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Geothermal Energy in Sedimentary Basins: A New Horizon for the Oil Industry in Ecuador

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ABSTRACT

Geothermal energy in Ecuador has seen significant advancements, especially in the context of volcanic resources; however, there is still unquantified potential for geothermal energy in sedimentary basins. This article aims to document the analysis and results of the first geothermal potential estimates conducted in two (2) major blocks of the Oriente Basin of Ecuador—an area with active oil fields characterized by promising temperature gradients.

The study summarizes the most relevant aspects of geothermal energy in sedimentary basins associated with the oil industry. Temperature gradients were verified using publicly available data from existing wells, and geothermal resources were assessed using the volumetric Heat-in-Place (HIP) method combined with Monte Carlo simulations. Concurrently, the regulatory framework and energy policies in Ecuador were analyzed, along with current advancements in the field, to ensure the viability of geothermal projects. Finally, the socio-economic impacts of utilizing geothermal energy in oil operations and nearby communities were explored.

The estimation of geothermal potential in these oil blocks yielded optimistic results between 133 and 254 MWt (Block A) and between 14.8 and 26.2 MWt (Block B), with temperature gradients ranging from 18 to 69°C/km at accessible depths. Despite being classified as low to medium enthalpy, these resources can be integrated into existing oil operations to create a sustainable business model, given that a large part of the operational infrastructure is already in place. Moreover, the availability of subsurface and well information will facilitate a robust quantification of geothermal reserves and their implementation in the short- and medium-term.

1 INTRODUCTION

Ecuador is situated in a geologically active zone, defined by the subduction of the Nazca Plate beneath the South American Plate and the subsequent presence of 22 active and more than 40 inactive volcanoes. This location provides the country with an exceptionally favorable geological setting for the existence of significant geothermal resources. Despite this potential, geothermal energy use in Ecuador has historically been limited to recreational purposes, such as spas and thermal pools, with no significant infrastructure yet developed for industrial-scale power generation.

Beyond volcanic systems, the Oriente Basin—Ecuador's most prolific region for hydrocarbon production—also presents favorable geothermal conditions within a sedimentary context. Recent studies (Angulo, 2020) identified four (4) thermal anomaly zones in fields such as Pungarayacu-San Carlos, Bermejo-El Rayo, Cowi, and ITT. These areas exhibit geothermal gradients between 18 and 69 °C/km, suggesting the presence of low-to-medium enthalpy resources with significant potential for energy diversification.

With over 5,000 oil wells drilled since 1944, the existing infrastructure in the Oriente Basin—including platforms, permitted wells, access roads, and electrical grids—combined with the oil industry's extensive knowledge base, represents a strategic advantage. Utilizing these assets could significantly reduce initial investment costs, turning geothermal development into a sustainable business model. Furthermore, integrating geothermal energy into oil operations could optimize oil production processes, such as heating crude oil to reduce its viscosity or providing thermal conditioning for facilities, yielding both environmental and economic benefits (Zhang et al., 2009). Meanwhile, energy surpluses could also enhance the quality of life in local communities, for instance by improving facilities at river ports.

This study focuses on the evaluation of the geothermal potential in two oil blocks of the Oriente Basin—with electrical potentials ranging between 0.6 and 10.3 MWe—and proposes their partial reconversion toward a hybrid energy model. This approach aims to contribute to the diversification of the national energy matrix, reduce

dependence on fossil fuels, and promote the social development of surrounding communities through the deployment of a clean, and renewable energy source.

2 GENERAL BACKGROUND

According to the Economic Commission for Latin America and the Caribbean (CEPAL; Coviello, 2000), formal studies on the potential of geothermal resources in Ecuador began in 1979 with the "National Geothermal Reconnaissance Study of the Republic of Ecuador." This study was conducted by the Latin American Energy Organization (OLADE) with the participation of the European firms Aquater (Italy) and BRGM (France). Between 1980 and 1982, various exploration projects focused on medium- and low-enthalpy resources; subsequently, between 1986 and 1999, the first pre-feasibility studies for large-scale geothermal projects were initiated.

In 2010, the former Ministry of Electricity and Renewable Energy (MEER) published the "Plan for the Exploitation of Geothermal Resources in Ecuador" (MEER, 2010), which identified 21 geothermal prospects. Of these, 11 were categorized as high-enthalpy, with the following being highlighted:

- Chachimbiro: 50–178 MWe (Imbabura Province).
- Chacana: Including the Jamanco (15 MWe) and Chacana Cachiyacu (45–83 MWe) prospects (Napo Province).
- Tufiño-Chiles-Cerro Negro: 100–330 MWe (located on the Ecuador-Colombia border).
- Baños de Cuenca: 10–26 MWe (Azuay Province).

Regarding the magnitude of the national geothermal potential, the 2010 plan estimated a figure exceeding 900 MWe. This was later updated in the Master Electricity Plan (PME) 2023–2032, which indicates a potential of more than 2,000 MWe (MEM, 2023). However, research conducted by Ecuadorian universities and other academic sources suggests a much broader geothermal potential, ranging between 1,700 and 6,500 MWe (Lloret and Labus, 2014; Beate et al., 2009).

On the other hand, while nations such as China, Poland, Indonesia, Croatia, and—within the Americas—the United States, Mexico, and Colombia have intensified efforts to integrate geothermal energy into oil operations, research in Ecuador has predominantly focused on the Ecuadorian volcanic arc. Despite the maturity of the oil industry in the Oriente Basin, available documentation on the geothermal potential of its sedimentary basins remains scarce (Angulo, 2020; Suntaxi, 2023). Even less evident are concrete efforts to assess and exploit this potential, representing a significant opportunity for the country's energy transition.

3 GEOLOGICAL FRAMEWORK OF THE ORIENTE BASIN OF ECUADOR

Continental Ecuador is divided into three (3) regions (Figure 1): The Coast, the Highlands (Andes), and the Oriente (Amazon). Volcanic terrains extend along the Highlands, where almost all the geothermal areas studied to date are located (Almeida et al., 1992). The Oriente Basin is found in the Amazon region—also known as Amazonia (Figure 1)—which contains the country's main oil fields, specifically in the provinces of Sucumbíos, Orellana, Napo, Pastaza, and Morona Santiago.

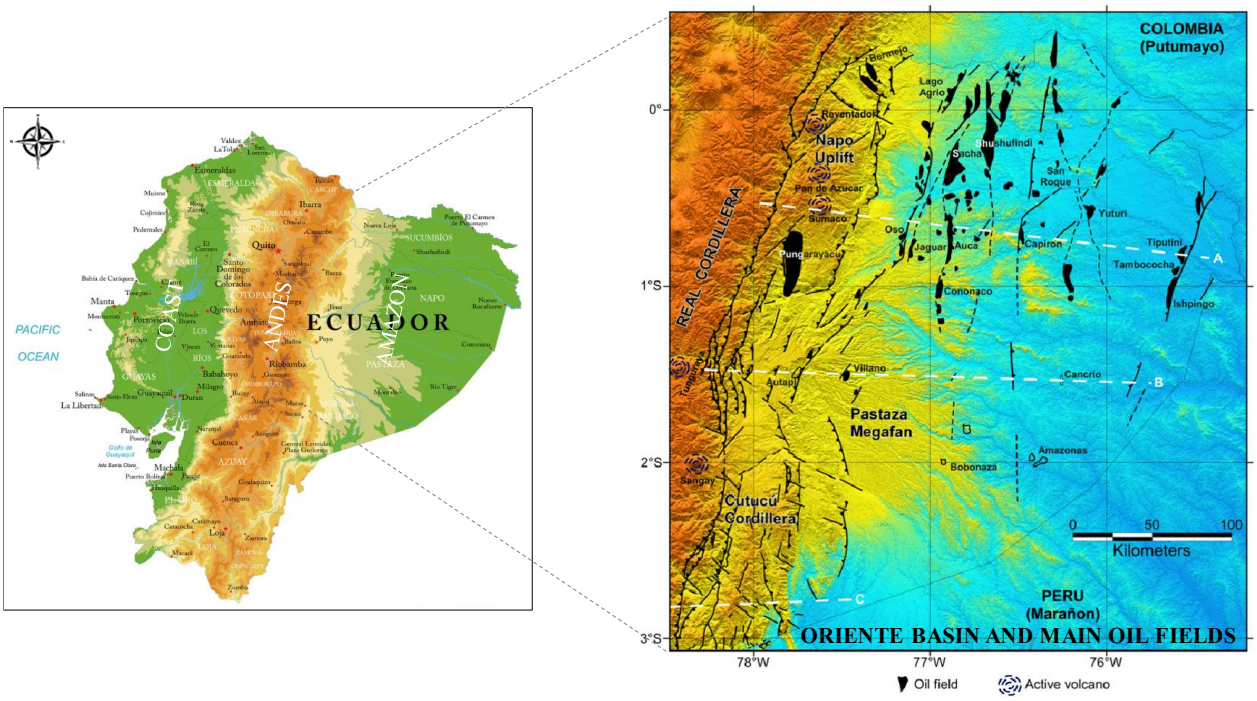


Figure 1. Physical map of Ecuador with major relief forms (Source: Adapted from factsinstitute.com and Baby et al., 2004).

The Oriente Basin is part of the back-arc foreland basin system that developed in the transition zone between the Central Andes and the Northern Andes during the Late Cretaceous. It is deformed by a thick-skinned thrust system, which extends from the Cordillera Real to the easternmost thrust fault in Tiputini. This system is connected to a detachment zone within the basement that dips beneath the Sub-Andean zone and the Cordillera Real (Baby et al., 2004). The tectonic deformation affecting the cover and basement rocks divides the basin into three tectonic domains (Baby et al., 2004), as shown in Figure 2:

- The Western Domain (Sub-Andean Domain): From north to south, this domain consists of three morpho-structural zones: (1) the Napo Uplift, an immense anticline elongated in a NNE-SSW orientation; (2) the Pastaza Depression, where faults exhibit increased thrusting at the contact with the Eastern Cordillera; and (3) the Cutucú Cordillera, characterized by a structural reorientation from N-S to NNW-SSE and the occurrence of Triassic and Jurassic formations.

- The Central Domain (Sacha-Shushufindi Corridor): This region is deformed by transpressive mega-faults that become vertical at depth and evolve into flower structures toward the surface (Baby et al., 2004). This corridor contains the majority of the high-reserve and high-production oil fields.

- The Eastern Domain (Capirón-Tiputini System): This region is characterized as an extensional basin, currently tectonically inverted, and formed by listric faults.

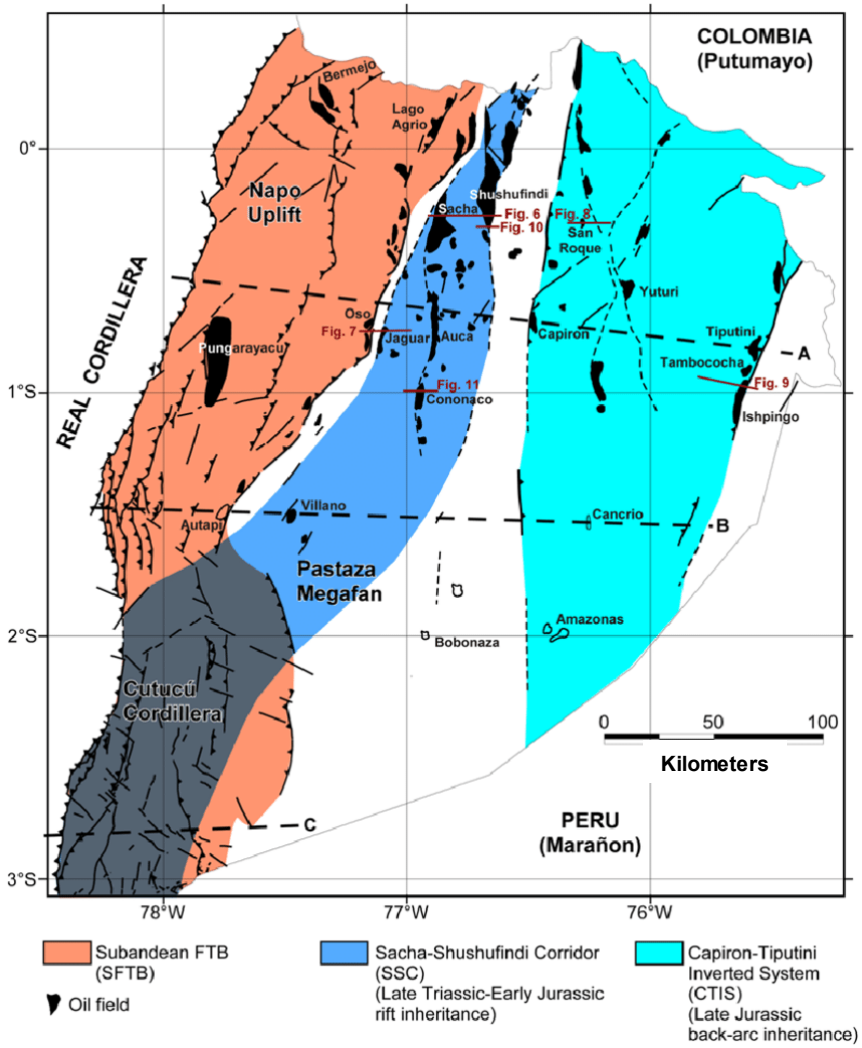


Figure 2. Map of the tectonic domains of the Oriente foreland basin defined by structural style and pre-Cretaceous inheritance (Baby et al. 2004).

Stratigraphically, the basin consists of a sedimentary sequence resting directly on a Precambrian basement associated with the Guyana Shield, with ages ranging from the Paleozoic to the Present (Figure 3). The formations that constitute this sequence outcrop only in the Sub-Andean System, particularly those of Jurassic age. Paleozoic and Triassic units outcrop exclusively in the southern part of the Cutucú Cordillera, while in the center of the basin, these formations are known only through well drilling and seismic data. The primary hydrocarbon reservoirs are located within the Cretaceous Hollín and Napo sandstone formations:

- The Hollín Formation: This unit consists of thick layers of clean quartz sandstones deposited in a fluvial environment, interbedded with sandstones, shales, calcareous siltstones, and coal beds deposited in a shallow marine environment (Baby et al., 2013). Toward the top of the Hollín Formation, there is a transition from proximal to distal facies, marking the progression into the Napo Formation. Limestone C (Caliza C) defines the top of the Hollín Formation and consists of massive limestones and black shales with glauconite and phosphatic fossil remains.

- The Napo Formation: This formation is composed of interbedded shales, limestones, and sandstones deposited in transitional fluvial-to-marine environments.

Block A is located in the Sub-Andean Zone of the Oriente Basin, while Block B is situated within the Capirón-Tiputini Corridor. Both blocks encompass extensive oil fields and reservoirs that, in addition to exhibiting thermal anomalies, possess strong aquifers with sufficient porosity and permeability to facilitate fluid flow, as well as effective seal rocks that prevent heat dissipation.

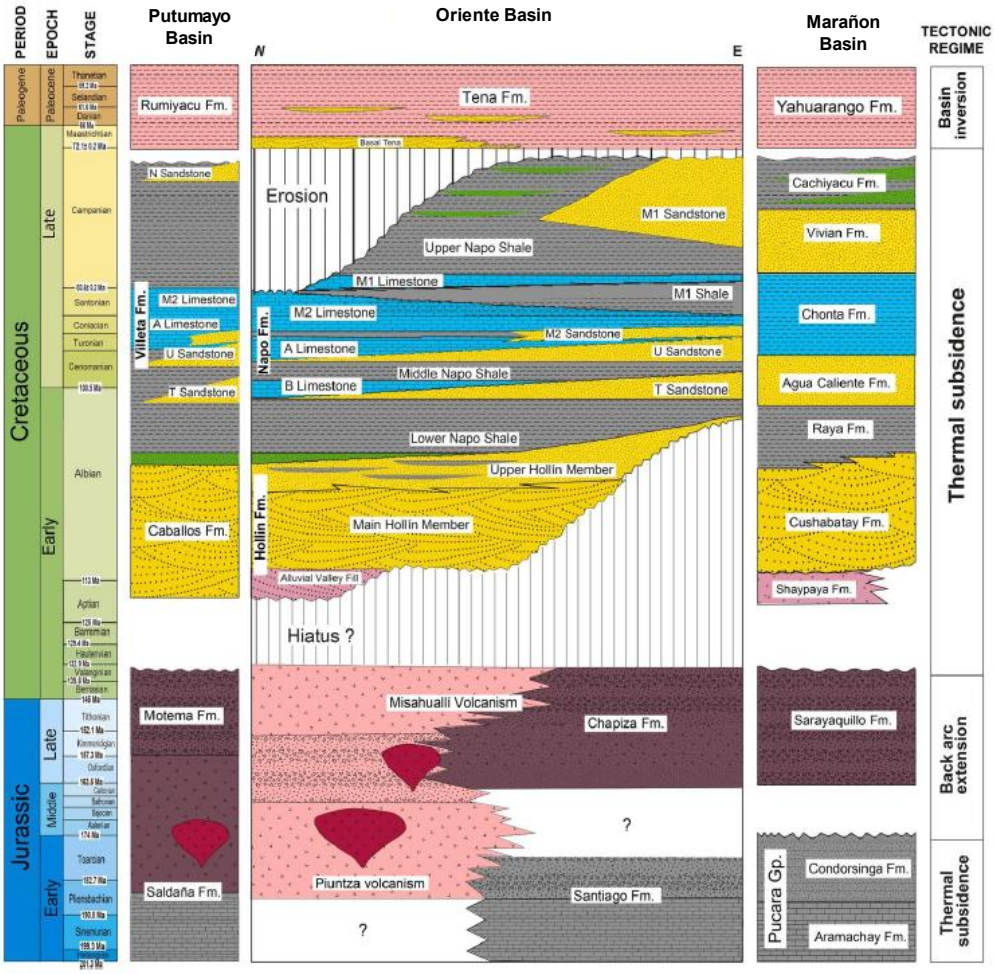


Figure 3. Stratigraphic column of Oriente Basin and its correlation with neighboring oil and gas basins Marañón and Putumayo basins (Source: Vallejo et al. 2021).

4 ESTIMATION OF THE GEOTHERMAL POTENTIAL IN TWO (2) BLOCKS OF THE ORIENTE BASIN

Prior to estimating the geothermal potential of Block A and Block B in the Oriente Basin, geothermal gradients were verified. The results indicate gradients ranging from 18 to 69 °C/km for Block A, with an average of 41 °C/km, and from 29 to 46 °C/km for Block B, with an average of 37.5 °C/km (Figure 4).

Using a geothermal gradient of 30 °C/km as a reference threshold, it was determined that values exceeding this benchmark occur in 50% of the drilled wells in Block A and 75% of the wells in Block B. Consequently, a precise delineation of these anomalies within each block is essential; developing 2D and 3D models will be necessary to capture gradient heterogeneity and to more accurately delimit the anomaly areas used for the estimation of geothermal resources.

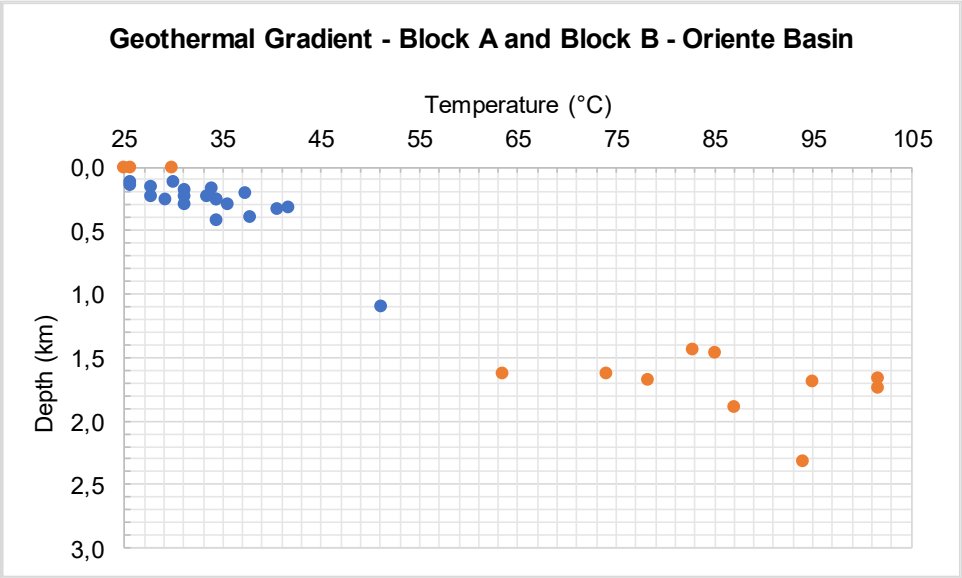


Figure 4. Geothermal gradient verification in Blocks A and B of the Oriente Basin. Source: Author's own elaboration.

To estimate the resources, this study utilizes the volumetric Heat-in-Place (HIP) method (Muffler and Cataldi, 1978). This method is widely applicable across diverse geological environments and is suitable for high-, medium-, or low-enthalpy resources (Arkan and Parlaktuna, 2005). Furthermore, the HIP method relies on available parameters—such as reservoir volume, average temperature, heat capacity, density, and the porosity of both the rock and geothermal fluids. Major uncertainties associated with this method, such as the recovery factor and heat recharge, typically decrease as more data becomes available during project development. The reservoir thermal energy is calculated as follows:

$$Q_R = Ah(T_r - T_a)\bar{C} \quad (1)$$

Where,

Q_R: Reservoir thermal energy [kJ]

A: Reservoir area [m^2]

h: Reservoir thickness [m]

T_r: Average reservoir temperature [°C]

T_a: Mean annual surface temperature [°C]

$\bar{C}$: Volumetric specific heat of rock-fluid system [kJ/m^3°C]

This equation accounts for the heat stored in both the rock matrix and the fluid within the pore spaces. The volumetric specific heat, $\bar{C}$, is calculated by considering the different hydrocarbon phases present in the reservoir (Zhang et al., 2009):

$$\bar{C} = \rho_r C_r(1 - \emptyset) + (\rho_w C_w S_w + \rho_o C_o S_o + \rho_g . C_g . S_g)\emptyset \quad (2)$$

Where,

$\rho_r, \rho_w, \rho_o, \rho_g$: Densities of rock, water, oil, and gas, respectively.

C_r, C_w, C_o, C_g: Specific heat capacity of rock, water, oil, and gas, respectively.

S_w, S_o, S_g: Water saturation, oil saturation, and gas saturation, respectively.

∅: Rock porosity.

In the blocks analyzed here, gas saturation can be considered negligible; therefore, the specific heat of the formation is primarily influenced by the oil and water phases (Yan and Yu, 2000). Nonetheless, gas data were included in the calculation to maintain a conservative approach and reduce the risk of overestimating the geothermal resource.

To estimate the potential electrical power generation from the stored heat, the thermal recovery factor (Rg) is introduced. This factor represents the fraction of the total heat that can be extracted in the future. The recoverable geothermal energy ($Q_R{}'$ in kJ) is calculated using the following equation:

$$Q_R{}' = Q_R R_f \tag{3}$$

To determine the amount of thermal power (T) over specific period (t), where t is the operational lifespan of the project in years, the following equation is used to obtain values in MWt (megawatts thermal):

$$T = \frac{Q_R{}'}{31536.10^6 t} \tag{4}$$

Finally, the electrical power (E) in MWe (megawatts electric) is calculated by applying the conversion efficiency factor (η) and the plant capacity factor (P_f). Unlike other renewable energy sources, geothermal energy is independent of weather conditions and seasonal changes, typically allowing for a capacity factor exceeding 90%. However, for this study, a more conservative capacity factor between 70% and 90% was applied:

$$E = TnP_f \tag{5}$$

The equations were applied probabilistically to evaluate the geothermal and electrical potential of the two blocks in the Oriente Basin. Given that these are active oil fields with dozens of drilled oil wells, triangular distributions were assigned to variables with abundant data, while uniform distributions were used for the remaining parameters. Regarding the thermal recovery factors, values of 5% and 20% were applied. Furthermore, a conversion efficiency below 10% (Nathenson and Muffler, 1975) and an economic lifespan of between 15 and 25 years were considered.

The estimated geothermal thermal power (T) for each block, prior to calculating the electrical power potential, is detailed in Table 1. The results obtained after running 5,000 iterations with Crystal Ball™ software are as follows:

- Block A (Figure 5): The simulation yielded an electrical potential (E) of 5.2 MWe (P10), 7.4 MWe (P50), and 10.3 MWe (P90), with a standard deviation of 2.0 MWe. According to the tornado diagram (sensitivity analysis), the variable with the greatest impact on the calculation was the thermal recovery factor (28.5%), followed by the reservoir area (23.1%) and reservoir thickness (15.2%)

- Block B (Figure 6): The estimated electrical power (E) was 0.6 MWe (P10), 0.8 MWe (P50), and 1.1 MWe (P90), with a standard deviation of 0.2 MWe. The tornado diagram indicates that the most influential variable was the thermal recovery factor (32.6%), followed by the useful life (18.5%) and the conversion efficiency factor (13.2%).

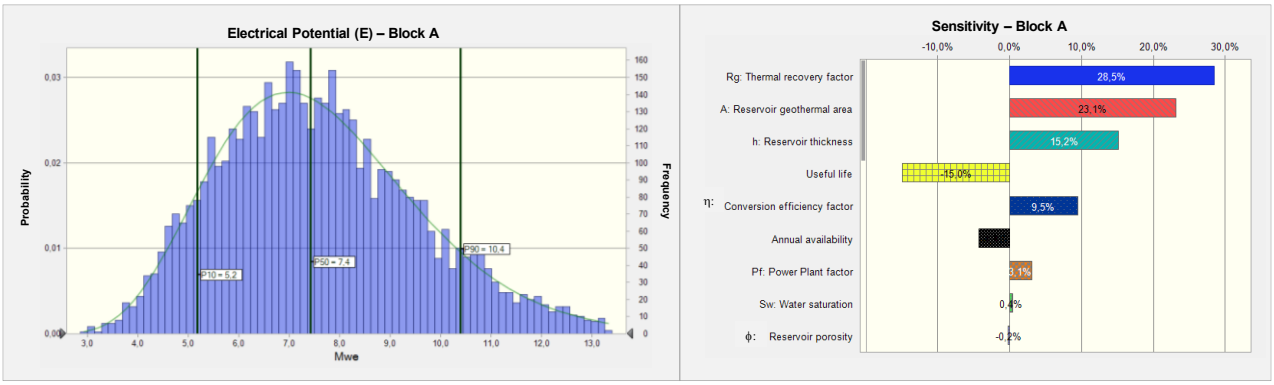


Figure 5. Probabilistic estimations of electrical potential and tornado (sensitivity) diagram for Block A.

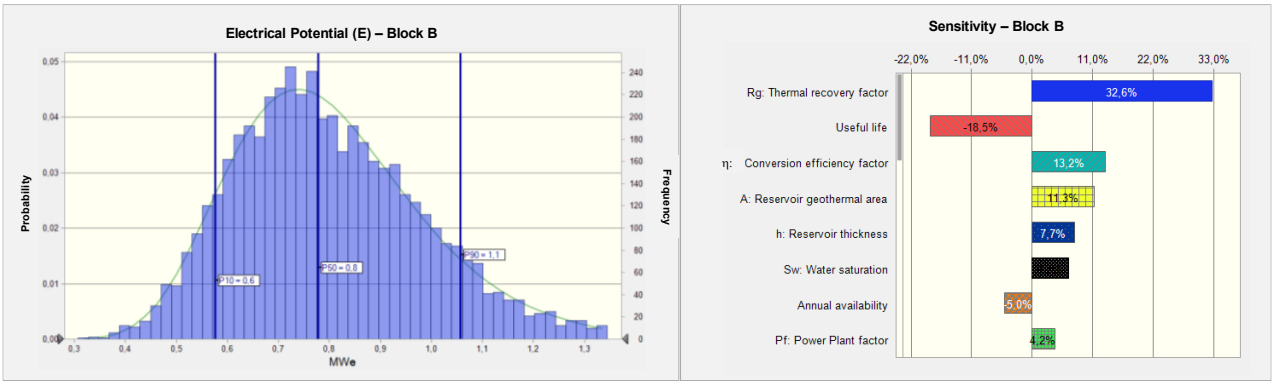


Figure 6. Probabilistic estimations of electrical potential and tornado (sensitivity) diagram for Block B.

Block A possesses a significantly larger area and reservoir thickness compared to other fields or blocks in the Oriente Basin. This geological advantage explains why both variables exert a substantial impact on the magnitude of its estimated potential relative to Block B.

The estimations of geothermal potential in both blocks of the Oriente Basin (Table 1) underscore the importance of this region—not only as a source of hydrocarbons but also as a promising area for renewable energy generation that can be integrated into oil operations. While these preliminary calculations indicate significant potential, it is fundamental to conduct more detailed studies, including numerical reservoir simulations, to validate these estimations and comprehensively evaluate the technical and economic feasibility of geothermal development in the region.

Table 1. Estimated geothermal and electrical potential summary for Block A and Block B, Oriente Basin of Ecuador.

Block	Block A			Block B		
	P10	P50	P90	P10	P50	P90
Reservoir geothermal energy, QR´ (Joules x10^{12})	52	70	91	7.7	9.9	12.5
Thermal power, T (MWt)	133	187	254	14.8	19.7	26.2
Electrical power potential, E (MWe)	5.2	7.4	10.3	0.6	0.8	1.1

Since the costs of existing and planned facilities—as well as the expenses associated with well drilling and data acquisition for each block—were not quantified for an economic assessment, the volumes estimated in this study are classified as geothermal resources rather than reserves.

5 USES OF GEOTHERMAL ENERGY ASSOCIATED WITH OIL OPERATIONS

Similar to hydrocarbon reservoirs, a geothermal reservoir is defined by three essential physical characteristics: (1) an aquifer, consisting of water hosted within a porous and permeable geological formation; (2) a trapping mechanism formed by impermeable layers (seal rocks) that prevents the escape of the energy-bearing fluid; and (3) a heat source. While hydrocarbon reservoirs are composed of complex organic mixtures, they invariably contain connate water and are often connected to bottom or lateral aquifers. When these conditions coincide with thermal anomalies, they create a favorable environment for geothermal energy exploitation.

The utilization of geothermal energy depends primarily on the resource temperature and, more specifically, on the geothermal gradient (Gonzalez, 2015). Enthalpy levels are generally classified as follows, although specific thresholds may vary depending on the author:

- High enthalpy: Temperatures above 150°C and temperature gradients exceeding 80–100°C/km.
- Medium enthalpy: Temperatures between 90–150°C and temperature gradients ranging from 40 to 80°C/km.

- Low enthalpy: Temperatures below 90°C and temperature gradients under 40°C/km.

Generally, high-enthalpy zones allow for the use of extracted water or steam in electricity generation. Meanwhile, medium- or low-enthalpy resources are traditionally suited for direct-use applications, such as space heating, domestic hot water supply, and various agricultural or industrial processes.

Although most hydrocarbon reservoirs evaluated for geothermal purposes exhibit medium or low enthalpy — which limits their application in conventional electricity generation—modern technologies allow for more extensive applications of this low enthalpy. These include geothermal heat pump systems to increase the heat of the resources or Binary Organic Rankine Cycle (ORC) power plants. ORC systems can operate with inlet temperatures as low as 65–70°C, utilizing the geothermal fluid to vaporize an organic working fluid that drives a turbine and generates electricity. In both cases, existing oil wells can be repurposed as dedicated geothermal wells or operated for co-production (the simultaneous extraction of hydrocarbons and thermal energy).

In the evaluated blocks (Block A and Block B), the resources are predominantly of low enthalpy. Their potential applications include:

- Providing electricity to communities or villages adjacent to oil fields.
- Implementing climate control systems for schools or community centers.
- Operating irrigation systems, greenhouse lighting, and small-scale agricultural product drying or food processing.
- Supporting small-scale local productive activities, such as artisanal workshops.
- Powering auxiliary systems for river transport (lighting, communications, and other port equipment) at nearby docks.
- Furthermore, within oil operations, the generated electricity can be used to replace diesel generators that power pumping units and monitoring systems, or for directly heating crude oil to reduce viscosity and meeting other electrical needs in the field.

A significant portion (30% to 45%) of the total cost of a geothermal project is concentrated in the first two stages: resource exploration and confirmation (Phase I) and the drilling of production and injection wells (Phase II). Considering that this investment has already been amortized in oil fields, leaving only the costs associated with part of the surface facilities and the construction of the power plant or energy conversion system, the initial investment is significantly reduced, facilitating the economic viability of this type of project.

6 REGULATORY FRAMEWORK FOR GEOTHERMAL ENERGY IN ECUADOR

Despite the fact that geothermal energy is an excellent alternative for diversifying Ecuador's energy matrix—both regarding the high-enthalpy resources associated with the volcanic arc and the low-enthalpy potential in the Oriente Basin's oil fields—the country currently lacks specific legislation regulating the procedures for the allocation, exploration, and exploitation of geothermal resources (Carcelén and Izquierdo, 2022).

A general framework is available, composed of the Organic Law of the Public Electric Energy Service (LOSPEE), enacted in 2015, which provides a broad structure applicable to all non-conventional renewable energies. More recently, in February 2024, Executive Decree No. 176 issued the Regulations to the Organic Law of Energy Competitiveness, introducing technical reforms with the primary objective of establishing rules and procedures for its application.

The efforts to increase the participation of renewable energies in its energy matrix are evident; however, in the geothermal context, it is necessary to evolve towards the enactment of a specific law that offers the necessary legal certainty to encourage private investment and promote development in this sector.

7 CONCLUSIONS

- The evaluation of the two oil blocks in the Oriente Basin using the volumetric method estimates a promising geothermal potential ranging from 14.8 to 254 MWt. These results suggest the feasibility of a strategic transition toward a hybrid energy model. The existing oil infrastructure represents a critical competitive advantage, as it significantly reduces the high initial CAPEX

associated with geothermal exploration and drilling, thereby fostering a more sustainable and economically viable business model.

- The evolution of integrated geothermal research within oil operations in Ecuador—combined with a proactive legal framework—will create a favorable landscape for the development of geothermal potential in Ecuador's sedimentary basins. This integration offers opportunities to optimize production processes and generate both economic and environmental benefits. Furthermore, it establishes a solid foundation for addressing the opportunities and challenges Ecuador faces in utilizing geothermal energy as a sustainable alternative, representing significant progress in mitigating the environmental impact associated with fossil fuels in both oil operations and community use.

8 RECOMMENDATIONS

- While preliminary studies have been conducted, it is necessary to invest in more comprehensive research—including detailed geological, geophysical, and geochemical surveys, as well as numerical simulation models—to validate the identified geothermal potential in the Oriente Basin.

- Analogous to hydrocarbon resource classification, the geothermal potential for Blocks A and B should be re-evaluated under a commercial framework to transition from resources to reserves as economic and technical data evolve.

- Given the established technical expertise and infrastructure of the oil industry, the state should encourage strategic alliances and knowledge transfer between the geothermal and hydrocarbon sectors. This collaboration is vital to reduce costs, accelerate the development of hybrid projects, and optimize the repurposing of mature oil wells.

Acknowledgements

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NOMENCLATURE

A	Reservoir area
$\bar{C}$	Volumetric specific heat of rock plus fluids
°C	Celsius
C_g	Gas specific heat capacity
C_o	Oil specific heat capacity
C_r	Rock specific heat capacity
C_w	Water specific heat capacity
E	Potential electrical energy
Ø	Rock porosity
h	Reservoir thickness
kJ	Kilojoules
Km	Kilometer
m	Meter
m^3	Cubic meters
MW	Megawatt
MWe	Megawatt electric

n Efficiency factor

P_f Plant factor

Q_R Reservoir thermal energy

$Q_R{}'$ Reservoir thermal energy that can be utilized in reality

S_g Gas saturation

S_o Oil saturation

S_w Water saturation

t Length of time of power generation

T Thermal power that can be utilized for a period of t years

T_a Mean annual surface temperature

T_r Average reservoir temperature

R_f Recovery factor

ρ_g Gas density

ρ_o Oil density

ρ_r Rock density

ρ_w Water density

SI METRIC AND ENGLISH CONVERSION FACTORS

BTU × 778.17 = ft-lb

BTU × 0.252 = kCal

BTU × 1.0551 = kJoule

BTU × 2.931 = E-04 kW-hr

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