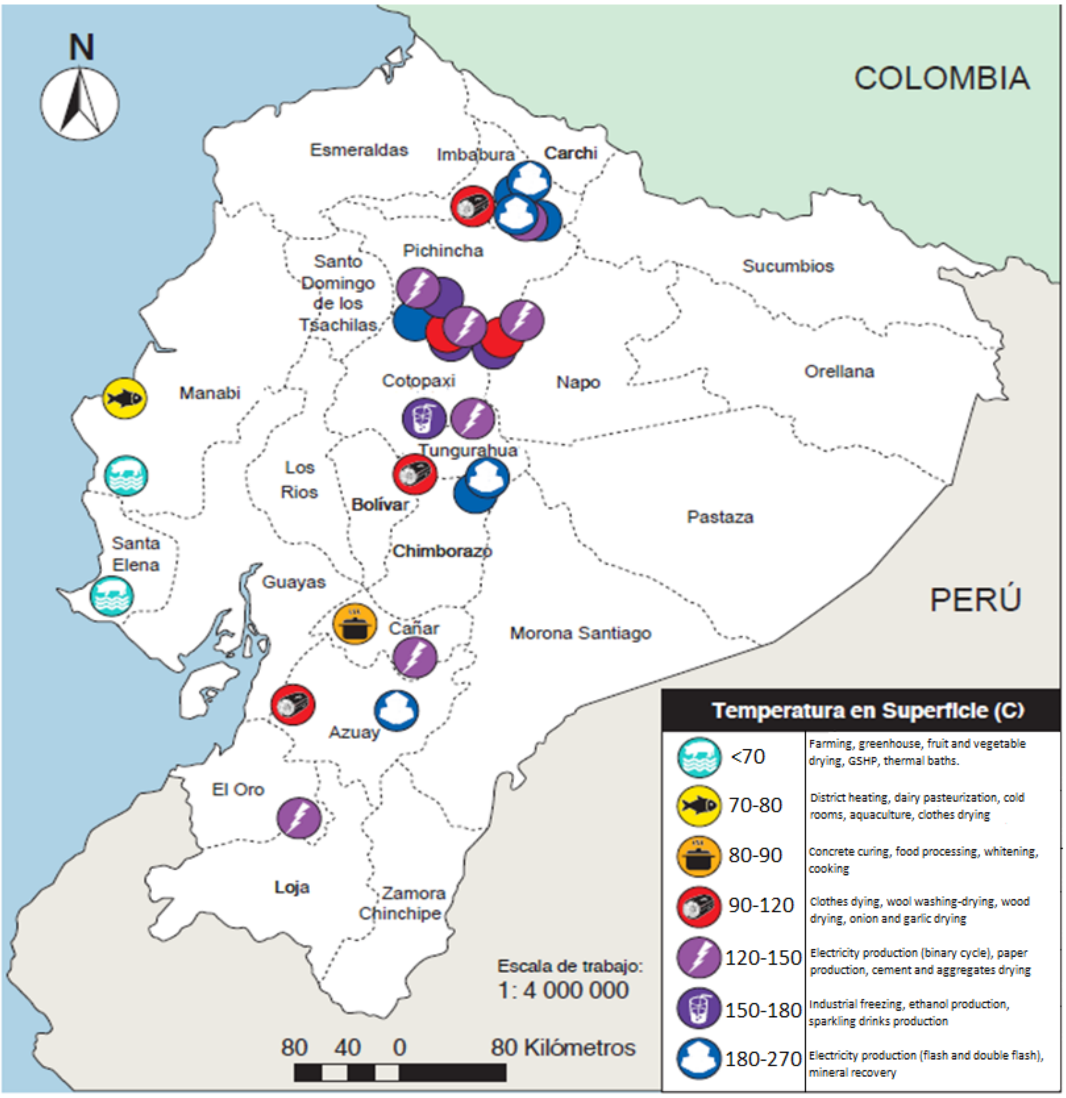

Figure 4. Geothermal Resource identification of the usable geothermal potential in Ecuador for direct use purposes. Modified from IIGE (2020).

5. BIRTH OF THE ECUADORIAN GEOTHERMAL ASSOCIATION

2021 marked the birth of the Ecuadorian Geothermal Association (AGE for its Spanish acronym; Urquizo et al., 2023). From its creation, under the wing of Women IN Geothermal (WING), AGE was aimed at promoting research and the sustainable use of geothermal resources through the dissemination, construction and strengthening of national and international exchange networks. AGE targets the public, private and academic sectors to contribute to environmental sustainability, energy security and social equity in Ecuador under the values of cooperation, gender equality and respect for nature. This, by using a holistic approach that addresses technical, environmental, social, legal, and political problematics in synergy.

The core members of the association belong to widely different backgrounds (Oil and gas industry, power companies, academia, construction companies, legal associates, social/environmental professionals, engineering and geological consultants, etc.). These members work collectively along several main objectives that aim to strengthen a holistic development of geothermal energy in Ecuador, supporting fundamental aspects that are: 1) Networking and synergy creation between actors; 2) Diffusion of information, capacity building and overall education; 3) Project incubation; 4) Assistance with policymaking and development of regulations; among others.

Paying members can register to AGE based on yearly renewable memberships (asogeotermicaec.com). A special discount is given to students and non-active professionals. The most involved and active members can become partners of the association, and all partners officially join during the yearly or bi-yearly general assembly. The association has and welcomes corporate and academic sponsors who can support activities, actively develop projects, and overall advance the country's geothermal expertise. The members benefit from early access to produced intellectual property and active discussions led within AGE, as well as other, ever-expanding sponsor benefits detailed in the membership brochures of AGE.

In the short term (2022-2023), AGE has created several working groups to deal 1) with the legal and organizational matters of the association; 2) Promote direct use of geothermal energy and Ground-source Heat Pumps; 3) Carry preliminary investigations on to the repurposing of Oil and Gas Wells in the Oriente basin; 4) Promote the development of academic and industrial projects; 5) create a national geothermal database and information repository; 6) Promote and disseminate the core values of Women IN Geothermal; 7) develop effective communication strategies for the association; 8) support the Ecuadorian Geothermal Round Table (GRT). One by one, the associations fixed, short-term goals are being accomplished.

In the long term (2022 onwards), AGE aims to disseminate as much high-quality information about geothermal energy as possible; act as a project incubator from a holistic point of view, accounting for technical, environmental, social, legal, and political problematics in synergy; and help bring together the many actors (academia, industry, communities, general public, government) in the geothermal community nationally and internationally.

As the world starts to view Geothermal energy as an important player in the energy transition, AGE aims at being the official voice and memory of Geothermal energy in Ecuador.

6. GEOTHERMAL ROUNDTABLE

The geothermal roundtable aims to make a holistic analysis of geothermal in Ecuador from 5 main axes: regulatory, technical, social-environmental, financial-economical, and direct uses. The first stage is to make a diagnosis of the current state of every axis. Then, the objective is to build a roadmap with strategies and concrete goals to establish a geothermal development environment. The roundtable will have workshops with the main actors from the public, private, financing, academic and other sectors to obtain recommendations and solutions tailored to the national reality.

The regulatory axis is focused on analyzing the Ecuadorian regulatory framework that intervenes in the development of a High Enthalpy Geothermal Project. It will be compared with the legal framework and international good practices in countries that have successfully carried out geothermal projects. Finally, a regulatory framework will be proposed.

The technical axis will analyze the technical information, infrastructure, and technical capacities available in the public, private and academic spheres. After that, a new strategy for geothermal research and development will be proposed. This axis will also work on optimizing the terms of reference for the next study to carry out geothermal mapping in Ecuador, also financed by the IDB.

The social environmental axis will show and analyze the social and environmental regulatory framework to develop high enthalpy geothermal projects, as well as the categorization and considerations of international financiers to implement an online GIS-interactive web platform with at least 4 projects with the information available and a guide to continuing to provide feedback to help future developers find the information in one place.

The financial – economical axis is going to financially gauge a high enthalpy geothermal project in Ecuador. In addition, this axis will make an economic assessment of the impacts of this kind of projects, such as number of jobs, types of complementary industries, poverty reduction, government savings, reduction of subsidies, etc. Economic and financial barriers are going to be presented and compared with examples of financial tools and policies used around the world. Finally, a plan will be proposed to integrate new policies and financial tools.

The last one is the direct use axis, which aims to measure the direct use industry for medium, low and very low enthalpy projects. The first stage includes a map of resources and industries that require heat/cold. As well else, the financial and economic evaluation of different types of projects. In addition, an analysis of the legal, social, and environmental framework will be carried out. Also, all the obstacles that are not allowing the rapid development of this industry. Finally, normative, and political initiatives and a whole plan to promote the direct uses of geothermal energy will be proposed.

The five axes will integrate a Geothermal Master Plan with specific goals and policies that should be the compass of the Ministry of Energy and Mines to make the geothermal industry a reality.

7. DISCUSSION

Standard Tables 1 to 8 clearly show that conventional energy generation by hydro (58.5%) and fossil fuels (39.2%) dominates by far the Ecuadorean energy market, with a total installed capacity of 8734.41 MWe and a gross production of 32571 GWh/yr in 2021, where 26089.4 GWh (80%) are from renewables, 6123.3 GWh are from fossil fuels and 388.3 GWh (1.1%) are from interconnexion with neighboring countries (ARCERNNR, 2022).

They also show that, at present, other forms of energy production, i.e., nuclear and geothermal are non-existent and renewables like biomass, biogas, wind and solar energy are still marginal (190.8 MWe and 487.15 GWh/yr). In the future, the general trend is to favor hydro, with an increase in renewables and a substantial decrease in fossil fuel, which in turn favors geothermal energy development.

Because there is no electricity production from geothermal in Ecuador, Standard Table 2 is not included.

Standard Table 3 shows the utilization of geothermal energy for direct use, without changes since the last update in 2020. This information has to be taken as a minimum estimate for hot spring waters used for swimming pools. Inlet-temperature is a safe parameter, but outlet-temperature has been arbitrarily assumed to be 35°C if temperature is above 40°C, 20°C if it is between 30 and 40°C and 15°C if it less than 20°C. The average flow rate has been assumed to be 63% of the maximum flow rate, which is also arbitrary. The maximum flow rate has been measured at the spring in most cases, but in others it has been estimated. This activity has been improving towards efficiency in the last years, but is difficult to assess due to lack of data and specific studies.

Standard Table 4 shows the very first GSHP installed in Ecuador in 2019, which is running at full potential.

Standard Table 5 shows a summary of geothermal direct heat uses since the last update in 2020. This table includes all direct use applications currently in use, and direct utilization from hot spring water for balneology purposes.

Standard Table 6 includes the only and first deep geothermal exploration well in Ecuador (PEC1), completed in November 2017 at the Chachimbiro Geothermal Project to a total depth of 1987m; BHT reached 235 ºC.

An earlier shallow (540m) gradient hole was drilled by the government in 2009 at the Ecuadorean side of the Bi-National Tufiño Geothermal Project. The temperature gradient was not measured, but reached the uppermost of the smectite seal of the deep geothermal system. (Chancusig, 2017).

Some very shallow wells have been drilled in the last decades to obtain water for swimming pools, but data are scarce and wells are not included here as geothermal wells; most wells have been drilled to obtain water only for agricultural or industrial uses, without using any heat.

Allocated professional personnel to geothermal activities (Standard Table 7) has increased substantially in the first half of the previous period, mainly from the side of the government with CELEC EP and INER/IIGE and less so with MERNNR and universities in Quito (EPN and Yachay Tec), although it diminished strongly in the second half due to government funding restrictions, which does continue in this period 2020-2023; there is no professional geothermal personnel employed by the private industry.

Standard Table 8 shows that public investment has been allocated to geothermal activities in the last five years of the previous term (2015 to 2020) in the amount of 15 MUSD for research of the Chachimbiro geothermal project, including the drilling of one deep exploration hole. This has been possible due to the positive political decision of the previous administration to explore and develop the geothermal resources in Ecuador and with the straight forward participation of JICA/gov. of Japan. In this period 2020-2023, Chachimbiro project is on hold.

Regarding geothermal play #6 (Oriente foreland basin, see section 3), a lowest bound on possible installed power from this area can be given by a first order, non-official calculation considering purely advective heat flux $\dot{q} \sim \dot{m} \,.\, c_p . (T_R - T_0)$. With $\dot{m}$ the mass flow rate (200000/6.11 m^3/day * 1100 kg/m^3 ~ 36e6 m^3/day) and, c_p specific heat (4.180 kJ/kg/K) of the extracted fluid, T_R, T_0 the maximum and minimum temperatures (85 and 25 ºC). The minimal power from this area could be at the very least 8.8 e9 kJ/day or ~100 MWt which are currently discarded as co-produced water cooling and disposal.

General policies and planning regarding electrical energy are issued by the government through the MERNNR (Ministry of Energy and Non-Renewable Resources). The MERNNR coordinates the electric energy issues with ARCONEL, which is in charge of the regulation of the sector, its electrification master plan, of supervising power generation projects, concessions/contracts for power generation, prices and environmental issues. One of the problems in the electricity market is the availability of energy, rather than the installed capacity, since the reservoirs for hydro generation are in some cases small and fossil fuels are expensive and not always at hand. This situation favors the demand of geothermal power as base load. The problem was temporarily solved by importing energy from Colombia and Peru, but this tendency has reversed in the last years, with the commissioning of the new hydro projects.

Any project to generate electricity, including geothermal, needs a permit issued by ARCONEL, which in turn demands a water-use permit) and an environmental permit, both from the Ministry of the Environment (MAE). According to the current constitutional law, energy in any form belongs to the state and its exploration and development is strictly regulated by the government, since energy is a strategic issue.

8. FUTURE DEVELOPMENT AND INSTALLATIONS

The next immediate step towards geothermal electricity generation in Ecuador is the field development of the Chachimbiro project through an ODA loan from JICA to CELEC EP. This phase is planned to start in the near future and involves the drilling of 5 appraisal wells and the installation of a 5 MWe well-head power plant with a budget of around 65 MUSD. This project will push forward other geothermal proposals as well as give experience to local staff and local companies, and create new opportunities for surrounding communities and academia.

Also, in parallel, JICA, probably in coordination with other multilaterals, is going to support the making of the specific terms of regulation and applicable model for the feasibility to bring in more investment to develop additional geothermal projects. At the same time, dissemination campaigns are taking place to inform society, authorities and politicians about the benefits of each stage of geothermal development and pointing out the necessity to complement the current electrical matrix, which consists mainly of hydroelectricity, to cope with yearly worsening dry seasons.

An inter-institutional cooperation at government levels is planned to efficiently share resources like lab facilities and geo-scientific staff, in order to build core capabilities for a continuous development of geothermal resources.

Many efforts have been made by the government of Ecuador to eliminate the use of fossil fuels in the Galapagos Islands in the short term. Although a promising geothermal field exists on Isabela Island´s Alcedo volcano as already mentioned in GT play 2, it is located far away from the nearest town and within a protected natural area. Therefore, electricity generation from geothermal resources seems unlikely for now. Direct uses on the other hand are a much more plausible option. A proposal for a geothermal energy-driven desalination plant has been handed out to local authorities for further consideration (Lloret, 2015). Presently, the project has been submitted for national and international grant funding to finance reconnaissance studies aimed to increase the prospect´s geo-scientific data.

IIGE has resumed exploration of geothermal prospects in the country with special attention in low and medium enthalpy resources. Gas and water samples are being collected, and geophysical studies, which include resistivity and magnetotelluric surveys, are also expected to be carried out. The main purpose is to update and reassess the information obtained in previous studies and monitor changes in geothermal systems that are already known. Similarly, weather stations have been placed in close range from known geothermal prospects to study hydrological changes that may influence the development of geothermal projects in the future. Finally, geological and geochemical mapping is also being carried out in underexplored locations where locals have reported geothermal activity.

In 2022, the article "Exploration of geothermal resources in South America using an innovative GIS-based approach: a case study in Ecuador" was presented to SAES JOURNAL in its special issue: Geothermal Systems in South America. This alternative document was the work of many professionals and researchers from the national and international academy, IIGE and the Ecuadorian Geothermal Association. The results indicate that approximately 49.2% of the national territory of Ecuador has promising areas to explore and develop geothermal systems. In addition, new areas were identified, which contributes to increasing national inventories of geothermal energy. This work demonstrates the use of open geodata as an effective method to make decisions and plan future research at the national level. This work has not been published at the time of this writing, but will probably be available for the World Geothermal Congress 2023.

Several regions in the country remain unexplored for geothermal resources, namely the sedimentary basins in the Costa, the back-arc volcanic chain with recently active alkalic volcanoes and the sedimentary foreland basin in the Oriente, as well as the Galapagos Archipelago at both, the hot spot and the nearby spreading center. This increases the exploration potential for geothermal resources in the country, in addition to the follow up exploration of the prospects cited above. Application of actual and future technology will allow to tap hidden resources, those where geothermal evidence at surface is nil (Duffield and Sass, 2003) and consider EGS targets as well.

Ecuador needs to take advantage of its highly skilled workforce in its long-lived oil and gas industry which has most of the needed expertise to develop a sustainable and profitable geothermal industry (Umam et al., 2018; Ball, 2021). This workforce is comprised of widely different skillsets such as geologists, geophysicists, geochemists, drillers, engineers, hydrologists, business and project managers, operators, maintenance personnel, etc. The simple addition of high-temperature, high-flow rate handling skills into these areas of expertise should be straightforward with cooperation with experienced countries/industry in the geothermal domain.

A good start will be to produce both, the heat flow map and the geothermal map of Ecuador with updated data. In this regard, IIGE is keen to work on the Geothermal Atlas of Ecuador in the following years. It is imperative to get the necessary funding (public and private) to drill the most promising prospects and tap geothermal power in Ecuador.

And Chachimbiro Geothermal Project, with its first 2000m deep exploratory well, is a promising enterprise in the right direction, with CELEC EP as a clear and strong leader.

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REFERENCES

Angulo, E., and Beate, B.: Temperature Distribution and Zoning of the Geothermal Gradient in the Oriente Basin, Ecuador. *Abstract 8th ISAG Conference*, EPN, Quito – Ecuador (2019).

ARCERNNR.: Annual and Multi-annual statistics of the Ecuadorian Electricity Sector, Quito, Ecuador (in Spanish) (2022), pp. 178, website: https://www.controlrecursosyenergia.gob.ec/

Asimbaya, D., Urquizo, M., Sugioka, M., Nishijima, J., Ibarra, D.: Geological Structure Identification from Gravity Data in Baños de Cuenca Geothermal Prospect, Ecuador. *Proceedings of the World Geothermal Congress, Reykjavik* (2020+1).

Baby, P., Rivadeneira, M., Barragán, R., Christophoul, F.: Thick-skinned tectonics in the Oriente foreland basin of Ecuador, *Geological Society,* London, Special Publication, **377** (2013), pp. 59 – 76.

Baldock, M.W.: Geology of Ecuador, explanatory bulletin of the national geological map of the Republic of Ecuador 1: 1000000 scale, *DGGM-IGS*, London (1982), pp. 54.

Ball, P. J.: A review of geothermal technologies and their role in reducing greenhouse gas emissions in the USA. *Journal of Energy Resources Technology*, **143**(1), (2021), pp. 15.

Barba, D., Barragán, R., Gallardo, J., Salguero, A.: Geothermal Gradients in the Upper Amazon Basin derived from BHT data. *International Journal of Terrestrial Heat Flow and Applied Geothermics*, **4** (1), (2021), pp 85-94.

Barba, D.: Gradiente Geotermal de la Cuencas de Ante-Arco del Ecuador (in Spanish). *VIII. Jornadas Ciencias de la Tierra*, EPN. Quito (2017), pp. 5.

Barberi, F., Coltelli, M., Ferrara, G., Innocenti, F., Navarro, J., & Santacroce, R.: Plio-Quaternary volcanism in Ecuador. *Geological Magazine*, **125**(1), (1988), pp. 1-14.

Barragán, R., and Baby, P.: Magmatismo Alcalino Intra-placa en la Cuenca Cretácica Oriente, Ecuador: Evidencias Geoquímicas, Geocronológicas y Tectónicas (in Spanish). *In: La Cuenca Oriente, Geología y Petróleo. Baby, P., Rivadeneira, M. &Barragán, R., editors. IFEA-IRD-Petroamazonas EP.* Quito – Ecuador (2014), pp. 81 – 102.

BCE, (2019): Central Bank of Ecuador, website: https://www.bce.fin.ec/index.php/informacioneconomica/ (in Spanish)

Beate, B., Urquizo, M., Lloret, A.: Geothermal Country Update of Ecuador: 2015-2020. *Proceedings of the World Geothermal Congress, Reykjavik* (2020+1), pp. 13.

Beate, B. & Urquizo, M.: Geothermal Country Update for Ecuador, 2010 – 2015. *Proceedings of the World Geothermal Congress, Melbourne, Australia* (2015), pp. 14.

Beate, B., and Salgado, R.: Geothermal Country Update for Ecuador, 2005 - 2010. *Proceedings of the World Geothermal Congress, Bali, Indonesia* (2010), pp. 16 p.

Beate, B.: Plan para el Aprovechamiento de los Recursos Geotérmicos en el Ecuador (in Spanish). *Unp.Tech.Report for MEER*, Quito (2010), pp. 165.

Beate, B., Monzier, M., Spikings, R., Cotten, J., Silva, J., Bourdon, E., Eissen, J.P.: Mio-Pliocene adakite generation related to flat subduction in southern Ecuador: The Quimsacocha volcanic center. *EPSL*, **192** (2001), pp. 561-570.

Beate, B.: Geología y Petrografía de la Isla Genovesa, Galápagos (in Spanish). *Thesis*, Quito: EPN, (1978), pp. 81.

Burgos, J., Baby, P., Christophoul, F., Soula, J., Rochat, P.: Cuantificación de las erosiones Terciarias y Plio-Cuaternarias en la parte sur de la Cuenca Oriente (in Spanish). *In: La Cuenca Oriente, Geología y Petróleo. IFEA-IRD-Petroamazonas EP*. Quito – Ecuador (2004), pp. 115–130.

Chancusig, G.: Caracterización de la secuencia litoestratigráfica y de la mineralogía de alteración hidrotermal del pozo PGT-1 del proyecto geotérmico Tufiño-Chiles, provincia del Carchi (in Spanish). *Thesis,* Quito: EPN, (2017), pp. 155.

Choi, Y., Lee, C., and Song, J.: Review of renewable energy technologies utilized in the oil and gas industry. *International Journal of Renewable Energy Research*, **7**(2), (2017), pp. 592-598.

De Grys, A., Vera, J., Goossens, P.: A Note on the Hot Springs of Ecuador. *Geothermics* (1970), pp. 1400-1404.

Duffield, W., Sass J.: Geothermal Energy-Clean Power from the Earth's Heat. *USGS-Circular,* **1249,** (2003).

Ego F., Sebrier, M., Lavenu, A., Yepes, H., Egüez, A.: Quaternary state of stress in the northern Andes and the restraining bend model for the Ecuadorian Andes. *Tectonophysics*, **259**, (1996), pp. 101-116.

Geist, D., Howard, K., Jellinek, MA & Rayder, S.: The volcanic history of Volcan Alcedo, Galapagos Archipelago: A case study of rhyolitic oceanic volcanism. Bull. *Volcanology*, **56**, (1994), pp. 243 – 260.

Goff, F., McMurtry, Counce, D., Stimac, J.A, Roldan-Manzo, A.R. & Hilton, D.R.: Contrasting hydrothermal activity at Sierra Negra and Alcedo volcanoes, Galapagos Archipelago, Ecuador. *Volcanology,* **62**, (2000), pp. 34 – 52.

Gutscher M.A., Olivet, D., Aslanian, J.P., Maury, R.: The "lost Inca Plateau": cause of flat subduction beneath Peru? *Earth Planet* (2000), pp. 335-341.

Hall, M., Samaniego, P., Le Pennec, J.L., Johnson, J.B.: Ecuadorian Andes volcanism: A review of Late Pliocene to present activity. *Journal of Volcanology and Geothermal Research*, **176**, (2008), pp. 1 - 6.

Hall, M.L and Beate, B.: El Volcanismo Plio-cuaternario en los Andes del Ecuador (in Spanish). *Est. Geogr.,* **4**. Corp. Edit. Nacional. Quito (1991). pp. 5 - 17.

Harpp, K.S., and Geist, G.J.: The Evolution of the Galapagos volcanoes: An Alternative Perspective. *Frontiers in Science*, **6** (50), (2018), pp. 16.

Harpp, K.S., Fornari, D.J., Geist, D.J. and Kurz, M.D.: Genovesa Submarine Ridge: a Manifestation of Plume-Ridge Interaction in the Nortern Galapagos Islands. *Geochem. Geophys. Geosyst.,* **4 (**8511), (2003), pp. 27.

Harpp, K., and Geist, D.: Wolf-Darwin Lineament and Plume Ridge Interaction in Northern Galapagos. *Geochem. Geophys. Geosyst.,* **3** (11), (2002), pp. 19.

Horton, B., and Folguera, A (editors).: Andean Techtonics. *Elsevier*, 1st Edition, (2019), pp 719.

Icaza-Alvarez, D., Jurado, F., Tostado-Véliz, M., Arevalo, P.: Decarbonization of the Galapagos Islands. Proposal to transform the energy system into 100% renewable by 2050. *Renewable Energy*, **189** (2022), pp. 199-220.

IGA-IFC.: Best Practices Guide for Geothermal Exploration. *IGA Service GmbH*, Bochum, Germany, (2014), pp. 194.

IIGE.: Desarrollo de escenario prospectivo del ingreso de la geotermia de media y baja entalpía en la matriz energética y productiva en Ecuador. Mapa de usos potenciales del recurso geotérmico, Anexo 6 (in Spanish), (2020).

IIGE.: Evaluación del Recurso Geotérmico de Baja Temperatura para el Incremento de la Productividad Agrícola en Invernaderos (in Spanish). Informe Técnico de Gestión: VIII Periodo. (2020), (Un-published report).

IGM.: Ecuadoran Military Geographic Institute, (2019). website: http://www.geoportaligm.gob.ec/portal/index.php/descargas/geoinformacion/ (in Spanish)

INEC.: National Institute of Statistics and Censuses, (2019). website: http://www.ecuadorencifras.gob.ec/institucional/home/ (in Spanish)

Jara-Alvear, J., Urquizo, M., Asimbaya, D., and Graw, V.: Geothermal Potential in Galapagos Islands: Supporting Sustainable Energy Transition, *Proceedings of the World Geothermal Congress, Reykyavik,* (2020+1), pp. 12.

Litherland, M., Zamora, A. and Egüez, A.: Mapa Geológico de la República del Ecuador 1:1'000.000. *CODIGEM-BGS*, Quito. (1993).

Lloret, A.: Suitability Assessment to Establish an Industrial Park with Thermal Energy from Chalpatan Geothermal Field, Ecuador. *Proceedings of the World Geothermal Congress, Reykjavik* (2020+1), pp. 14.

Lloret, A.: Use of geothermal energy for seawater desalination in the Galápagos Islands. *Geothermal Training Programme* (2015), pp. 27.

Londsdale, P.: Ecuadorian subduction system. *AAPG*, **62**, (1978), pp. 2454-2477.

Spikings, R., Cochrane, R., Villagómez, D., Van der Lelij, R., Vallejo, C., Winkler, W., Beate, B. (2015). The geological history of northwestern South America: From Pangea to the early collision of the Caribbean large igneous province (290-75 Ma). *Gondwana Research*, **27** (1), (2015), pp. 95-139.

Spikings, R.A., Winkler, W., Seward, D., Handler, R.: Along-Strike variations in the thermal and tectonic response of the continental Ecuadorian Andes to the collision with heterogeneous oceanic crust. *EPSL*, **186**, (2001), pp. 57-73.

Umam, M. F., Purba, D. P., Adityatama, D. W., and Campen, B. V.: Drilling manpower and equipment transfer from petroleum to geothermal industry: a preliminary study on skill assessment. In *The 6th Indonesia International Geothermal Convention & Exhibition (IIGCE)*, (2018), pp. 10.

Urquizo, M., Acosta, M., Lloret, A: Ecuadorian Geothermal Association (AGE): towards holistic development of Geothermal energy in Ecuador. *Proceedings of the World Geothermal Congress, Beijing,* (2023), (in progress).

Vaca, S., Vallée, M., Nocquet, J.-M., Alvarado, A.: Active deformation in Ecuador enlightened by a new waveform-based catalog of earthquake focal mechanisms. *Journal of South American Earth Sciences*, **93**, (2019), pp. 449-461.

Vallejo, C.; Romero, C.; Horton, B.K.; Spikings, R.A.; Gaibor, J.; Winkler, W.; Esteban, J.J.; Thomsen, T.B.; Mariño, E.: Jurassic to Early Paleogene sedimentation in the Amazon region of Ecuador: Implications for the paleogeographic evolution of northwestern South America. *Global and Planetary Change*, **204**, (2021).

Vallejo C.: Evolution of the Western Cordillera in the Andes of Ecuador (Late Cretaceous–Paleogene). Ph.D. thesis, *ETH Zürich*, (2007), pp. 208.

Wang, K., Yuan, B., Ji, G., Wu, X.: A comprehensive review of geothermal energy extraction and utilization in oilfields. *Journal of Petroleum Science and Engineering* (2018), pp. 30.

Williams, D.L., von Herzen, R.P., Sclater, J.G. and Anderson, R.N.: The Galapagos Spreading Centre: Lithospheric Cooling and Hydrothermal Circulation. *Geophys.* J. R. Astr. Soc. **38**, (1974), pp. 587 – 608.

Yepes, H., Audin, L., Alvarado, A., Beauval, C., Aguilar, J., Font, Y. and Cotton, F.: A new view for the geodynamics of Ecuador: Implication in seismogenic Source definition and seismic hazard assessment. *Tectonics*, **35**, (2016).

STANDART TABLES - NOTE: TABLE 2 IS NOT INCLUDED.

TABLE 1. PRESENT AND PLANNED PRODUCTION OF ELECTRICITY

	Geothermal		Fossil Fuels		Hydro		Nuclear		Other Renewables (wind)		Other Renewables (biogas)		Other Renewables (biomass)		Other Renewables (solar)		Total	
	Capacity Mwe	Gross Prod. GWh/yr	Capacity Mwe	Gross Prod. GWh/yr	Capacity Mwe	Gross Prod. GWh/yr	Capacity Mwe	Gross Prod. GWh/yr	Capacity Mwe	Gross Prod. GWh/yr	Capacity Mwe	Gross Prod. GWh/yr	Capacity Mwe	Gross Prod. GWh/yr	Capacity Mwe	Gross Prod. GWh/yr	Capacity Mwe	Gross Prod. GWh/yr
In operation in December 2021			2837	6118	5072	25575	0	0	21	62	7	42	136	373	27	37	8101	32207
Under construction in December 2021					254	0											254	0
Funds committed but not yet under construction in December 2021	5	0							100						200		305	0
Estimated total projected use by 2022	0	0	2981	6310	5122	26375	0	0	21	62	7	42	136	373	27	37	8294	33199

https://www.recursosyenergia.gob.ec/wp-content/uploads/2022/08/Balance_Energe%CC%81tico_Nacional_2021-VF_opt.pdf

http://www.cenace.gob.ec/energia-neta-producida-por-las-centrales-de-generacion-gwh/

https://www.controlrecursosyenergia.gob.ec/wp-content/uploads/downloads/2022/04/Estadistica2021.pdf

TABLE 3. UTILIZATION OF GEOTHERMAL ENERGY FOR DIRECT HEAT AS OF 31 DECEMBER 2019 (other than heat pumps)

1) I = Industrial process heat
C = Air conditioning (cooling)
A = Agricultural drying (grain, fruit, vegetables)
F = Fish farming
K = Animal farming
S = Snow melting
H = Individual space heating (other than heat pumps)
D = District heating (other than heat pumps)
B = Bathing and swimming (including balneology)
G = Greenhouse and soil heating
O = Other (please specify by footnote)

2) Enthalpy information is given only if there is steam or two-phase flow

3) Capacity (MWt) = Max. flow rate (kg/s)[inlet temp. (^oC) - outlet temp. (^oC)] x 0.004184 (MW = 10^6 W)
or = Max. flow rate (kg/s)[inlet enthalpy (kJ/kg) - outlet enthalpy (kJ/kg)] x 0.001

4) Energy use (TJ/yr) = Ave. flow rate (kg/s) x [inlet temp. (^oC) - outlet temp. (^oC)] x 0.1319 (TJ = 10^{12} J)
or = Ave. flow rate (kg/s) x [inlet enthalpy (kJ/kg) - outlet enthalpy (kJ/kg)] x 0.03154

5) Capacity factor = [Annual Energy Use (TJ/yr)/Capacity (MWt)] x 0.03171
Note: the capacity factor must be less than or equal to 1.00 and is usually less,
since projects do not operate at 100% of capacity all year.

Note: please report all numbers to three significant figures.

Locality	Type[1]	Maximum Utilization					Capacity[3]	Annual Utilization		
		Flow Rate	Temperature (^oC)		Enthalpy[2] (kJ/kg)			Ave. Flow	Energy[4]	Capacity
		(kg/s)	Inlet	Outlet	Inlet	Outlet	(MWt)	(kg/s)	(TJ/yr)	Factor[5]
Baños Cuenca	B	8.000	73.000	35.000	-----	-----	1.272	5.040	25.261	0.629
Baños Tungurahua- Virgen	B	5.120	53.000	35.000	-----	-----	0.386	3.226	7.659	0.629
El Salado	B	5.000	44.300	35.000	-----	-----	0.195	3.150	3.864	0.628
Palictahua	B	2.800	40.700	35.000	-----	-----	0.0067	1.764	1.326	0.627
Chachimbiro- Toma	B	1.500	58.000	35.000	-----	-----	0.144	0.945	2.867	0.631
Pitzantzi	B	0.950	40.800	35.000	-----	-----	0.023	0.599	0.458	0.631
Naugulvi	B	2.000	52.000	35.000	-----	-----	0.142	1.260	2.825	0.631
Cununyacu- Chimborazo	B	1.400	47.500	35.000	-----	-----	0.073	0.882	1.454	0.632
Guayllabamba- Chimborazo	B	5.000	40.000	35.000	-----	-----	0.105	3.150	2.077	0.627
Ilaló- Cununyacu	B	8.000	27.000	15.000	-----	-----	0.402	5.040	7.977	0.629
Tingo	B	1.200	32.000	20.000	-----	-----	0.060	0.756	1.197	0.633
San Antonio	B	12.000	35.500	20.000	-----	-----	0.778	7.560	15.456	0.630
Ushimana	B	1.000	19.000	15.000	-----	-----	0.017	0.630	0.332	0.619
Chunchi	B	2.000	29.500	15.000	-----	-----	0.121	1.260	2.410	0.632
Ilaló	B	5.000	35.000	20.000	-----	-----	0.314	3.150	6.232	0.629
Papallacta- Termas	B	1.100	53.000	35.000	-----	-----	0.083	0.693	1.645	0.628
El Tambo	B	1.000	50.000	35.000	-----	-----	0.063	0.630	1.246	0.627
Jamanco	B	2.000	66.000	35.000	-----	-----	0.259	1.260	5.152	0.631
Cachiyacu	B	1.200	68.000	35.000	-----	-----	0.166	2.756	3.291	0.629
Portovelo- Río Amarillo	B	1.200	57.000	35.000	-----	-----	0.110	0.756	2.194	0.632
Tufiño- Aguas Hed.	B	3.000	53.000	35.000	-----	-----	0.226	1.890	4.487	0.630
San Vicente	B	2.000	38.000	20.000	-----	-----	0.151	1.260	2.991	0.628
TOTAL		72.470					5.157	47.625	102.401	

TABLE 4. SUMMARY TABLE OF GEOTHERMAL DIRECT HEAT USES AS OF 31 DECEMBER 2019

This table should report thermal energy used (i.e. energy removed from the ground or water) and report separately heat rejected to the ground or water in the cooling mode. rejected to the ground in the cooling mode as this reduces the effect of global warming.

1) Report the average ground temperature for ground-coupled units or average well water or lake water temperature for water-source heat pumps

2) Report type of installation as follows: V = vertical ground coupled (TJ = 10^{12} J)
H = horizontal ground coupled
W = water source (well or lake water)
O = others (please describe)

3) Report the COP = (output thermal energy/input energy of compressor) for your climate - typically 3 to 4

4) Report the equivalent full load operating hours per year, or = capacity factor x 8760

5) Thermal energy (TJ/yr) = flow rate in loop (kg/s) x [(inlet temp. (°C) - outlet temp. (°C)] x 0.1319
or = rated output energy (kJ/hr) x [(COP - 1)/COP] x equivalent full load hours/yr

6) Cooling energy = rated output energy (kJ/hr) x [(EER - 1)/EER] x equivalent full load hours/yr

Note: please report all numbers to three significant figures
Due to room limitation, locality can be by regions within the country.

Locality	Ground or Water Temp. (°C)[1]	Typical Heat Pump Rating or Capacity (kW)	Number of Units	Type[2]	COP[3]	Heating Equivalent Full Load Hr/Year[4]	Thermal Energy Used[5] (TJ/yr)	Cooling Energy[6] (TJ/yr)
Riobamba	17.5	22	2	H	4.11	8760	1.4	1.3
TOTAL	**17.5**	**22**	**2**			**8760**	**1.4**	**1.3**

TABLE 5. SUMMARY TABLE OF GEOTHERMAL DIRECT HEAT USES AS OF 31 DECEMBER 2020

1) Installed Capacity (thermal power) (MWt) = Max. flow rate (kg/s) x [inlet temp. (°C) - outlet temp. (°C)] x 0.004184
or = Max. flow rate (kg/s) x [inlet enthalpy (kJ/kg) - outlet enthalpy (kJ/kg)] x 0.001

2) Annual Energy Use (TJ/yr) = Ave. flow rate (kg/s) x [inlet temp. (°C) - outlet temp. (°C)] x 0.1319 (TJ = 10^{12} J)
or = Ave. flow rate (kg/s) x [inlet enthalpy (kJ/kg) - outlet enthalpy (kJ/kg) x 0.03154

3) Capacity Factor = [Annual Energy Use (TJ/yr)/Capacity (MWt)] x 0.03171 (MW = 10^6 W)
less, since projects do not operate at 100% capacity all year

4) Other than heat pumps

5) Includes drying or dehydration of grains, fruits and vegetables

6) Excludes agricultural drying and dehydration

7) Includes balneology

Use	Installed Capacity[1] (MWt)	Annual Energy Use[2] (TJ/yr = 10^{12} J/yr)	Capacity Factor[3]
Individual Space Heating[4]			
District Heating[4]			
Air Conditioning (Cooling)			
Greenhouse Heating	0,16	5,19	0,61
Fish Farming			
Animal Farming			
Agricultural Drying[5]			
Industrial Process Heat[6]			
Snow Melting			
Bathing and Swimming[7]	5,157	102,401	0,31
Other Uses (specify)			
Subtotal	**5,317**	**107,591**	
Geothermal Heat Pumps	0,044	1,06	0,76
Total	**5,361**	**108,651**	

TABLE 6. WELLS DRILLED FOR ELECTRICAL, DIRECT AND COMBINED USE OF GEOTHERMAL FROM JANUARY 1, 2015 TO DECEMBER 31, 2019 (excluding heat pump wells) RESOURCES

Include thermal gradient wells, but no ones less than 100m deep.

Purpose	Wellhead Temperature	Number of wells Drilled				Total Depth (km)
		Electric Power	Direct Use	Combined	Other (specify)	
Exploration	(all)	1				1,987
Production	>150 C					
	150-100 C					
	<100 C					
Injection	(all)					
Total		1				1,987

The well reached 1978m deep, the first meter was drilled in august 2017 and the last one on November 2017 and the last temperature registered in march 2018 was 235°C.

TABLE 7. ALLOCATION OF PROFESSIONAL PERSONNEL TO GEOTHERMAL ACTIVITIES (Restricted to personnel with University degrees)

(1) Government
(2) Public Utilities
(3) Universities
(4) Paid Foreign Consultants
(5) Contribute Through Foreign Aid Program
(6) Private Industry

Year	Professional Person / Years of Effort					
	(1)	(2)	(3)	(4)	(5)	(6)
2020	6	2	1	----	----	----
2021	6	2	1	----	----	----
2022	6	2	2	----	----	2
Total	**18**	**6**	**4**	**0**	**0**	**2**

Since 2019, an AOD loan with JICA was negotiated and the whole process asked by the Ministry of Economy and Finances was accomplished. Sadly, the Ministry send a letter saying it cannot issue the Sovereign Guarantee until CELEC include in their passives the debt of Coca Codo Sinclair and Sopladora (2300MUSD). Because, this decision requires to increase the tariffs, the government does not find a final solution and Chachimbiro Project is still on hold.

TABLE 8. TOTAL INVESTMENTS IN GEOTHERMAL IN (2022) US$

Period	Research &Development	Field Development	Utilization		Funding		
			Direct	Electrical	Private	Public	Cooperation
	Million US$	Million US$	Million US$	Million US$	%	%	%
2000 - 2004	----	----					
2005 - 2009	0,37	----				100%	
2010 - 2014	7,2	----				100%	
2015 - 2019	15	----	0,23			30%	70%
2020 - 2022	0,11	----				100%	