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# Techno-Economic Simulation of a Geothermal Energy Generation System at the Machin Volcano in Colombia

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**Abstract:** Colombian geothermal potential for power generation is interesting due to the presence of the three Andean mountain ranges and the existence of active volcanoes in junction with springs and underground reservoirs with the consequent closeness of available hydrothermal water-wells. The Machin volcano is a small mountain placed in the middle of the country, that has a considerable geothermal potential with wells in a temperature range of 160 to 260 °C. For that reason, a techno-economic simulation for a Geothermal Energy Generation System is proposed in this paper, using for that the System Advisor Model software. The purpose of this research is to present a more encouraging picture for public and private investors interested in exploiting this energy potential in Colombia. Simulation results include technical and economic aspects as annual and monthly energy production, geothermal resource monthly average temperature, and the Time Of Delivery Factors are also considered. Some tables with system configuration, plant and pump costs, Capacity Factor, and real and nominal Levelized Cost of Energy are also shown.

*Keywords:* Colombian Thermal Gradients, Feasibility Analysis, Geothermal Energy, Renewable Energy Generation Systems, System Advisor Model.

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## 1. INTRODUCTION

The high costs and depletion of fossil fuels, global warming, the need to reduce $CO_2$ emissions, make renewable energies crucial in the development of a sustainable economy for an overpopulated and highly inequitable globe today. Of all the possible forms of sustainable energy that exist, Geothermal energy, which is the usable heat coming from inside the earth, plays a fundamental role in the various productive and recreational sectors, whether from the thermal baths, passing through the heating of residential areas, and ending in industrial uses of both steam and electricity generation Gehringer (2012); Ingrid Stober (2013).

The geothermal potential of the planet is 5000 % greater than that of oil, natural gas, organic wastes, and coal Mamani and Guillen (2019). It has a competitive advantage over other types of renewable energy, has greater reliability, sustainability, high load factors, good competitiveness and generates 80 % less $CO_2$ compared to fossil fuel plants Trillo and Angulo (2012). A global framework for the geothermal energy presents The United States as World power followed by Indonesia and the Philippines, México representing Latin America in an important sixth position with 951 Megawatts, El Salvador, Honduras, the Dominican Republic with a new incentive and support scheme, could be moving forward in the next years Jorquera (2019); Ritcher (2019). The International Energy Agency (IEA) has motivated governments to develop logistic frameworks for geothermal policies that have environmental, social, economic, regulatory needs, and support for scientific research and sustainable development. The world top 10 for GT Energy in 2018 is illustrated in Figure 1.

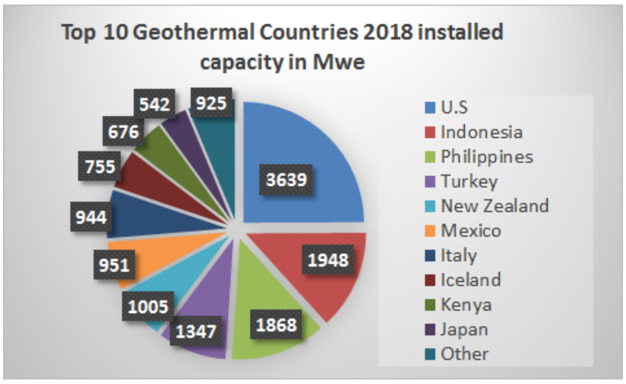

Figure 1. Geothermal World Energy Top 10 Jorquera (2019).

In Colombia, the geothermal study began in 1968, when the National Electricity Authority of Italy receives an investigation request by the Caldas Hydro-electric Power Plant (CHEC) for research into the Nevado del Ruiz volcano, where the geothermal features in a 1,500 $km^2$ area, were evaluated. However, the work did not continue until fifteen years later, again by CHEC, and in 1983 a pre-feasibility study was completed, selecting three places of interest with significant geothermal potential: the Nereidas' Valley, located in Caldas province, the Otún's Lagoon, located in Risaralda province, and the Cerro Machín Volcano, located in the Tolima province. Until 2016, 300 thermal sources and 11 fumaroles have been identified, located in the Andean region, all of them associated with volcanoes.

Four geothermal projects are currently being installed in Colombia, all of them on the pre-feasibility stage: The Tufiño Chiles - Cerro Negro binational GT Project in collaboration with Ecuador, the Azufral volcano GT Project placed in the western of the southwest of Andean mountain range in Nariño province, the Paipa GT Prospect located in the eastern Andean mountain range, at the Boyacá department and, the Nevado del Ruiz volcano GT Project as part of an active volcanic complex placed in the western Andean Colombian mountain range. Bona and F.Coviello (2016).

The Cerro Machin is classified as an explosive volcano, composed by a pyroclastic ring complex with a maximum diameter equal to 2.4 km, with domes plugging its crater. It is an active volcano that has thermal water deposits with temperature ranges between 42 and 90°C. These temperatures were taken using conductive chalcedony and adiabatic quartz geo-thermometers (with a range from 190 to 260 °C), identifying it as a medium temperature reservoir, characterized with a thermal gradient between 90 to 190 °C TermalesInv (2019). Its deeps are from 1500 up to 4000 m and could be used for power generation applications due to the water phase change that can already make to produce steam for increase the enthalpy in a significant manner. Thus, a geothermal plant placed there, could works in a proper and efficient way as is explained in Cerpa (2018) master's work and in a recent paper written by Casallas et al. (2020). This volcano is placed in the municipality of Cajamarca, Tolima. Machin volcano has 2750 meters above sea level and its distant from Bogotá DC for 150 km at the southwest, 17 km to the west of Ibagué city, and 30 km to the east of Armenia city.

For all the above, this paper presents a techno-economic simulation for a GT Energy Generation System (GEGS), using detailed geothermal and meteorological data about Cerro Machín volcano injunction with the System Advisor Model (SAM) software, provided by NREL - National Renewable Energy Laboratory (2018). The computational model simulated here, estimate the balanced cost of electricity (LCOE) for a renewable energy project through the use of GT power. The model requires some predetermined inputs as the geothermal total resource potential, the temperature, and depth of the water-well. Thus, the cost of generation, based on several resource scenarios can be estimated as is depicted by Casallas et al. (2020); Cerpa (2018); Alberto Gemelli (2013).

For achieving that, the authors propose the following order for this paper: In Section 2 the GT Plant Configuration is explained. Then, in Section 3 the main costs of the GEGS are resumed. Next, Section 4 shows the techno-economic simulation results, and finally, in Section 5 a conclusion of this case study is written.

## 2. GEOTHERMAL PLANT CONFIGURATION

### *2.1 Location and Resource*

For obtaining the solar radiation level in $kWh/m^2$ for Cerro Machín volcano, the National Solar Radiation Database (NSRDB) web viewer NREL (2019) is used. A summary of these international data sets are provided below in Table 1.

| **Region** | Mexico/Central America |
|---|---|
| **Data set** | Physical Solar Model (PSM) V. 3.0 |
| **Temporal Resolution** | 1/2 hour |
| **Spatial Resolution** | 4 x 4 km |
| **Years Covered** | 1998-2017 |

Table 1. Solar Data Resource Model.

For this case, the geographical coordinates of the Machin are 4° 29' 30" and 75°,23' 30" W.

In Table 2, the satellital parameters for the project location are shown.

| **Type of Radiation / Other Factor** | **Value** |
|---|---|
| Global Horizontal | 4.63 $kW/m^2/day$ |
| Direct Normal (Beam) | 3,1 $kW/m^2/day$ |
| Diffuse Horizontal | 2,86 $kW/m^2/day$ |
| Annual Albedo | 0,136 |
| Average Temperature | 16.2 °C |
| Elevation | 2514 meters above sea level |

Table 2. Solar and Weather Parameters at Machín.

Additional inputs for the solar radiation model can be read in Perez et al. (2002, 2004).

### *2.2 Geothermal Gradients in Machin Volcano Influence Area*

According to studies carried out by the Colombian Geological Service (SGC) and the Engineering School of Antioquia (EIA), through the Geological Engineering Program over the Cerro Machín volcano, seven water sources were found and were classified as hot springs, with temperature ranks varying between 42 and 90 °C, at an average distance of 2 km from the crater of the volcano. The estimation was done by geo-thermometers obtaining a temperature range in depth of the possible reservoir Cerpa (2018).

Further studies should be carried out during the prospecting or exploration stage on the magmatic-hydrothermal system of the Cerro Machín volcano and verify that the temperatures are within these ranges, to be used for industrial processes since it would be considered a high enthalpy reservoir Cerpa (2018); TermalesInv (2019); Casallas et al. (2020).

### *2.3 Number of Wells to Drill*

The software calculates the number of production wells, power generation, that is based on the plant inputs and the main components menu of SAM as Plant and Equipment, Power Block, Systems Costs, etc. GT resource menu is explained in detail in subsection below NREL - National Renewable Energy Laboratory (2018):

*Confirmation Wells* The number of required production wells to be drilled must be specified by user. Since to the confirmation wells can sometimes be used for energy production, a portion of the confirmation wells will be used must be considered in the analysis. This value is calculated by multiplying the number of confirmation wells with the percentage of these wells used for power generation. It is also known as the ”Number of Confirmation Wells” components menu of SAM NREL - National Renewable Energy Laboratory (2018).

*Injection Wells* The number of injection wells is typically a function of the number of production wells. It must be specified this ratio, keeping in mind that this equal to the injection vs the total number of production wells. It is important consider here that is not the number of production wells that have to be drilled. This value will be multiplied by the total Production Wells that must be required value to calculate the number of Injection Wells to be Drilled Coury Associates et al. (1982).

In this case, a total of Production Wells analyzed was equal to 7.

### *2.4 Geothermal Reservoir*

The software uses the well temperature value to calculate the number of times that new drilling will be required, in order to renew the GT resource, based on the reservoir temperature reduction over time, and during the draft life cycle. NREL - National Renewable Energy Laboratory (2018); Coury Associates et al. (1982).

As the system works and extracts heat from the reservoir, its temperature decreases. After a few years, the heat may be insufficient to maintain the temperature of the steam required to produce energy in the plant, making it necessary to search for new wells to renew the resource and thus explore another reservoir section where there is enough heat for the power generation Harrison et al. (1990); Boden (2016). Finally, the reservoir can be cooled to the point that it is impossible to find more heat by drilling from this plant site.

The geothermal potential of the Cerro Machín volcano according to studies developed by Cerpa (2018), TermalesInv (2019), and Casallas et al. (2020) has 7 underground thermal deposits, confined in an area equal to 20 hectares. Each of these GT deposits has a heat potential of 25 MW approx. These GT wells can be considered as a high enthalpy reservoir. The total estimated geothermal resource was determined at around 175 MW when only one inspection well was drilled Cerpa (2018).

### *2.5 Plant Configuration and Efficiency*

Power generation from geothermal energy can be done using several types of plants. These include, for example, binary type, flash, and double flash types, dry steam and counter-pressure plants. In SAM, the plant configuration depends on the type of resource obtained during the exploration phase Eicker (2014).

A binary plant works with a geothermal resource with temperatures between 190 °C and 260 °C, using a secondary working fluid, usually organic n-pentane with a low boiling point, and a high vapor pressure, governed with low temperatures DiPippo (2016b,a); Entingh et al. (1994), as indicated in Figure 2.

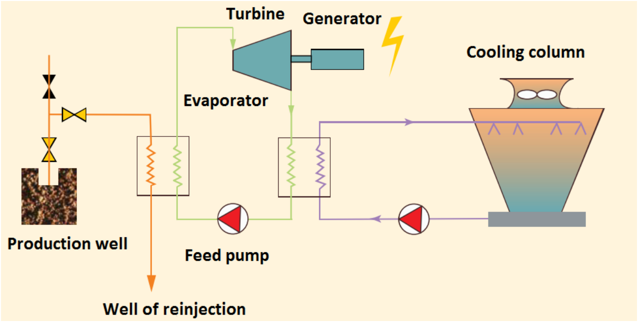

Figure 2. Typical binary power plant, Rankine cycle Gehringer (2012).

The plant must operate through a conventional Rankine cycle, that is, the geothermal fluid gives heat to the secondary fluid through heat exchangers, where it is heated and vaporized. The steam produced drives a turbine then cools and condenses and the cycle starts again NREL - National Renewable Energy Laboratory (2018).

The efficiency of binary plants has been increasing during the last years. In its beginnings, efficiencies close to 10% were obtained, however, today, efficiencies between 45% and 60% have been achieved. This depends mainly on the fluid inlet temperature.

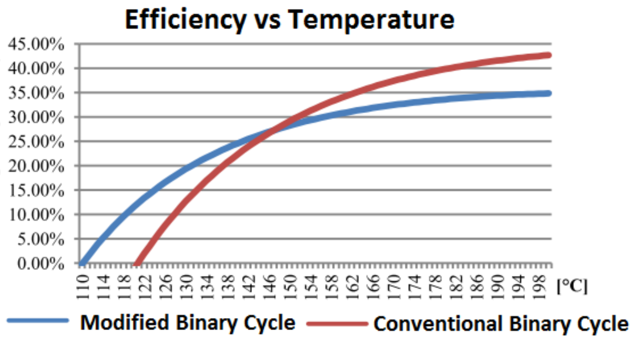

Figure 3. Efficiency in modified conventional binary plants Aviña (2013).

Variation in efficiency is shown in Figure 3. If the geothermal fluid inlet temperature is modified, it is possible to determine the optimum operating range for each of the heat cycles. Therefore, if there is a geothermal resource below 146 °C, the most efficient option will be to use a modified binary cycle plant and, on the opposite, if a geothermal resource with a higher temperature is available, then a GT plant based on a conventional binary cycle, it is advisable to be used Aviña (2013).

### *2.6 Power Block*

The Power Block specify the parameters to convert the thermal energy of the geothermal resource into electrical power, using a conventional steam Rankine cycle plant. The energy cycle uses a hybrid system for cooling.

The computational model for the geothermal plant runs a simulation with a time range of several years of the plant's life, in order to account for the decrease in geothermal resource on a monthly basis. The monthly energy block analysis results in 360 calculation sets ($12\ months/year \times 30\ years = 360\ months$).

Since it is unlikely that there will be meteorological data for each of the years of the analysis period, the computational model uses the same meteorological file for all the years of project life. The only value that changes annually in the performance model, is the temperature range of the geothermal resource as it degrades over time NREL - National Renewable Energy Laboratory (2018). In this case, a GT plant of power rated equal to 33 MW is considered. A summary of simulation data for geothermal plant and power block is presented, for reader clarity, in Appendix A.

## 3. GEOTHERMAL BALANCE OF SYSTEM

The Geothermal model is used to calculate the total installed and operating costs for its application in the financial model. The cost data are meant to be realistic as is explained in Short et al. (1995); Energy Information Administration (2016).

SAM's financial models can represent residential and commercial projects, that buy and sell electricity at retail prices and Power Purchase Agreement (PPA) type projects, to meet the requirements of the internal rate of return NREL - National Renewable Energy Laboratory (2018).

Main cost categories included in this model are briefly explained below, in accordance with Entingh et al. (1994):

### *3.1 Exploration and Confirmation Costs*

The cost for exploration ($C_{expl}$) and the confirmation wells ($C_{Conf}$) are expressed as a function of the cost of a production well.

$$C_{expl} = C_{conf} \times CM \times \#_{wells} \tag{1}$$

A factor known as cost multiplier ($CM$) affect the production well cost to estimate the Cost per Well. Then, this value is multiplied by the number of wells that is defined by user and thus estimate the drilling costs.

### *3.2 Drilling and associated costs*

This kind of cost consider the production wells that must be drilled and will incur in the energy production. The number of production wells is calculated by subtracting these from the total production wells required.

The number of injection wells is typically a function of the number of the production wells. It must be specify the ratio of injection wells to production wells, that is, not the number of production wells that have to be drilled. Then, it will be affected by the Total Production Wells required to calculate the Number of Injection Wells to be drilled, this is shown in (2):

$$C_{drill} = C_{expl} \times \#_{prodwells} \times ROI \tag{2}$$

where, $ROI = \frac{\#wells_{prod}}{\#wells_{inj}}$ is the Ratio Of Injection.

### *3.3 Production and Injection Costs*

These costs are specified as a function of the well depth where the resource is available. The drilling cost per well can be calculated using a function that relating the well depth to cost and is also known as the chosen cost curve (Low, Medium, and High) elaborated by Sandia National Laboratories drilling data NREL - National Renewable Energy Laboratory (2018).

The cost per well for production and injection wells is also known as the Cost per Well. Also, the non-drilling costs it can be specified. These will be added to the drilling cost to calculate the total cost for production and injection wells.

### *3.4 Surface Equipment, Installation and Stimulation Costs*

These type of costs are assumed as a function of the total number of production and injection wells. The cost per well must be multiplied by the number of wells to calculate the total Non-drilling costs.

### *3.5 Plant Capital Costs*

*Plant Cost* This can be expressed in per kW basis, that it means, can be defined in dollars per kW, and then multiply this value by the plant unit size, this is also known as the Power Plant Cost.

$$W = (E_Q - E_{rein}) - I = E_{Q,av} - I \tag{3}$$

Where: $W$ is the output power, $E_Q$ is the exergy flux associated to the GT source, $I$ is the exergy losses associated to the power GT plant and $E_{rein}$ is the residual exergy of the GT fluid that is reinjected to the well, as is explained in Franco and Vaccaro (2014).

Therefore, the plant cost can be written in this way:

$$C_{plant} = \frac{\$USD}{kW} \times W \tag{4}$$

*Pump Cost* It can be defined as a function of the pump depth and pump size. The pump cost is specified on a per horsepower basis to determine the cost per pump.

$$\begin{aligned} C_{Pump} \times \#_{prodwells} = \left( \frac{\$USD}{HP} \times HP \right)_{pump} + \\ (C_{inst} + C_{cas}) \times D_{pump} \end{aligned} \tag{5}$$

The total cost of this items includes the installation and casing costs and these are specified on a per meter basis and then multiplied by the pumping depth. Finally, the total installed cost per pump is the sum of the pump cost and the installation and casing cost. This is multiplied by the total number of production wells required to calculate the total pump cost.

### *3.6 Total Installed Costs*

The total installed cost is the sum of all of the direct and indirect capital costs. This value is useful to calculate the project's net capital cost, which is the total installed cost less any cash incentives and plus any additional financing costs. Two main categories are including in these kind of costs:

*Indirect Capital Costs* Indirect capital costs are divided into five different types: Engineering, Procurement, Construction Project, Land and Miscellaneous costs, Including a Sales tax. This is depicted in Eq.(6):

$$C_{ind} = [C_{eng} + C_{proc} + C_{const} + C_{land} + C_{misc}] \times S_{Tax} \tag{6}$$

The first two can be defined as a percentage of direct costs, or as a stand alone value, or both. The sales tax percentage is applied to some portion of the direct cost. These five types of indirect costs are added to the total indirect cost.

*Recapitalization ($C_{recap}$)* The recapitalization cost can be added each time that the resource has to be re-drilled to reach a new section of the geothermal resource in order to increase the production well temperature.

### *3.7 Cost of Electricity ($C_{in}$)*

Finally, Equation (7) express the GEGS cost of electricity ($C_{in}$):

$$C_{in} = C_{expl} + C_{dril} + C_{prod} + C_{plant} + C_{Pump} + C_{ind} + C_{recap} \tag{7}$$

This is the sum of all type of costs defined above.

## 4. SIMULATION RESULTS

Next Section present both, the techno and the economic results for GEGS. Taking into account the parameters described in previous Sections for the Machin Volcano.

### *4.1 Technical Results*

In the Figure 4 shows the annual production of electrical energy of the geothermal plant, the first year the generation is 234 $GW/h$ and there is an annual decrease of 2.5 % up to 25 years with a generation of 210 $GW/h$. Having a plant with an installed capacity of 33.4 $MW$.

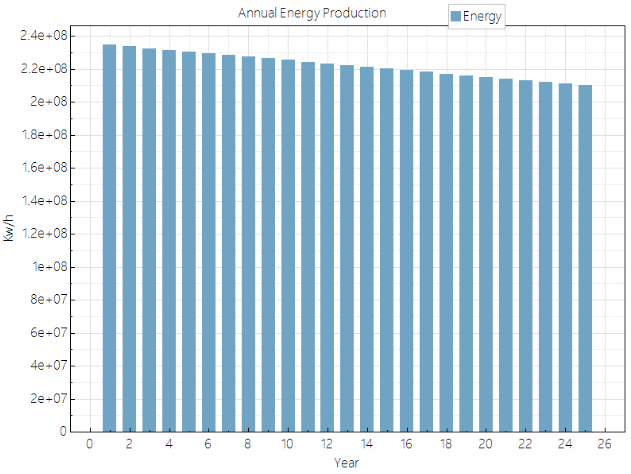

Figure 4. Annual energy production in kW/h.

Figure 5 discloses the monthly electricity production of the plant for 300 months, with peaks between 22 GW/h month and 16 GW/h month, reaching 121,000 households monthly, taking an average monthly consumption of 150 kW/h.

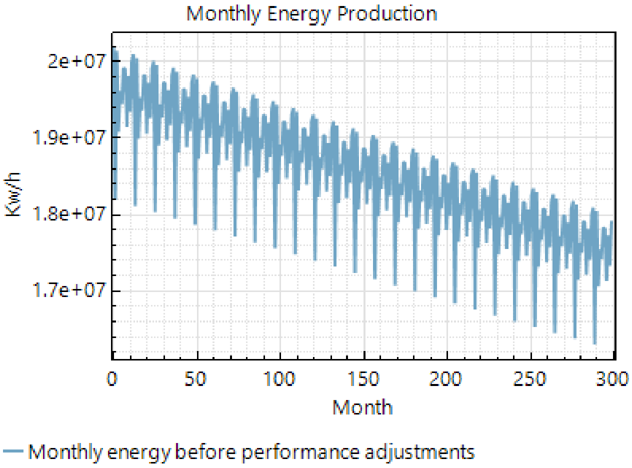

Figure 5. Monthly energy production in $kW/h$.

Temperature of the working fluid monthly, during 25 years, the first month has an average temperature of 190 ° C, if a decrease of 0.04 % monthly, is considered until a month with a temp. equal to 168 ° C is achieved. It can be seen that, after a long time elapsed, super-heated steam is still obtained before making the next drilling.

In the Figure 6 the power plant annual average profile is presented. A peak value around 26,3 MW is present between 11:00 h. and 13:00 h.

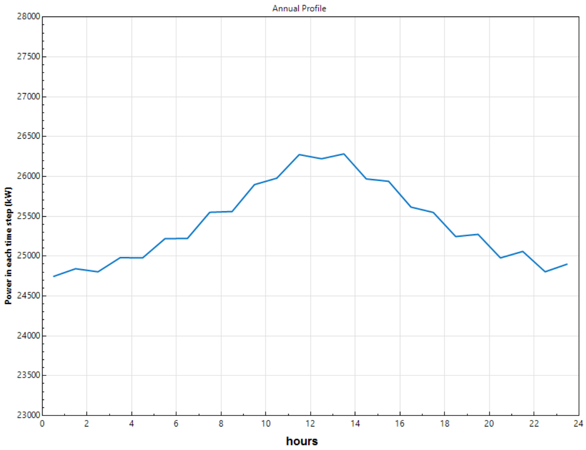

Figure 6. Power Plant in each time step in kW.

Figure 7 represents the time to deliver energy at different price factors throughout the day. The daily annual average of energy produced by the geothermal plant that is delivered to the national mains is present in this figure. The highest TOD factor (of almost 1.3 times) occurs in the course of 15:00 h. to 21:00 h. owing to the highest demand for energy users is presented. In this case, the TOD is configured in accord the Power Generation and Energy (PG&E 2016) profile available in SAM NREL - National Renewable Energy Laboratory (2018).

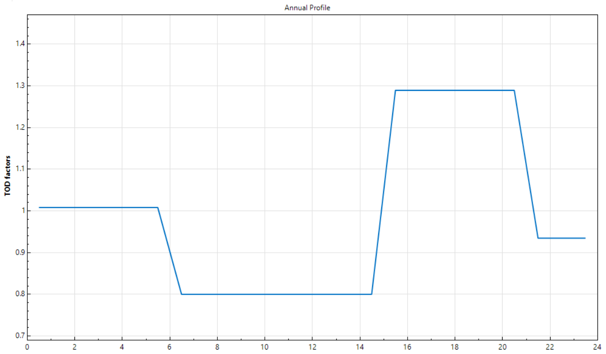

Figure 7. Time Of Delivery TODs for GEGS at Machin Volcano.

### *4.2 Economic Results*

Tables 3, 4 and 5 resume some interesting GEGS costs and some economical results, obtained after running the simulation case:

*Plant Cost* Results for the GEGS plant costs are resumed in following Tables below:

| Plant Capital Cost | |
|---|---|
| Gross Plant Output | 41,559.898 kW |
| Baseline Cost | 1,300.00 $/kW |
| Power Plant Cost | $ 54,027,868 USD |

Table 3. GEGS Plant Costs

*Pump Cost* The Pump is an extremely important component in a GEGS. The software uses the rated power of the plant, the number of production wells and its cost per HP, for the estimation of Pump in HP and its cost in $/HP. This is resume in Table 4.

| **Pump Cost inputs** | |
|---|---|
| Installation and casing cost | 50.00 $/ft |
| Pump depth | 1,336.896 ft |
| Pumping Cost | 12,479.20 $/HP |
| Pump Size | 893.61 HP |
| # of pumps Required | 7 |
| Cost of Pump | $ 439,889 USD |
| Total Pump Cost | $ 3,079,225 USD |

Table 4. GEGS Pump Costs.

Some important economical results are displayed in Table 5 after running the SAM project for Machin's GEGS, these are: Net Present Value, (PPA) Price escalation, Internal rate of return (IRR) and Net Capital Costs.

| Metric | Value |
|---|---|
| Annual energy (year 1) | 234,957,168 kWh |
| Capacity factor (year 1) | 89.4% |
| PPA price escalation | 1 %/year |
| Levelized COE (Nominal) | 8.76 ¢/kWh |
| Levelized COE (Real) | 6.99 ¢/kWh |
| Internal rate of return (IRR) | 15 % |
| Net capital cost | $ 123,049,496 USD |

Table 5. GEGS Economic Results.

## 5. CONCLUSION

The Machin volcano surrounding, where the geothermal potential is located, is characterized by being a national pantry of agricultural products, due to its variation in temperature zones and its water wealth. It has a high biodiversity of flora and fauna, making the electricity generation through a renewable resource (as a geothermal resource) a mandatory alternative to contribute to the sustainable development of that region. The simulation carried out in SAM on the geothermal potential of the Cerro Machin volcano and the results obtained shown in Figure 4 (Annual energy production in $kW/h$) shows an average annual generation can be obtained during the first 25 years of the project life and a total of 234,671,280 $kW/h$ year, it can be obtained. It is a very good production for medium enthalpy geothermal fields and an installed capacity less than 40 MW. This is due to an average temperature of 179 °C, with a decrease of 0.04 % monthly. The fluid does not change its phase and its calorific value is almost constant throughout the life cycle of the project. The total cost of the project has a value of $123,049,496 USD, an internal rate of return (IRR) of 15 % and a plant capacity factor of 89.4 % is achieved. Paralleling the geothermal power plant project in Copahue (30 MW) in Argentina is stated to be viable in similar economic ranges respect to Cerro Machin volcano Project presented here Gonzalez (2019).

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## Appendix A. SIMULATION DATA

Main input data for running the GEGS simulation correctly are resumed in Table A.1

| **Resource Characterization** | |
|---|---|
| Total Resource Potential | 175 MW |
| Resource Temperature | 190 °C |
| Resource Depth | 1500 m |
| **Plant Configuration** | |
| number of wells | 7 |
| Net plant Output | 33.426 MW |
| Plant Type | Binary |
| Plant Efficiency | 60% |
| **Power Block Model Hourly** | |
| Rated cycle conversion efficiency | 0.17 |
| Design inlet temperature | 190 °C |
| Design outlet temperature | 90 °C |
| Boiler operating pressure | 2 bar |
| **Cooling System** | |
| Condenser type | Hybrid |
| Ambient temperature at design | 15 °C |
| Cooling system part load levels | 8 |

Table A.1. GEGS Simulation Data