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Economic Feasibility of Utilizing Geothermal Energy in Colombia

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ABSTRACT

Colombia has 2,210 MW resource potential for geothermal energy. However, the country's current utilization of this resource is limited to direct uses such as bathing, swimming, and localized heating. Using the modified hotelling for geothermal resources, this report will look into the economic feasibility utilizing geothermal energy in Nevado del Ruiz Volcano Geothermal Prospect located in Colombia. Further, a review of legal and policy framework for geothermal energy within Colombia is also covered on this report.

1. INTRODUCTION

Colombia's current energy mix is composed of approximately 70% hydroelectric power, 29% fossil fuels and the remaining percentage from various sources such as biomass, wind and solar (International Trade Administration, 2021). Colombia is highly dependent on hydroelectric power, while this is renewable energy resource, it is subject to drought and water scarcity. This could impact production in the coming years, causing further reliance on fossil fuels.

Fossil fuels however are not a carbon neutral option, and the Colombian government has looked for further renewable energy sources- including geothermal energy. Colombia has high volcanic activity due to the subduction between the Nazca and South American tectonic plates, resulting in promising depth temperatures conductive to geothermal power generation (Salazar et al., 2017). Currently, geothermal generation is limited to localized heat pumps with nothing larger scale.

Several areas in Colombia had been identified as potential sources of geothermal energy, one of the most studied is the volcanic region of Nevada del Ruiz. Investigation into the feasibility of this area began in 1968 by an Italian company that confirmed geothermal activity in the area. In 1983, the National University of Colombia continued studying the feasibility of the area such as parameters and characteristics of the hydrothermal system. In 1997 the first geothermal well was drilled in the western flank of the Nevada del Ruiz, with a depth of 1,469 meters, temperatures measured at the bottom were approximately 200 °C. Studies suggested the temperature of the reservoir could exceed 250 °C. Research in the area has continued with studies into the structural geology of the region, but no further infrastructure has been developed (Moreno et al., 2020).

This report will determine the economic feasibility of installing a geothermal power facility in the Nevada del Ruiz region. A review of legal and policy framework for geothermal energy within Colombia is also covered in this report.

2. METHODOLOGY

To determine the economic feasibility of utilizing geothermal energy in Colombia, this report includes literature review and geothermal resource optimization using modified hotelling for geothermal resources.

2.1 Geothermal Utilization in Colombia

In Colombia, the utilization of geothermal systems is limited to direct uses such as bathing, swimming, and localized heating. Studies supported by the Latin American Energy Organization and the Colombian Institute of Electricity show that Colombia has at least nine (9) areas of interest for geothermal power generation or direct use. Colombia's total geothermal potential has been estimated at 2,210 MW, and current installed capacity for localized direct use is about 14.4 MW (Mejía E., Rayo L., Méndez J., Echeverri J., 2014). Potential uses for installed capacity include power generation, further direct use potential (heating and cooling), along with various industry potential such as crop drying.

Currently, Colombia is the fourth largest producer of Coffee Arabica, producing 22% of the world's supply (Villaba L., Grisales E., Rodriguez, E.,2017). Within this process, drying of the coffee beans is required, which could utilize geothermal heat. Colombia is also the third largest producer of cassava in Latin America, a staple crop used for food, livestock feed, and planted on more than 200,00 hectares of land (Balcazar A., Mansilla H., Bogota S., 2020). Cassava is often dried for consumption, using sub drying or on a large-scale hot air-drying oven. This crop is another potential use for geothermal heat.

Today, geological studies are being performed by the Colombian Geologic Service at Nevado del Ruiz, Tufiño-Chiles-Cerro Negro, Azufral, Paipa, and the area of San Diego to establish the viability of developing geothermal projects on these areas (Moreno et al., 2020). The group will take a closer look at the potential within the Nevado del Ruiz geothermal prospect.

2.2 Legal Framework

Developing a geothermal resource for power generation involves large investment with high risk. In this section, the group will conduct a literature review on the legal issuances that provide fiscal and nonfiscal incentives in developing the project. Determining the legal framework plays a very important role in evaluating the feasibility of a project as some of the fiscal and nonfiscal incentives aim to reduce and/or recover the capital cost. The policies found were divided into four (4) main topics: natural resources, environment, renewable energies, and geothermal development in Colombia. The main policies are the following:

2.2.1 Natural Resource

Decree 2811, 1974: It is the renewable resources and protection of the environment national code of Colombia. On this code, it defines the geothermal resources as a combination of a geothermal fluid (above 80°C, mostly water), with a subterranean heat resource resulting in the production of warm water and steam. This resource can be used in different activities as energy production, direct use for industrial purposes, heating and cooling and mineral extraction (Colombia, 1974).

2.2.2 Environment

Law 99, 1993: Created the Ministry of Environment as the entity in charge to preserve the natural renewable resources and define that any company who wants to approach the resources must acquire an environmental license to proceed with the project. (Colombia, 1993)

Decree 1076, 2015: Established the provisions for the development of geothermal activities to generate electricity. Defined the steps, the technical requirements, and the environmental requirements that the stakeholders must do to carry out a project (Colombia 2014)

Law 1930, 2018: Defined the protection of the moorland's ecosystem in front of the exploitation of any resource (mine, oil & gas mainly). (Colombia, 2018)

2.2.3 Renewable Energy

Law 1715, 2014: Integration of non-conventional renewable energy in the national energy system. Promotes the investment, research, and development in clean technologies (Colombia, 2014). This law also provides incentives in developing renewable energy resource, such as:

- 15 years to deduct 50% of investment from income tax
- Exemption of the National Value Added Tax (IVA by Spanish acronym) of 19% for equipment and services
- Exemption of import duty for equipment not produced locally
- Up to 20% of accelerated depreciation per year for the investment

2.2.4 Geothermal Development

Law 1955, 2019: It issued the National Development Plan for 2018-2022. One of the goals is to define the final geothermal framework, continue the geothermal exploration by the Colombian Geological Survey and establish the environmental terms of reference for the exploitation of the resource (Colombia, 2019).

In the last two years, the Colombian Government published the Law 2099 of 2021, which defines the development and deployment of non-conventional source of energy including geothermal energy. Also, the Decree 1318 of 2022 to regulate the geothermal activities with the main purpose of power generation and the Resolution 40302 of 2022, which establish the technical requirement and the exploration and exploitation permits necessary to utilize the geothermal resource.

3.CONVERTING GEOTHERMAL ENERGY INTO POWER

3.1 Nevado del Ruiz Volcano Geothermal Prospect

The prospect covers an area of 1,026 km^2 and show signs of geothermal energy below the ground thru the presence of thermal manifestations and presence of fault lines within the area. Within this area, it was determined that the prospect has 108 km2 surface area that is suitable for geothermal utilization (Colombian Geological Service, 1997). Further study on the area also provided the parameters for the volumetric assessment of the prospect as shown in Table 1.

Table 1. Nevado del Ruiz Volumetric Assessment.

INPUT VARIABLES	UNITS	MINIMUM	MOST LIKELY	MAXIMUM
Surface area	(km^2)	5		10
Thickness[4]	(m)		1000	
Rock Density[1]	(kg/m^3)		2700	
Porosity[1]	(%)		4%	
X|	(J/kg-°C)		900	
Temperature[1]	(°C)	250		260
Fluid Density[2]	(kg/m^3)	798.6		783.2
Fluid Specific Heat[2]	(J/kg-°C)	4860		4980
Recovery Factor[1]	(%)		5.0%	
Conversion Efficiency[3]	(%)	10.0%		17.0%
Plant Life	(years)		30	
Rejection Temperature[1]	(°C)		158	

[1.] (Colombian Geological Service, 1997); [2.] (engineeringtoolbox.com, 2021); [3.] (Moon and Zarrouk, 2012); [4.] (Ortiz, J. A., ACGGP (2021).

For this report, surface area was limited from 5 to 10 km^2 as it was assumed that the other parameters would not be the same on the other portion of the prospect. Additionally, if the surface area considered was too wide, the transfer of thermal fluid from well location to the power plant could also present challenges.

Using the parameters obtained for the Nevado del Ruiz Geothermal Prospect, Monte Carlo Simulation was used to determine the potential capacity of the prospect for power generation. The result of the simulation is shown on Figure 1.

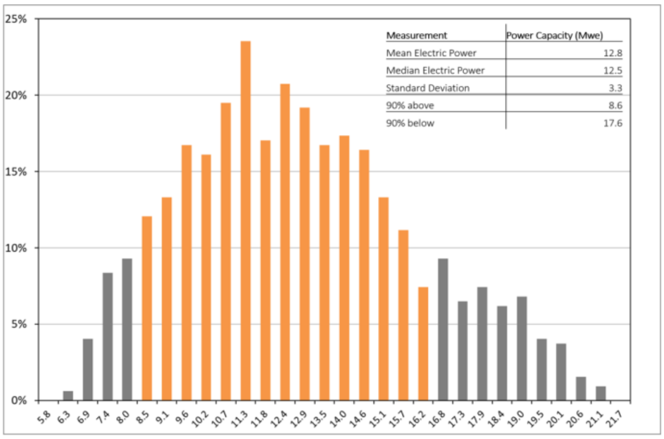

Figure 1: Monte Carlo Simulation for Nevado del Ruiz Geothermal Prospect.

Figure 1 shows that the prospect has a mean electric power potential and median electric power potential of 12.8 MWe and 12.5 MWe, respectively. Typically, the values obtained in this simulation is enough to create the power plant model. However, in this report, the economic feasibility will be determined by optimizing the given parameters to reach the maximum Net Present Value (NPV). To do that, we will use the Modified Hotelling for Geothermal Resources as described in Section 3.3.

3.2 Reservoir Parameters

On this report, the parameters of the reservoir will be based on the available data gathered from Nereidas 1, the only geothermal well drilled in the geothermal prospect in 1997. Nereidas 1 showed that it has a well head potential of 7 MWe with a mass flow rate of 46 kg/s (Colombian Geological Service, 1997). However, to be more conservative in the model, the wellhead potential was based on the data from the volumetric assessment, and it was determined that a well could have a minimum wellhead potential of about 5.6 MWe. Additionally, the depth of the reservoir is estimated to be located within 2000 m to 3000 m (Colombian Geological Service, 1997). On this report it was assumed that the average depth of the wells to be drilled is 2500 m.

3.3 Modified Hotelling for Geothermal Resources

This report will adapt the Modified Hotelling Model for geothermal resources presented in the “Optimizing production strategies for geothermal resources” by Juliusson and Bjornsson (2021). However, due to insufficient data available and different objective, this report will make some minor revisions in the optimization model. The first revision made is the objective function. To determine the best setup for the economic feasibility of the geothermal prospect, the model will maximize the NPV instead of profit, as shown in Equation 1. Other than the objective function, this report will simplify the recharge rate in the constraints and assume it to be 90% of the average extraction rate. This simplification is done as there is no sufficient data available to measure the recharge rate of the system. Additionally, the 90% of average extraction rate assumption for the recharge rate was based on the fact that all of the extracted geothermal fluid will be reinjected back to the systems through the reinjection well and since the size of the reservoir is so large it was assumed that the utilization for power generation has a small effect to the entire reservoir. In consideration of the changes made, the model will be optimized while satisfying the resource constraint, well capacity, minimum energy reservoir limit, maximum energy reservoir limit, maximum extraction limit, minimum extraction limit, and boundary constraints as shown in Equations 2 to 8, respectively.

Objective function:

$$Max\ NPV\left(i,\ \sum_{t=1}^{30}\left(P_t^e G_t^e - P_t^{O\&M}\right)\right) - C_0^e \tag{1}$$

Subject to:

$$\sum_{t=1}^{30}\left(S_t^r - S_{t-1}^r + E_t^r + R_t^r\right) = 0 \tag{2}$$

$$E_t^r - N_t^G W_p \leq 0 \tag{3}$$

$$S_{min}^r - S_0^r \leq 0 \tag{4}$$

$$S_0^r - S_{max}^r \leq 0 \tag{5}$$

$$E_t^r - E_{max}^r \leq 0 \tag{6}$$

$$E_{min}^r - E_t^r \leq 0 \tag{7}$$

$$P, G, C, i, S, E, R, N, W \geq 0 \tag{8}$$

Where:

P_t^e	= price of electricity, USD
G_t^e	= annual generation, kWh
$P_t^{O\&M}$	= cost of operations and maintenance (O&M), USD
C_0^e	= total initial cost of the project, USD
i	= discount rate, %
S_t^r	= stock in the reservoir on the given time, TJ
S_{min}^r	= minimum stock of the reservoir, TJ
S_{max}^r	= maximum stock of the reservoir, TJ
E_t^r	= extraction rate of the reservoir on the given time, TJ
E_{min}^r	= minimum extraction rate, TJ
E_{max}^r	= maximum extraction rate, TJ
R_t^r	= recharge rate, TJ
N_t^G	= number of geothermal wells
W_p	= geothermal production well capacity, TJ

This nonlinear optimization model has three (3) main decision variables. The first decision variable is the stock in the reservoir, S_t^r, this set of variables shall determine how much power is available in the reservoir at a given time. The next decision variable is the average extraction rate, E_t^r, this variable would indicate the amount of energy taken-out in the reservoir. It is important to note that to simplify the model we assumed that the average extraction rate will be the same all throughout its plant life. The last decision variable is the number of wells in operation, N_t^G, this decision variable shows how many wells are operating every time. To simplify the nonlinear optimization model, we assumed that the wells drilled will be productive for 30 years.

4. FINANCIAL EVALUATION

4.1 Costs

To determine the economic feasibility of the prospect, the group will provide estimation for costs in developing the prospect into power generating unit and the cost of its operation. For this report, the group will categorize the costs into three (4) categories: exploration, drilling, power plant, and operations and maintenance (O&M). To get a conservative model, the group will only consider the maximum cost on these categories on the optimization model.

4.1.1 Exploration

Exploration cost is affected by several factors such as location, surveying methods, permitting, and others. These costs are primarily composed of the geoscientific surveys and estimated to 0.2 to 0.8 million USD/MW (Purwanto, E. H., 2019).

4.1.2 Drilling

Drilling cost depends on the depth and type of well to be drilled. While Colombia has only one geothermal well currently, to figure a good estimate for the drilling cost, the group shall be based its cost estimates to other country's cost of drilling as shown in Table 2.

Table 2: Country comparison of average drilling costs, depth and type of well (Purwanto, E. H., 2019)

Country	Year	Drilling cost with US PPI 2019 (MUSD)	Av. depth	Av. no. of days	Unit cost (USD/m)	Size of well	Reference
Turkey	2018	3.4	4500	45	752	Standard	Gul and Aslanoglu, 2018
Philippine	2019	9.0	2500	-	3,600	Large	Jarque, pers. comm., 2019
Kenya 1	2013	6.7	3200	-	2,093	Large	Ngugi, 2013
Kenya 2	2013	6.2	3000	63	2,076	Large	Kipsang, 2015
Iceland 1	2002	2.4	1500	-	1,602	Standard	Stefánsson, 2002
Iceland 2	2012	4.9	2175	43.5	2,235	Large	Thórhallsson and Sveinbjörnsson, 2012
Iceland 3	2014	4.4	2235	45	1,961	Large	Sveinbjörnsson and Thórhallsson, 2014
Iceland 4	2017	4.1	2500	45	1,638	Standard	Pálsson, 2017a and b
N. Zealand 1	2006	4.2	2600	-	1,621	Standard	Hole, 2006
N. Zealand 2	2007	5.2	2500	-	2,506	Large	Barnett and Quinlivan, 2009
N. Zealand 3	2010	3.7	2306	33	1,610	Standard	Bush and Siega, 2010
N. Zealand 4	2010	7.3	2558	63	2,855	Large	Bush and Siega, 2010
Indonesia	2018	8.1	2000 - 2700	60	3,960	Large	Author's analysis

Table 2 shows that the minimum cost of drilling is in Turkey wherein it only cost around 752 USD/m. On the other hand, Indonesia has the highest cost of drilling wherein it cost 3960 USD/m.

In cost estimation for geothermal wells, it is important to note that the drilling has the highest risk in developing a geothermal resource. To include this factor in this report, the group shall use the total number of wells drilled in the calculation of the total cost. To do this, the group wills use the estimation made by the International Finance Corporation (IFC). According to IFC (2013), the average well drilling success rate varies by project phase: 59 percent of wells are successful during the exploration phase, 74 percent during the development phase, and 83 percent during the operation phase. The author plans to calculate the total number of wells to be drilled for this study using a conservative well drilling success rate of around 60%. The group will presume that unsuccessful or non-producing wells can be use as reinjection wells. However, in practice, this isn't always practicable because certain drilled wells aren't suitable for production or reinjection.

4.1.3 Power Plant

Power plant cost is one of the most expensive portions in developing geothermal prospect. This includes power plant major components and others such civil, engineering, and erection. The cost of the power plant major components and others are estimated to be 1.08 MUSD/MW and 0.28 MUSD/MW, respectively (World bank, 2010).

4.1.4 Operation and Maintenance

Cost of O&M will be calculated to be between 1.9 and 2.3 UScents/kWh (Lovekin, 2000; Owens, 2002). For this report, it is also assumed that the O&M is conducted annually and takes up to 25-days to complete.

4.2 Economic Feasibility

As mentioned on previous section, the group will determine the economic feasibility of the project using the MS Excel functions to solve for NPV and Internal Rate of Return (IRR). For NPV, the group assigned 10% discount rate and multiplied this by net cash flows calculated over the lifespan of 30 years, subtracted by our initial costs (See Equation 1). To determine the IRR, the following formula shown in Equation 9 was used in MS Excel.

$$IRR\left(\sum_{t=1}^{30}(Revenue_t - Expenses_t)\right) \tag{9}$$

For both NPV and IRR, the revenue shall be calculated from the product of determined installed capacity, number of days in operation (340 days), net power operation (95%), and electricity price (0.13 USD/ kWh, XM sumando energias, (2021)). On the other hand, the annual expense is the cost of O&M.

5. RESULTS AND DISCUSSIONS

To determine the optimal value of the model, the group optimized the model using the GRG Nonlinear Optimization in MS Excel. This model was obtained by 33 decision variables. Among these decision variables, the initial reservoir capacity showed to be 1,156,119.27 TJ which is 1,223,336.70 TJ less than the maximum reservoir capacity and 83,031.27 TJ above the minimum reservoir limit as calculate the constraints for the 30 years plant life. Additionally, the average extraction rate of the model was determined to be 105,752.82 TJ which requires two (2) operating geothermal production wells.

With the values obtained from the decision variables, satisfying all the prescribed conditions on the constraints, and the costing presented in the methodology, the model showed that the initial cost of developing the prospect amounts to 53.8 MUSD with annual revenue of 11 MUSD and annual O&M cost amounting to 2 MUSD. This resulted to positive NPV value amounting to 33.5 MUSD. Additionally, we determine that the power plant capacity to be 11.18 MW, which is relatively close to the mean and median capacity determined in the Monte Carlo Simulation which are 12.8 MW and 12.5 MW, respectively. Further, the model also determined the following information: annual generation is 86.6 GWh per year, the total number of wells drilled is 3, the IRR is 17.07%.

6. CONCLUSION

After assessment of geothermal potential in the Nevado del Ruiz region, if the full potential that has been assessed were to be utilized, generation capacity could reach up to 86.6 GWh/year. This can help bridge the gap if there is a decline in hydropower due to drought and reduce reliance on fossil fuels, adding to the Colombian governments desire to help reduce the impact of global climate change. While the project has a positive NPV and IRR, the project requires a high initial cost amounting to $53.8M USD which presents a challenge for gathering funds and investors.

Greater development of the country's geothermal resource base may be promoted by modifying the regulatory framework, adding incentives such as tax deductions, facilitating financing mechanisms and investment risk coverage. Training of personnel on the technical and scientific training needed to develop geothermal will be crucial in accelerating development as well.

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