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PRE-FEASIBILITY STUDY FOR THE IMPLEMENTATION OF A BINARY CYCLE POWER PLANT IN SAN VICENTE GEOTHERMAL FIELD IN EL SALVADOR

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ABSTRACT

Since its beginnings in geothermal energy venture, El Salvador has been one of the pioneer countries in generating electricity based on this resource. With two power generation plants operating since 1975 and 4 geothermal fields (two currently in operation and two in the process of development and exploitation), El Salvador is committed to increasing its installed capacity with the installation of new power generation plants in the Chinameca and San Vicente geothermal fields, the latter being the focus of study in this document. With well pads, access to sites, relatively stable climatic conditions, and production and reinjection wells in the San Vicente Geothermal Field, it is essential to start exploiting the resource to take advantage of studying it. For this reason, the pre-feasibility survey for the installation of a binary cycle power plant is evaluated in this work. The main characteristics of the geothermal resource were taken into consideration together with the analysis and thermodynamic modelling of the plant using the programming language Python, and the economic analysis of the current Salvadoran electricity market.

1. INTRODUCTION

The study of the San Vicente Geothermal Field began in the 1960s with UNDP assistance. Drilling two gradient wells (PESV-1, 551 m deep; and PESV-2, 506 m deep) and an exploratory well with a commercial diameter (SV-1, 1,346 m deep) followed the surface exploration of this region. The greatest temperature observed in the SV-1 exploratory well was 250 °C, indicating that the area has geothermal potential. Many scientific surface research studies and testing of pre-existing wells were conducted between 2005 and 2008. Findings led to a new conceptual model which emphasizes the importance of continuing subsurface investigation through drilling. The conceptual model was used to locate deep exploratory drill locations which required an environmental permit.

Between 2009 and 2015, additional geoscientific research in the San Vicente Geothermal Field was completed, together with the installation of access roads, water supply infrastructure, and new well pads. In this time, wells SV-1A, SV-2A, SV-3, SV-5A, SV-5B, SV-5C, and SV-2B were drilled. These wells intercepted a high-temperature liquid-dominant reservoir with an average temperature of 240 °C, confirming the conditions necessary for commercial-scale utilization. However, the utilization of any resource to produce electrical energy must be optimized to maximize the benefits by producing higher quality energy.

Considering the current status of the San Vicente Geothermal Field, the number of wells drilled, the geothermal resource available, and the electrical market in El Salvador, this report provides the essential inputs for preparing a feasibility report that can outline the development path of the project.

2. DESCRIPTION AND APPLICATION OF THE STUDY

2.1 The focus of the work

Since its beginnings in producing electricity from geothermal energy, El Salvador has been one of the countries considered "pioneers" in such work. So far, two geothermal fields have been successfully developed with the installation of power plants that have been efficiently taking advantage of the geothermal resource for more than forty-five years in the case of the Ahuachapán geothermal power plant and twenty-nine years in the case of the Berlin geothermal power plant. With a proven resource of approximately 644 MWe (Guidos and Burgos, 2012), El Salvador continues to develop its capacity to generate electricity through the exploitation of geothermal resources and is now focusing on the development of the Chinameca and San Vicente geothermal fields.

For the present work, the San Vicente Geothermal Field has been selected as a case study. According to its geothermal potential, its electrical energy production capacity will be evaluated in the first phase of development. Data from production tests of existing geothermal wells will be analysed. The main characteristics of the geothermal field and the national electricity market will be considered to define a viable exploitation alternative.

2.2 The objective of the work

The main objective of this work is to carry out a technical pre-feasibility study for the construction of a binary cycle plant in the SV-5 platform of the San Vicente Geothermal Field. A computer model of the plant will be run to obtain optimal power values according to the proven resource in the field, and all the information available to date will be used for this purpose. Likewise, an economic analysis of the current situation of the Salvadoran electricity market will be carried out and other vital parameters will be considered to determine whether the installation of such production equipment is viable or not.

2.3 Programs and tools for the calculations

Several libraries of thermophysical properties can be used to run a thermodynamic model of a power plant. An example of this type of library is COOLPROP (Bell et al., 2014), which is widely used since it provides several tools and functions that facilitate the work of students and professionals who study thermodynamics and heat transfer.

In addition to COOLPROP, libraries such as Engineering Equation Solver (EES), and others provide various benefits to engineers to perform their work activities. However, the reality in an increasingly competitive world is that not everyone can access these programs due to the high costs related to their licenses. This is where open-source software that can provide the same or better features to users becomes essential.

For the realization of this project the program Anaconda (Anaconda Software Distribution, Vers. 2-2.4.0), was used which is a free and open-source distribution of Python and R programming languages widely used in scientific computing in branches such as Data Science, Machine Learning and Big Data. In addition to these branches, Anaconda can be used in engineering where it is applied to the study of thermodynamic phenomena since it offers tools that facilitate both the modelling and analysis of these phenomena.

FIGURE 1: Development environment used for the model

Anaconda installs a varied number of applications that can be used for diverse purposes, but for our specific case three were used which are Spyder (Figure 1), MatplotLib and Numpy. Spyder was used as the integrated development environment in which we wrote the code of our model, the working console allows instant debugging and evaluation of the code written in the editor and integrates graphics and images using the plotting library MatplotLib. After running our code, the variables created during its execution can be explored and edited utilizing the Numpy matrix.

Since Spyder is only a development environment, it needs libraries to perform the calculations. CoolProp is an open source thermophysical properties library written in C++ (Bell et al., 2014) which includes 110 pure and pseudo-pure substances (among them forty incompressible fluids and moist air). The thermodynamic properties of all fluids implemented in CoolProp are based on the widely used Helmholtz energy equations of state. In addition, CoolProp includes the properties of eight secondary working fluids and thirteen aqueous solutions and a selection of fourteen other secondary working fluids and five brines, as well as thermodynamic properties of moist air. Also, CoolProp uses interpolation methods to improve the speed of evaluation of the equation of state, the main ones being the Tabular Taylor Series Expansion (TTSE) method and the bicubic interpolation method. These two methods share the requirement that the values of the state variables are tabulated on a regularly spaced grid (linearly or logarithmically) as well as the derivatives of the state variable concerning the two independent variables.

3. GEOTHERMAL FIELDS AND POWER PLANTS IN EL SALVADOR

El Salvador is the smallest of the seven Central American countries with an area of 21,040 square kilometres and a population of approximately 6.187 million inhabitants (Ministerio de asuntos exteriores, 2021). It is located in the southwestern sector of Central America and is bordered to the north and east by Honduras, to the west by Guatemala, and the south by the Pacific Ocean (Figure 2).

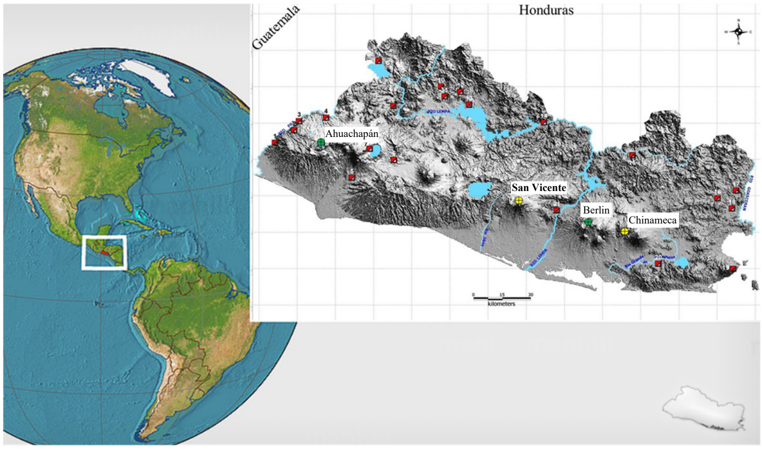

FIGURE 2: Location of El Salvador (modified from Guidos and Burgos, 2012)

When talking about its geology, we can mention that it is characterized by volcanic materials resulting from relatively intense volcanism from the beginning of the Tertiary to the present which has led to the formation of numerous volcanic edifices. Due to these formations and the presence of numerous faults, there are abundant thermal resources that can be used for the generation of electric energy through geothermal power plants (Mata and Puiguriguer, 2000).

The exploration and search for geothermal resources in El Salvador began in the mid-1960s with the support of the United Nations. Eighteen areas were recognized as having geothermal resource potential, and five of these were selected for investigation. The Ahuachapan and Berlin geothermal fields were two of these five areas and have been successfully developed and exploited to date (Guidos and Burgos, 2012). Since the geothermal potential in the region had been previously established, the preparation of new sites is ongoing. To date, two geothermal fields in El Salvador have undergone their first steps towards development. The Chinameca and San Vicente geothermal fields already have platforms for drilling equipment, access to these platforms, and commercial diameter production and re-injection wells with the aim to obtain and manage sufficient geothermal resources to allow commercial exploitation of these fields.

3.1 Ahuachapan geothermal power plant

In El Salvador, electricity production using geothermal resources began in 1975 when Unit 1 of the Ahuachapán geothermal power plant began operations. The Ahuachapán geothermal power plant (Figure 3) is located 103 km west of the capital city in the northern sector of the Apaneca mountain range in a place known as Cantón Santa Rosa Acalcao, municipality and department of Ahuachapán (EcuRed, 2020a). It was the first power plant to use geothermal resources in the region, making El Salvador one of the pioneers in using geothermal energy for this purpose. In 1976, the production of electric energy increased with the start-up of Unit 2 of the plant. By that date, the Ahuachapán geothermal power plant had two Mitsubishi turbines and General Electric generators that increased the production of electric energy from 30 MWe to 60 MWe. Unit 3 of the plant was installed in 1981, a double flash Fuji turbine that increased the installed capacity from 60 MWe to the 95 Mwe, it has today.

In 1981, El Salvador suffered an armed conflict that impacted electricity generation. The transmission lines of the hydroelectric power plants were targets of attacks by armed groups, so the government was forced to use geothermal energy to supply the energy demand. That year, geothermal energy covered 41% of the national electricity demand. Given the overexploitation of the field and the lack of reinjection, the field's pressure suffered a drop causing production to drop from 95 MWe to 45 MWe in 1994 (Guidos and Burgos, 2012).

In 1996, and after several geoscientific and reservoir engineering studies, the stabilization and rehabilitation project of the Ahuachapán geothermal field was initiated, with the aim, among other things, to improve and modernize the geothermal power plant as well as to ensure production through the sustainable use of the geothermal resource. In the middle of the year 2000, the project called "Ahuachapán Total Re-injection" was developed which aimed to move the reinjection zone six kilometres to the east utilizing reinjection pumps to have better management of the residual waters and thus avoid incrustation problems in the reinjection piping system.

FIGURE 3: Ahuachapán geothermal power plant (LAGEO 2020d)

3.2 Berlin geothermal power plant

The Berlin geothermal field (Figure 4) is located 112 km east of San Salvador in a place known as Cantón Montañita in the municipality of Alegría, department of Usulutan (EcuRed, 2020b). The start of electricity production in the Berlin geothermal field was very different from that of the Ahuachapán geothermal field. Although this was one of the sites with the highest potential among the five selected, it was not until 1992 that the first megawatt of electricity could be produced in this field. The Berlin geothermal field began operations with the installation of two 5 MW wellheads.

FIGURE 4: Berlin geothermal power plant (LAGEO 2020d)

In 1992, peace agreements were signed in El Salvador which led to an economic reactivation of the country and its productive sectors increasing the electricity demand. This increase in the demand led CEL (the state-owned company in charge of managing the geothermal power plants at that time) to seek new ways to expand its generation capacity. In 1996, CEL secured financing from the Inter-American Development Bank for the construction of the Berlin geothermal power plant (Prevost, 2004) which began operations on July 10, 1999, with the commissioning of two FUJI single-flash units with capacities of 28 MWe each for a total installed capacity of 56 MWe. In 2007, the plant's installed capacity was increased with the start-up of Unit 3, this time with the installation of a 44 MWe Nuovo Pignone single-flashing turbine.

The total installed capacity of the Berlin geothermal power plant was reached in 2009 with the installation of the first binary cycle plant in the region with a capacity of 9.2 MWe, increasing the installed capacity of the plant from 100 MWe to 109.2 MWe, which is currently available and is expected to be increased with the installation of a new binary cycle plant in the coming years.

3.3 Chinameca geothermal field

Chinameca geothermal field is located 115 km east of San Salvador in the vicinity of the Limbo-Pacayal volcanic cones in Chinameca, department of San Miguel. Currently, the field has six drilling platforms. Four of these platforms are intended for drilling producing wells (CHI-3, CHI-4, CHI-5, and CHI-6) and the remaining two platforms (CHI-7 and CHI-8) for the drilling of the reinjection wells. Eleven wells, with depths ranging from 1,500 to 2,000 meters and one shallower well, had previously been drilled in Chinameca. Seven of them reach temperatures of 200°C to 240°C while the other three are between 160°C and 190°C. With total flow rates of 44, 73, and 77 kg/s and enthalpies of 1131, 1239, and 1217 kJ/kg, respectively, only three wells (CHI-3A, CHI-3B, and CHI-6A) are prolific enough to be designated producers. The three wells were tested at high pressures (8-11 bar-abs), but they might create more steam if the pressure was dropped slightly (Ritcher et al., 2021a).

In Chinameca, extensive geothermal surface exploration research was conducted, including geological, geochemical, and geophysical studies. To aid in defining the permeability structure of the geothermal system, magnetic and gravity investigations and resistivity surveys have been used to map the area's geological structure. All this information has been used to update the conceptual model of the geothermal field.

The development of the Chinameca geothermal field is proposed in two stages of execution. In both stages, the installation of power plants of up to 25 MWe is proposed, with a total installed capacity of up to 50 MWe at the end. In addition to installing the production equipment, it will be necessary to construct the gathering system for the geothermal fluid (steam and water), build civil infrastructure, improve access to well platforms and the plant platform, and install the transmission lines system (LAGEO, 2020a).

3.4 San Vicente Geothermal Field

San Vicente Geothermal Field is located 55 km from the city of San Salvador in the eastern part of the country on the northern slopes of the Chinchontepec volcanic complex in the municipality of Tepetitan, department of San Vicente. In both San Vicente and Chinameca, extensive geothermal surface exploration studies have been carried out. Geological, geochemical, and geophysical studies are among them. To aid in defining the permeability structure of the geothermal system, magnetic and gravity studies and resistivity surveys have been used to map the geological structure of the area. The extent of the reservoir is shown by resistivity models based on 1D and 3D inversion of MT data (LAGEO, 2020b).

Currently, the field has five well pads, three of which are designed to house the production wells (SV-4, SV-5, and SV-6) and one to house the reinjection wells (SV-2 and SV-1). A total of eight wells have previously been drilled at San Vicente, with depths ranging from 1,300 to 2,500 meters and one shallower well. Six of them have temperatures above 200°C while two have temperatures below 200°C. Only two wells (SV-5A and SV-5B) are prolific enough to be called commercial producers with total flowrates of 43 and 29 kg/s and enthalpies of 1406 and 1300 kJ/kg, respectively.

Like the Chinameca geothermal field, the development of the San Vicente Geothermal Field is proposed in two stages of execution. In the first stage, the installation of production equipment for up to 10 MWe capacity is proposed. The installation of this production equipment would allow for the confirmation of the resource and the feasibility for the execution of phase 2 where the installation of generation equipment of up to 20 MWe has been proposed for the completion of the development of the field. In addition, it will be necessary to construct the other main components such as the geothermal fluid transport system (steam and water), civil infrastructure, to improve access to platforms for wells and plant platform and to install the transmission lines system (Ritcher et al., 2021b).

3.4.1 Climatic conditions

Weather conditions such as temperature, humidity, wind direction, and others have been monitored by LAGEO since 2016 utilizing meteorological stations located on platforms SV-1, SV-2, and SV-5, so plenty of data is available for this project.

Ambient temperature

According to the altitude in meters above mean sea level, three thermal zones are distinguished in El Salvador according to the average ambient temperature throughout the year. From 0 to 800 m, the average temperature decreases with altitude, from 27 to 22°C in the coastal plains and from 28 to 22°C in the internal plains. From 800 to 1,200 m, the average temperature decreases with altitude from 22 to 20°C in the high plains and from 21 to 19°C in the foothills. Finally, from 1,200 to 2,700 m, the average temperature decreases from 20 to 16°C in the high plains and valleys, from 21 to 19°C in the foothills, and from 16 to 10°C in valleys and hollows above 1,800 meters.

Being at an altitude of approximately 800 to 1140 meters above sea level, the average temperatures in the San Vicente Geothermal Field should range between 20°C and 27°C. Table 1 shows the maximum, minimum, and average temperatures measured at the field separation stations.

TABLE 1: Ambient temperatures in the San Vicente Geothermal Field

Maximum Temperature (°C)	30.72
Average Temperature (°C)	23.97
Minimum Temperature (°C)	19.44

According to the meteorological data, April is the month with the highest temperatures. Temperatures near to 26.6°C have been recorded at station SV-2, showing a drop in temperature of close to 3°C after the onset of winter in the area.

Rainfall and relative humidity

The average annual rainfall in the San Vicente Geothermal Field is 1485 mm. The rainy period begins in April and ends in October, resulting in a rainy period of 7 months. According to information obtained from the meteorological stations, the atmospheric pressure in the San Vicente Geothermal Field varies from 920.69 to 926.04 mbar with an average atmospheric pressure of 922.80 mbar per year.

Relative humidity in the San Vicente Geothermal Field increases during the rainy months, reaching humidity levels of up to 90% in October and decreasing to values close to 59% in February.

Wind

In November and October, El Salvador is mainly influenced by winds from the Northeast that bring fresh air originating in the polar regions of North America that is significantly warmed as it crosses the Gulf of Mexico. Table 2. shows the predominant wind direction for the San Vicente Geothermal Field extracted from the monitoring stations located in the field.

TABLE 2: Predominant wind directions

Weather station	Predominant direction	Secondary direction
SV-1	SSO	E
SV-2	SO	E
SV-5	SE	ESE

3.4.2 Natural hazards

Seismic activity

The San Vicente Geothermal Field is in a high seismic hazard zone: PGA between 500 and 530 Gal for a return period of 500 years, and between 650 to 700 Gal for a return period of 1,000 years. In addition, due to its location, the Technical Standard for Earthquake Design of El Salvador indicates that it must be designed with the factors corresponding to Seismic Zone I, that means that the supports for the pipeline gathering system, the structures on the platforms and transmission towers must be designed following the provisions of the "Regulation for Structural Safety of Constructions"(LAGEO, 2020c).

Volcanic activity

The project is in the immediate vicinity (less than 3 km) of the main crater (Major et al., 2001) and therefore lying inside the proximal volcanic hazard zone which includes areas immediately surrounding the San Vicente volcano, extending about 8 to 10 km from the summit. This zone has a high risk to be subjected to devastating volcanic phenomena, including pyroclastic flows and surges, debris avalanches, lava flows, and ballistic flows. There is no known historical activity (last 500 years) of the San Vicente volcano. It is, however, considered an active volcano because it has fumarolic activity, a well-preserved morphology, and is located in one of the most active seismic areas of the country.

3.4.3 Geothermal resource

Production tests

Production tests have been performed for wells on platform SV-5, so there is enough data to estimate the amount of steam and water the wells will produce as well as head pressures, temperatures, enthalpies, and quality values for each well. For the present work, the data obtained from the production tests carried out in the SV-5A well have been used. The production curves are unusual since this well seems to have constant flow of geothermal fluid for head pressures of 8 to 14 bars-abs. Table 3 summarizes the main operating conditions for the SV-5A well.

TABLE 3: Well operating parameters

Measured parameters	Values
WHP (bar-abs)	8.5
Temperature (°C)	172.9
Enthalpy (kJ/kg)	1400
Quality (%)	33.03

Chemical analysis of geothermal fluids

From the production tests of wells on platform SV-5, samples have been extracted to perform chemical analysis of the fluids obtained in the cyclone separator (water and steam). In the case of geothermal water, such analysis is of vital importance since it can be used to determine the return temperature of the plant and this information is vital to avoid incrustation problems in the piping system or reinjection wells. Operating any plant at temperatures below the return temperature harms the efficiency and feasibility of the project since the use of inhibitors becomes indispensable for its operation. A summary of the water chemistry for wells SV-5A and SV-5B is shown in Table 4.

TABLE 4: Brine chemistry for SV-5A and SV-5B wells

Well	pH	Na	K	Ca	Mg	Cl	SO4	HCO3	SiO2	B	Li	C.E
		ppm										µs/cm
SV-5A	7.5	3019	533	157	0.011	5394	21.0	20.90	596	86	8.70	16005
SV-5B	7.94	3029	526	158	0.368	5208	84.6	33.70	686	61	9.10	15540

The geothermal fluids in the San Vicente Geothermal Field have similar chemical composition to those of the Ahuachapán and Berlín geothermal fields, therefore, the same equipment can be used.

From the silica saturation index analysis, a minimum return temperature of 140°C has been obtained, so operating the production equipment with temperatures lower than that would lead to scaling problems. At temperatures higher than 200°C, there is a potential for calcite incrustation in the wells, so it will be necessary. San Vicente Geothermal Field to use calcite inhibition chambers inside the wells.

The chemical analysis for the gases from wells SV-5A and SV-5B is shown in Table 5. It can be observed that the percentage of non-condensable gases (CNG) present in the steam obtained from the geothermal fluid of these wells is around 0.77% which is very low and will not have much influence on the thermodynamic properties of the stream.

TABLE 5: Chemical analysis of gases for SV-5A and SV-5B wells

Well	**He**	**H2**	**N2**	**Ar**	**CH4**	**O2**	**H2s**	**CO2**	**%NCG**
	mmol / 100 mol of steam								**%p/w**
SV-5A	0.001	1.3322	6.77	0.064	0.228	0.006	21.6	262.3	0.69
SV-5B	0.007	2.269	84.47	1.725	0.723	0.052	8.1	254.1	0.77

4. BINARY CYCLE POWER PLANTS

4.1 Technical characteristics of a Binary Cycle Power Plant

The Rankine cycle is the basic thermodynamic process of binary cycles in which the steam reaches a dry saturated state in the evaporator and condenses in the condenser. A geothermal binary cycle power plant consists of a primary loop containing the geothermal fluid and a secondary loop containing the organic fluid. The preheater, evaporator, turbine, cooling tower, and working fluid pump are the main components of a simple geothermal binary cycle power plant; these essential cycle components are depicted in Figure 5 in form of a schematic representation.

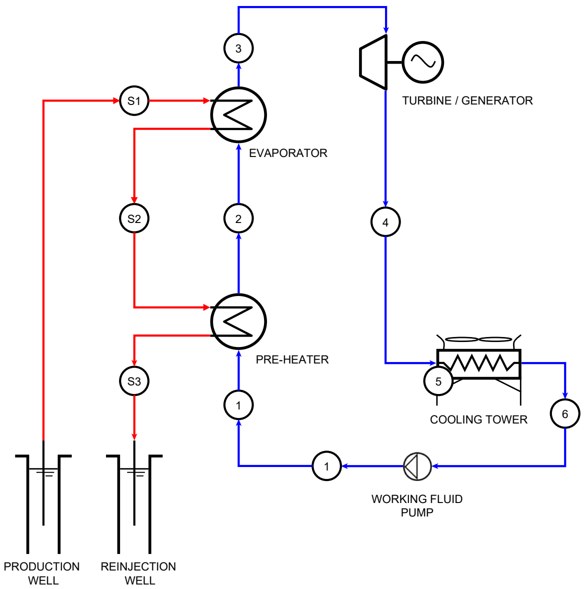

FIGURE 5: Basic schematic of a Binary Cycle Power Plant

The primary loop starts at the production wells and end at the reinjection wells. The field characteristics of the reservoir govern the temperature and flow rates of the geothermal fluid; for that reason, water or steam can be used as a source fluid. When the source fluid quality is zero, it is maintained at a pressure above its flash point at fluid temperature throughout the primary cycle to prevent it from flashing in the heat exchangers. The source fluid temperature must not fall below the silica scaling point after the primary cycle.

The working fluid in the secondary loop has a lower boiling point and different thermodynamic characteristics than water. The working fluid enters the pump as a saturated liquid at point 6 and is compressed isentropically to the evaporator operating pressure. Due to a slight decrease in the working fluid specific volume, the working fluid temperature rises throughout the isentropic compression process. At point 1, the working fluid enters the preheater as a compressed liquid and exits as saturated steam. The working fluid is typically reaching its boiling point in the preheater during the heating-evaporating process. The preheater and evaporator are massive heat exchangers that transmit the heat from the source fluid to the working fluid at constant pressure.

The evaporator is the equipment that vaporizes the working fluid at a constant temperature. Due to the saturated state of the liquid no droplets are entering the turbine. The super-heated steam at point 3 enters the turbine and expands isentropically, producing work by moving the turbine shaft which is coupled to an electric generator. The steam pressure and temperature drop at point 4 when the steam enters the cooling tower. By releasing heat into the atmosphere, steam is condensed at a constant pressure in the cooling tower. The saturated liquid working fluid exits the cooling tower and enters the working fluid pump, completing the cycle. The expansion and compression processes are modified by the turbine and working fluid pumps' efficiency, controlling the actual work in both components.

Unlike a simple flash power plant, a binary cycle power plant does not have steam condensate for cooling tower makeup. A separate cooling medium, such as freshwater or air, is frequently used in binary power plants. Air-cooled condensers are typically used in power facilities that do not have access to freshwater (Monroy Parada, 2013).

As mentioned before, the thermodynamic condition of the working fluids at the turbine exit is superheated steam. This thermodynamic condition enables the use of a recuperator in which superheated steam heats the working fluid. The load on the condenser is reduced by adding a recuperator since it needs to remove less heat to bring the superheated steam to a saturated state before starting the condensation process (Cideos, 2012).

4.2 Geothermal field requirements for the use of binary cycle power plants

The temperature of the geothermal resource influences the technology required to collect the available heat for geothermal energy utilization. Table 6 summarizes the geothermal field types based on temperatures, energy categorization, and physical parameters. In general, dry steam and flash steam technologies are utilized to generate electricity from high-temperature fields. Because binary cycle power plants work well with both medium and low-temperature geothermal sources, they are presently the most common way to generate electricity from low-temperature geothermal sources.

TABLE 6: Classification of geothermal fields (Saemundsson, 2009)

Temperature classification	Energy classification	Physical classification
Low-temperature (LT) Systems with reservoir temperature at 1 km depth below 150°C. Often characterized by hot or boiling springs.	***Low-enthalpy.*** Geothermal systems with reservoir fluid enthalpies less than 800 kJ/kg, corresponding to temperatures less than about 190ºC.	***Liquid-dominated.*** Geothermal reservoirs with the water temperature at or below the boiling point at the prevailing pressure and the water phase controls the pressure in the reservoir. Some steam may be present.
Medium-temperature (MT) Systems with reservoir temperature at 1 km depth between 150- 200°C.		***Two-phase.*** Geothermal reservoirs where steam and water coexist and the temperature and pressure follow the boiling point curve.
High-temperature (HT) Systems with reservoir temperature at 1 km depth above 200°C. They are characterized by fumaroles, steam vents, mud pools, and highly altered grounds.	***High-enthalpy.*** Geothermal systems with reservoir fluid enthalpies greater than 800 kJ/kg.	***Vapour-dominated.*** Geothermal systems where the temperature is at or above the boiling point at the prevailing pressure and the steam phase controls the pressure in the reservoir. Some liquid water may be present.

The temperature of the field, the mass flow availability, and the reinjection capacity are fundamental characteristics of every geothermal project. However, another essential aspect that needs to be taken into consideration for power plant design is its proposed location. The location can affect the development of a project as land is not always available, accessible, or affordable. The selection of the site at which the geothermal plant will operate also defines the type of technology that can be used. For remote locations where freshwater for wet cooling towers is impossible to obtain, it is logical to consider the use of condensers or dry towers that do not require makeup water for operation. Similarly, the design of transmission lines and substations will be subject to the type of terrain and the plant's location. The appropriate selection of the plant site is of high priority to not negatively affect the technical implementation of the project and economic aspects.

In addition to the location of the production equipment, the geothermal field must have accessible to allow for the interconnection of the drilling platforms with the location of the production equipment and other critical sites of the field. Good access to the sites is especially critical in cases such as the San Vicente and Chinameca geothermal fields. In many cases, the access roads have not been designed to transit heavy equipment such as dredges, lowboys, and cranes, making it difficult to move necessary equipment or construction material to the working areas. A recognition of the area and a study of the accesses to the geothermal field sites is a priority at the beginning of any geothermal project to include remodelling works or construction of new accesses according to the project's specific needs.

5. BINARY CYCLE POWER PLANT MODELING

The conditions and assumptions described in section 5.1 will be used to design a binary cycle power plant for the San Vicente Geothermal Field. The proposed model was run using Anaconda / Spyder / Python as a development environment and CoolProp as the main thermophysical properties library for the thermodynamic calculations. Different working fluids were evaluated at the end of the simulation to obtain the maximum net power output.

The well considered for this model is well SV-5A. The wells' technical characteristics and the geothermal fluid's thermodynamic properties have been described in section 3.3 of this document.

5.1 Boundary conditions and assumptions for the study

The boundary conditions for the proposed model are:

- Well head pressure = 8.5 bar
- Source Temperature = 172.9°C
- Mass flow rate = 40 kg/s
- Steam quality = 33.03%
- Well enthalpy = 1400 kJ/kg
- Return temperature = 140°C
- Non-Condensable Gases = 1% p/w

This study is based on a "worst-case" scenario since the San Vicente Geothermal Field currently has only two production wells with geothermal fluid that can be extracted from them, as well as two reinjection wells. Both pairs of wells have been tested for production and injectivity, respectively. The development of the field includes the drilling of at least six additional producing wells and four additional reinjection wells, so it is estimated that by the end of the development, there will be enough resources to install production equipment of greater capacity.

The assumptions made for the model are:

- Isentropic efficiency of turbine = 85%
- Efficiency of pump = 75%
- Ambient temperature = 26 ºC

- Pressure drops = Neglected
- Heat losses in the system = Neglected

The values for the overall heat transfer coefficient of heat exchangers are listed in Table 7 below.

TABLE 7: Heat transfer coefficient (Dr. Páll Valdimarsson, pvald ehf, pers. comm, September, 2021)

Equipment	U Value (W/m^2°C)
Vaporizer	1000
Pre-heater	700
Recuperator	300
Dry Cooling Tower	400

5.2 Working fluid consideration

A crucial consideration for a binary cycle power plant is the fluid selection, as the organic fluid dramatically impacts the performance of a binary power plant. There are several choices for working fluids in a binary plant. However, not every available fluid can be used for a given power plant, regardless of its thermodynamic properties for efficiency purposes as there are other considerations like safety, health, and environmental impacts.

Three fluids were studied for the proposed binary cycles. Below, in Table 8, some properties regarding health and environmental aspects are shown (DiPippo, 2008). When selecting the fluid, toxicity and flammability are two crucial factors regarding human safety, ozone depletion (ODP) and global warming potential (GWP) reflect environmental issues. For both the ODP and GWP, the lower the values of these two numbers, the safer they are.

TABLE 8: Environmental and health properties for the selected working fluids

Fluid	Formula	Toxicity	Flammability	ODP	GWP
Isopentane	i-C_5H_{12}	Low	Very High	0	3
n-Pentane	C_5H_{12}	Low	Very High	0	3
n-Butane	C_4H_{10}	Low	Very High	0	3

For the three fluids shown, the critical pressures and temperatures are much lower than those of water, for Isopentane they are 34.09 bar and 187.8°C, for n-Pentane 32.4 bar and 193.9°C, and for n-Butane 37.18 bar and 152 °C. These critical pressures and temperatures are essential parameters from a technical point of view since they are directly related to the source temperature (Ahangar, 2012). The three fluids listed above have 0% ODP meaning low environmental impact. The GWP is a relative assessment of how much heat a greenhouse gas retains in the atmosphere; it compares the amount of heat that would be captured by the same mass of carbon dioxide. For technical, environmental, and safety issues, proper selection of a working fluid can mean reduced project costs and can have significant implications on the overall efficiency of the power plant.

5.3 Thermodynamic analysis for principal components of the plant

Heat exchangers

The recuperator, preheater, evaporator, and superheater are heat exchangers. Generally, the most widely used heat exchangers at the industrial level are the shell and tube type because they offer several advantages such as flexibility, robustness, and ease of maintenance and repair. These heat exchangers consist of a matrix of small-diameter steel tubes placed in a pre-set arrangement inside a larger diameter steel shell. The design of heat exchangers is standardized by The Tubular Exchanger Manufacturers Association (TEMA). In heat exchangers, two constant flow streams coexist during operation. The source fluid (brine or geothermal steam) is conducted in the first stream, and in the second stream, the working fluid is transported. Temperature differences carry out the heat transfer.

For the thermodynamic analysis of this equipment, it is assumed that it is completely isolated from the environment, so there is no heat loss. This assumption helps the design since heat transfer is generated exclusively between the brine and the working fluid. It is also assumed that the flow rate is constant and that the differences between potential energy and kinetic energy are negligible. Considering everything as a thermodynamic system, the equation governing the preheater, steam preheater and the evaporator is the following:

$$\dot{m}_b\left(h_{SF,in}-h_{SF,out}\right)=\dot{m}_{wf}\left(h_{recuperator\ outlet}-h_{turbine\ inlet}\right) \tag{1}$$

Where: $\dot{m}_b$ = Brine mass flow rate
$\dot{m}_{wf}$ = Working Fluid Mass Flow

In the case of the recuperator, the hot source comes from the turbine exhaust gases and the cold source from the working fluid recirculation pump, so the previous expression must be modified as follows for the analysis of the equipment:

$$\dot{m}_{wf}\left(h_{turbine,out}-h_{condenser,inlet}\right)=\dot{m}_{wf}\left(h_{pump,outlet}-h_{preheater,inlet}\right) \tag{2}$$

If the brine has low concentrations dissolved solids and gases, the left-hand side of the equation can be replaced by using the specific heat of the fluid and the temperature drop in the equipment, but this method will not be used in the present work since only the enthalpy will be considered for our calculations.

The temperature versus heat transfer diagram that is shown in Figure 6 is used to analyse the heat transfer between the working fluid and the source fluid. The diagram shows how the preheater provides sensible heat to the working fluid to increase its temperature and bring it to its boiling point at point 5. Evaporation occurs from point 5 to point 1 in a constant isotherm. The spot where the source fluid and the working fluid experience the minimum temperature difference is called the pinch point and the value of that difference is designated as the pinch point difference. The thermodynamic properties at the preheater inlet and outlet and the evaporator outlet are known from the cycle specification. The compressed liquid is present at the preheater inlet and pump outlet; the saturated liquid is present at the evaporator inlet; and saturated steam is present at the outlet of the evaporator, the same at the turbine inlet.

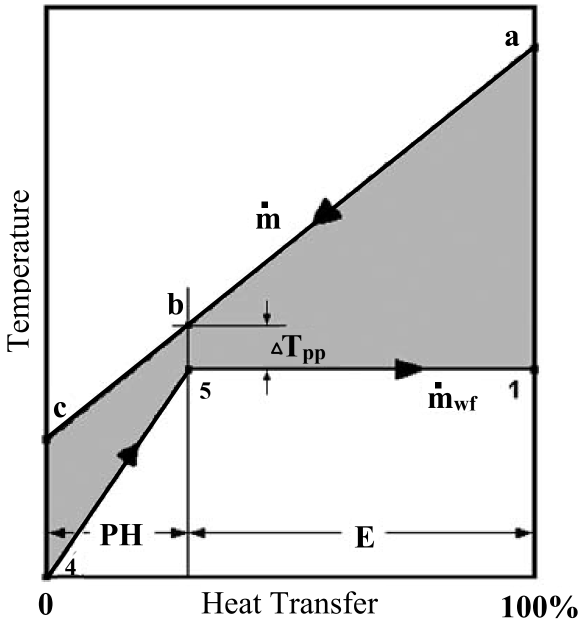

FIGURE 6: Temperature vs. Heat Transfer diagram (DiPippo, 2008)

Because temperature T_a which is the temperature of our source is always known and the pinch point temperature is generally known from the manufacturer's specifications, T_b can be found from a known value of T_5 (DiPippo, 2008).

Turbine

The turbines of binary cycle power plants work by expanding the steam to generate movement in them. In many cases, the vapor generated from the evaporation of the working fluid is highly volatile and therefore the vapor saturation curve in a T-s diagram has an inverted slope; the higher the temperature, the higher is the entopy of the saturated vapor. It follows from this that an isentropic expansion of a saturated vapor will expand the fluid into the superheat region on the T-s diagram, not the wet region.. Fluids with this property are called retrograde fluids. The advantage of this type of fluid is that the expansion process in the turbine does not generate moisture at the turbine outlet since it is in the superheated steam region and allows the use of thermal energy through a recuperator before the steam is condensed in the cooling tower.

With the initial assumptions that neglect the kinetic and potential energy values, together with the constant adiabatic operation of the equipment, the turbine power is defined by the following equation:

$$\dot{W}_t = \dot{m}_{wf}\, \eta_t\, (h_{turbine\ inlet} - h_{turbine\ outlet}) \tag{3}$$

Generally, the isentropic efficiency of the turbine is a known value and is provided by the equipment manufacturer. This efficiency is the ratio between the enthalpy change that occurs under operating or actual conditions and the enthalpy change in the equipment if operated ideally. Therefore, the actual enthalpy at the turbine outlet can be found using the following expression:

$$h_{turbine\ outlet} = h_{turbine\ inlet} - \eta_t\, (h_{turbine\ inlet} - h_{Isentropic\ turbine\ outet}) \tag{4}$$

Where : η_t = Isentropic efficiency of the turbine

Geothermal fluid circulating pump

The geothermal fluid circulation pump moves the fluid through the secondary circuit of the cycle, raising the pressure in the process. Assuming negligible values of kinetic and potential energy and an adiabatic operation of the equipment, the power delivered to the working fluid by the pump would be defined by the equation:

$$\dot{W}_p = \frac{\dot{m}_{wf}\, (h_{pump\ inlet} - h_{pump\ outlet})}{\eta_p} \tag{5}$$

Where : η_p = Isentropic efficiency of the geothermal fluid circulating pump

Dry cooling tower

Dry cooling towers use air to lower the temperature of the steam coming from the turbine and thus condense it to start its work cycle again as a liquid in the pump. This condensation process is achieved using fans driven by electric motors; these fans force the surrounding air through a series of finned tubes containing the exhausted steam from the turbine. Dry cooling towers are used when no makeup water supply is available near the plant.

The dry tower cooling systems are susceptible to environmental temperature variations, affecting the plant's power output. However, they have advantages and benefits over wet cooling towers, especially in low temperatures since there are no water freezing problems. They also have advantages in avoiding environmental impacts on the communities near the production equipment as dry cooling towers do not generate a geothermal fluid plume like wet cooling towers. Finally, maintenance and operating costs for dry cooling towers are low due to fewer components.

The following equation describes the energy balance:

$$Q_c = \dot{m}_{wf}\left(h_{wfc\,inlet} - h_{wfc\,outlet}\right) \tag{6}$$

Or:

$$Q_c = \dot{m}_{air}\, c_{p,air}\,(\Delta T_{air}) = \dot{m}_{air}\,(h_{air\,in} - h_{air\,out}) \tag{7}$$

The power required to move the air through the fans can be calculated as follows:

$$\dot{W}_{fan} = \frac{\dot{v}_{air}\,(\Delta P)}{\eta_{motor}} \tag{8}$$

$$\dot{v}_{air} = \frac{\dot{m}_{air}}{\rho_{air,output}} \tag{9}$$

Where :
ΔT = Difference between the inlet and outlet air temperatures
$c_{p,air}$ = Specific heat of air at constant pressure
$\dot{m}_{air}$ = Mass airflow
$\dot{v}_{air}$ = Volumetric airflow
ΔP = Pressure difference between fan inlet and fan outlet
η_{motor} = Fan motor efficiency
$\rho_{air,output}$ = Density of the air at the fan outlet

5.4 Area calculation for heat exchangers

An important parameter in the design of any binary cycle plant is the sizing of the plant's heat exchangers. Since such equipment will handle different amounts of heat, it is logical to assume that the total heat exchange area in each of them will be different and therefore their price will vary a well. In heat exchangers, convection and conduction processes occur, so it is convenient to use the heat transfer coefficient U to describe their characteristics. The heat transfer coefficient is influenced by the thickness and thermal conductivity of the materials and indicates in general terms the ease with which heat is conducted through a series of resistant media. The higher the value of the coefficient, the easier the heat transfer from the source to the working fluid.

The heat transfer coefficient values are given in W/m^2°C and for the heat exchangers of a binary cycle plant, the values shown in Table 7 will be considered.

In addition to the heat transfer coefficient, two other variables must be considered to calculate the total heat exchange area, these being the amount of heat given up or received in the equipment and the logarithmic mean temperature difference. The amount of the heat Q transferred in the equipment is calculated as the product of the fluid flow and the difference between the inlet and outlet enthalpy.

Since in most cases the temperature values at the inlet and outlet of the heat exchangers are different and the heat exchange between these points is not linear, the logarithmic mean temperature difference LMTD is used as the temperature value. It is calculated by means of the following expression:

$$LMTD = \frac{\left(T_{hot,in} - T_{cold,out}\right) - \left(T_{cold,in} - T_{hot,out}\right)}{ln\left[\frac{T_{hot,in} - T_{cold,out}}{T_{cold,in} - T_{hot,out}}\right]} \tag{10}$$

If the inlet and outlet temperatures of the heat exchangers are equal, then the LMTD value to be used is the difference between the highest and lowest temperature of the two fluids (hot fluid or cold fluid).

Now, given the values of U, Q and LMTD, the area of the heat exchanger can be calculated using the following expression:

$$A = \frac{Q}{U(LMTD)} \tag{11}$$

5.5 Thermal efficiency calculation

The calculation of the thermal efficiency of the cycle is done according to the first law of thermodynamics and is expressed as follows:

$$\eta_{th} = \frac{W_{net}}{Q_{in}} \tag{12}$$

Where W_{net} is the subtraction of the gross power generated by the turbine minus the plant self-consumption. For our case, the plant self-consumption is equal to the sum of the power used by the main fluid circulation pump and the total power used by the cooling tower fan system. Q_{in} is defined by the amount of heat the system receives from the source fluid in the heat exchanger arrangement of our system.

Another way to calculate the thermal efficiency of our plant is to use the heat rejected in the condenser and the heat that the system receives in the heat exchanger array using the following formula:

$$\eta_{th} = 1 - \frac{h_{cond,in} - h_{cond,out}}{h_{pre,in} - h_{vap,ou}} \tag{13}$$

5.6 Cycle modelling and results

Figure 7 shows the proposed model of a binary cycle plant for the San Vicente geothermal field. This proposed model shows several differences compared to the basic model shown in Figure 5. Generally, binary cycle plants in El Salvador and other parts of the world use brine from separation platforms as the source fluid, with sufficient temperature and flow to be used in this process.

For the San Vicente Geothermal Field, it is proposed to use the entire resource coming from the SV-5A well, and the installation of a cyclone separator is provided for. It is necessary to think of an arrangement of heat exchangers that efficiently uses the steam and brine coming from the cyclone separator, so it is proposed to install a steam preheater, an evaporator and a preheater. With the installation of these three heat exchangers, better use of the resource is ensured.

Another important point in the proposed model is the return temperature. In section 3.4.3 of this work it was stated that the return temperature for the San Vicente geothermal field cannot be lower than 140°C since any value lower than this temperature could lead to incrustation problems in the reinjection line or the reinjection wells. This limitation means that in our model, the return temperature must be set at that value. It is also necessary to install a recuperator which takes advantage of the heat in the steam coming from the turbine exhaust and helps to prevent a drop in the process's efficiency.

Due to the return temperature in our model being fixed by the chemical characteristics of the source fluid, the selection of the source fluid is facilitated since we will select the working fluid that allows us to obtain maximum energy generation. Of the three working fluids selected in Chapter 5.2 and for the operating conditions shown in Table 9, n-Pentane turns out to be the best option, giving an approximate net power generation of 6.69 MWe.

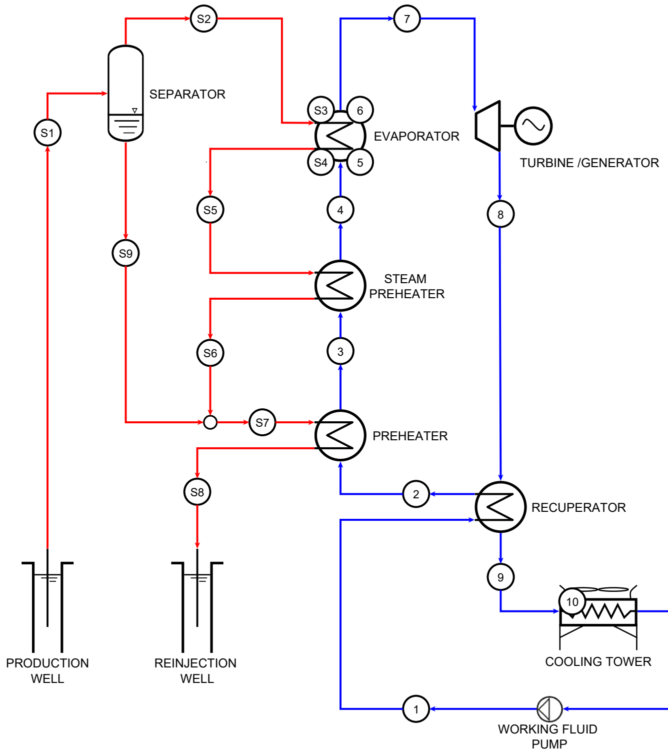

FIGURE 7: Proposed model for the binary cycle power plant in San Vicente

TABLE 9: Temperature, pressure, and enthalpy data for the operating points of the binary cycle power plant

Working fluid: n_Pentane (η_{th} = 19%)							
Source fluid side				**Working fluid side**			
Point	**T_s**	**P_s**	**H_s**	**Point**	**T**	**P**	**H**
S1	172.94	8.50	1400.00	1	41.18	20.84	13.71
S2	172.94	8.50	2770.76	2	73.16	20.84	92.49
S3	172.94	8.50	2735.67	3	104.23	20.84	174.53
S4	172.94	8.50	1730.97	4	163.94	20.84	355.81
S5	172.94	8.50	1692.84	5	165.94	20.84	363.01
S6	172.94	8.50	731.95	6	165.94	20.84	552.56
S7	172.94	8.50	731.95	7	167.94	20.84	559.18
S8	140.00	8.50	589.48	8	92.52	1.16	462.80
S9	172.94	8.50	731.95	9	51.18	1.16	384.02
				10	40.00	1.16	363.89
				11	40.00	1.16	9.38

Figure 8 shows the T-s diagram for the duty cycle of the proposed model using n-Pentane as a working fluid. It is confirmed in the diagram that the operating pressures of the working fluid vary from 20.84 bar at the turbine inlet to 1.16 bar at the turbine outlet. A small overheating zone is also identified within the diagram. The working fluid reaches a maximum temperature of 167.94°C at the turbine inlet and then drops to 40°C at the condenser outlet.

Table 10 shows the values of heat transferred and areas for the heat exchangers that are used in our plant, keeping n-pentane as the working fluid and using the equation presented in Chapter 5.4.

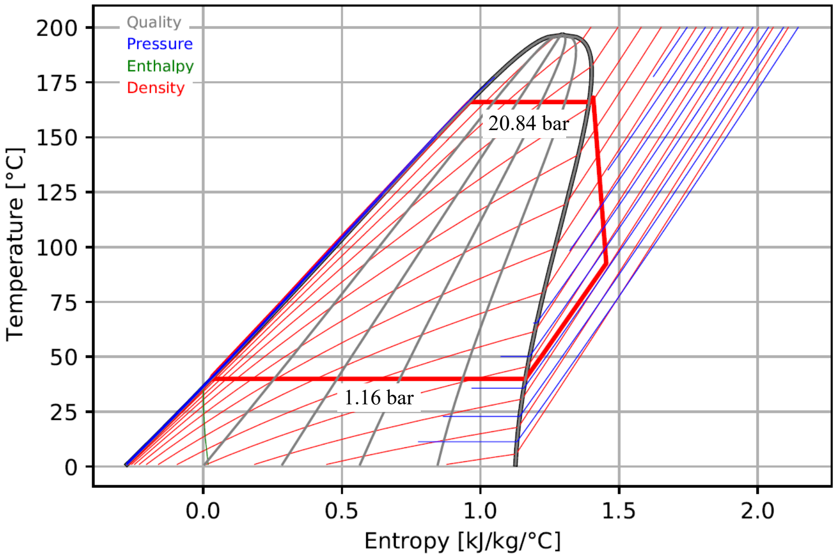

FIGURE 8: T – s diagram for the binary cycle power plant in San Vicente

TABLE 10: Calculated areas for heat exchangers of the binary cycle power plant

Equip	**Q (kJ/s)**	**Area (m^2)**
Preheater	5988.66	126.2385
Steam preheater	13233.95	1470.439
Vaporiser	14320.70	2409.259
Recuperator	5750.58	1352.73
Condenser	25879.04	5892.78

6. ECONOMIC STUDY

6.1 Electricity market in El Salvador

In El Salvador, there are two types of sources with which electrical energy can be produced. The first are traditional sources, which use non-renewable resources to produce heat. The combustion of these resources generates enough heat that can be used to produce steam that can be used for various industrial processes. The companies that use this type of resource are thermoelectric power plants and biomass power plants. On the other hand, there are renewable sources or clean energies, which are environmentally friendly since they use sustainable resources that can be exploited for relatively long periods. Among the main producers of electricity based on renewable resources in El Salvador are hydroelectric power plants, geothermal power plants, and photovoltaic plants. Figure 9 shows all the electricity producers in El Salvador that use traditional and renewable sources. Up to the first semester of 2020, a total of 27 electricity-generating companies have been identified, and a total installed capacity of 2013.14 MWe is estimated for the entire region (SIGET, 2020).

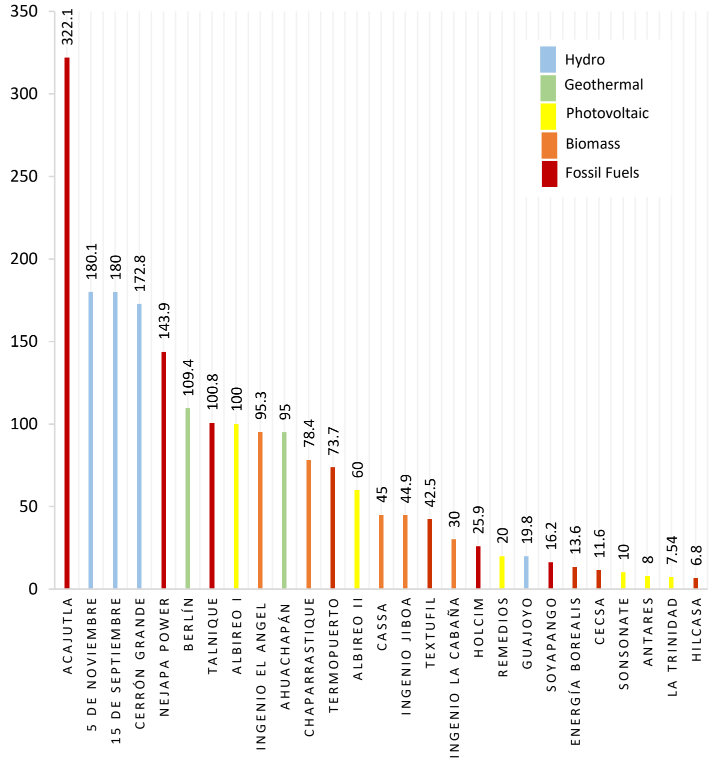

FIGURE 9: Total installed capacity in megawatts by electric power generators in El Salvador until June 2020 (SIGET, 2020)

Figure 10 shows the percentage of installed capacity by resource during the first half of 2020 in El Salvador. This figure shows that 38% of the installed capacity in the country comes from companies that use fossil fuels to produce electricity, and only 10% of the total comes from companies producing electricity from geothermal resources. It will be explained later that although the difference in installed capacity is approximately 28%, El Salvador is doing its best to ensure that the total demand is covered with renewable resources.

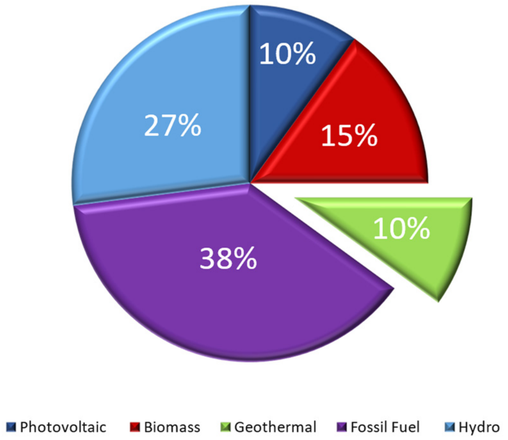

FIGURE 10: Installed capacity per resource in El Salvador in June 2020 (SIGET, 2020)

The Salvadoran wholesale electricity market promotes an efficient and competitive environment for the undertaking of energy transactions through the national transmission system, which the General

Electricity Law defines as "the integrated set of equipment for the high-voltage transportation of electric power." Market participants enrolled in the “Unidad de Transacciones, S.A. de CV” carry out power transactions through the national transmission system. The electricity market of El Salvador is characterized by the dynamic interaction among the various public and private market participants (SIGET, 2020). Table 11 shows some noteworthy market participants.

TABLE 11: Main participants in the Salvadoran market

Generator:	Market participant who owns one or more power production plants and trades production, in whole or part.
Transmitter:	Market participant, a transmission company, who owns facilities for transportation of energy through high-voltage networks and trades its services.
Distributor:	Market participant who owns and operates distribution facilities whose purpose is to deliver electricity in low-voltage networks and whose tariff schedule for end-users is approved by SIGET.
Marketer:	Market participant who buys electric power from other operators to resell it.

In 2020, the total energy demand in the first half of the year was 2,938.92 GWh which is a decrease of 9.7% compared to 2019. This change is mainly due to the decrease in demand due to the pandemic caused by COVID 19. Figure 11 shows the share of total injections by type of resource for the first half of 2020. The most significant proportion of injections comes from geothermal generation, which represents approximately 25% of the national energy demand, followed by hydroelectric generation (23%) and in third place fossil fuel-based thermal generation (19%). Biomass and solar energy occupy 15% and 8%, respectively, leaving imports with 10% (SIGET).

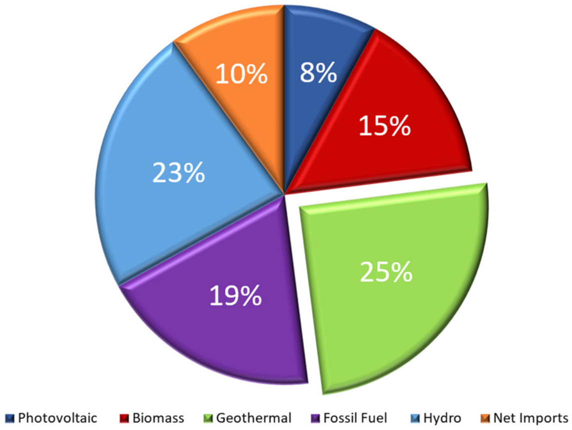

FIGURE 11: Distributed energy per resource until June 2020 (SIGET, 2020)

Figure 12 shows the behaviour of the average price of the regulated market of the electricity system in El Salvador for the period from June 2019 to June 2020. The highest average price of the entire period had to be paid in July 2019 when it was 121.9 US$/MWh. During the first half of 2020, the average price ranged between 85.84 and 61.99 US$/MWh. The average value during that period was 85.39 US$/MWh because of the low international prices for fuel for generation in regular hydroelectric plants.

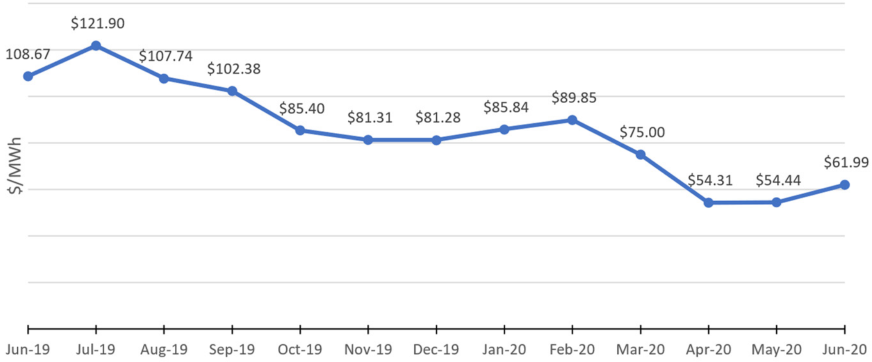

FIGURE 12: Behaviour of energy prices in El Salvador from June 2019 to June 2020 (SIGET, 2020)

6.2 Investment costs

Estimating investment cost for geothermal projects is complicated and almost impossible since no two geothermal fields in the world are alike. Although the geothermal resources may have similarities in specific points, each one should be analysed based on its main characteristics. Similarly, it depends on the region as to what taxes or additional costs need be considered to determine the total cost of the investment.

This section focuses only on the initial estimate for the acquisition of the main equipment that would compose the binary cycle unit. The reader should understand that in addition to the costs mentioned in this section, other costs such as pre-development costs for the geothermal field, costs of geoscientific studies, costs associated with the drilling of producing and reinjection wells, operation and maintenance of the plant, local taxes, loans, debts, interest, and others need to be taken into consideration as well.

We start with the cost calculation for the heat exchangers of the model proposed in this document. The areas have been previously calculated, and a value can be estimated from them. Table 12 shows the approximate cost for the heat exchangers of the model.

TABLE 12: Prices for heat exchangers per unit area (Dr. Páll Valdimarsson, pvald ehf, pers. comm, September, 2021)

Equipment	Price ($/m^2)
Vaporizer	300
Preheater	300
Condenser	500
Recuperator	200

Similarly, we can assume that for the turbine and the geothermal fluid recirculation pump the prices depending on their production or consumption of electrical energy are close to 500 USD/kW (Dr. Páll Valdimarsson, pvald ehf, pers. Comm, September, 2021). Table 13 summarizes the prices of the main equipment for a binary cycle plant with a capacity of 7 MWe, given the capacity calculated for our plant.

TABLE 13: Calculated prices for the purchase of main equipment and other additional works

DESIGN AND ENGINEERING		$ 989,744.62
MAIN EQUIPMENTS		$ 8,940,716.95
Turbine[1]	$ 3,500,000.00	
Working fluid pump[1]	$ 135,000.00	
Preheater[1]	$ 37,871.55	
Steam Preheater[1]	$ 441,131.70	
Vaporizer[1]	$ 722,777.70	
Recuperator[1]	$ 270,546.00	
Condensator[1]	$ 2,946,390.00	
Storage Tanks[2]	$ 160,000.00	
Piping[3]	$ 727,000.00	
SUPERVISION		$ 718,581.64
CONTROL SYSTEM PROGRAMING		$ 54,232.26
COMMISIONING TEST		$ 33,895.58
SPARE PARTS		$ 278,178.26
TOTAL		**$ 11,015,349.32**

[1]Prices based on model calculations; [2] Price calculation based on updated purchasing information in El Salvador; [3]Price based on Bejan et al. (1996)

7. RESULTS AND DISCUSSION

In the previous chapters, the proposal of installing a binary cycle plant in the San Vicente Geothermal Field has been analysed. It has been proven that it is technically possible to take advantage of the geothermal resource that the field has and start with its commercial exploitation. In this chapter, a brief comparison will be made between other technologies and other plant configurations that could be used to exploit the geothermal resource.

Case 1: Single Flash power plant

Firstly, installing a single flash plant is proposed to utilize the geothermal resource. It has been discussed in section 3.4.3. that the geothermal resource has a high enthalpy so that the contained energy could be better utilized. Figure 13 shows the basic scheme of a single flash plant. In this plant, the geothermal fluid enters the cyclone separator from which we obtain the steam that we use to drive the rotor of our turbine. After its expansion in the turbine, the steam is directed to a condenser, condensed, and pumped to the cooling tower. For the analysis of this simple model of a single-flash power plant, we have considered the same assumptions as those used to model the binary cycle plant, so no pressure drops in the system or heat losses are considered. Likewise, our model has not considered a gas extraction system since the chemical analysis of the gases indicates the presence of gases of less than 1% by weight.

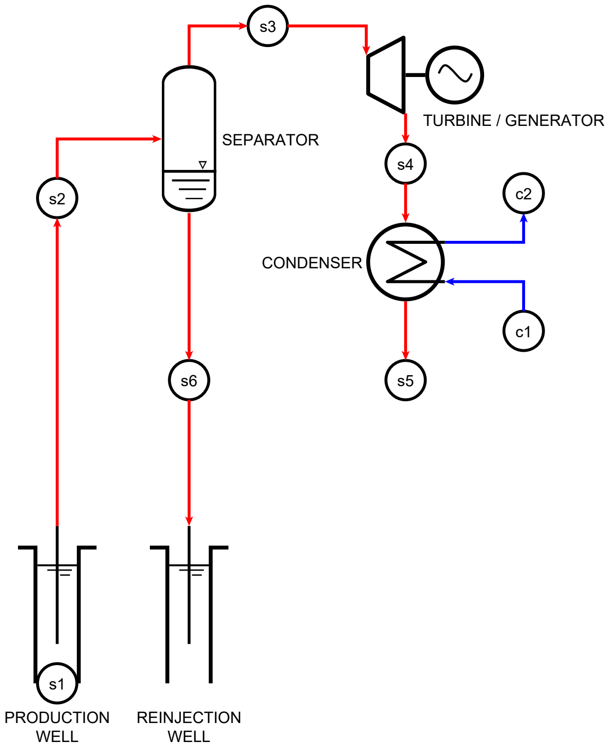

FIGURE 13: Case 1 basic single flash power plant

The separation pressure was calculated in two different ways. A constant flow from the wells was assumed in the first one, so our model presented operating values only for one given pressure. In the second approach, the information from the production tests was used to generate a well curve that allowed us to generate the power vs. separation pressure curve for our plant.

With the information obtained from the generated well curve, the model was run, obtaining a maximum power value of 7.92 MWe at a separation pressure of 6.7 bars. With these operating conditions, the SV-5A well would be working in a range of pressures close to 7.7 bars and would produce a total of 43 kg/s of geothermal fluid. These results are presented in Figures 14 and 15.

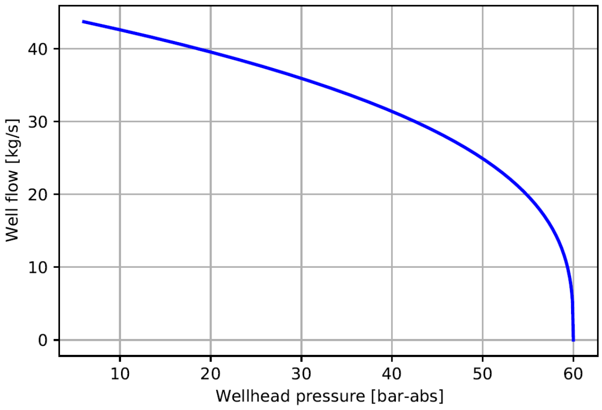

FIGURE 14: SV-5A well flow vs wellhead pressure curve

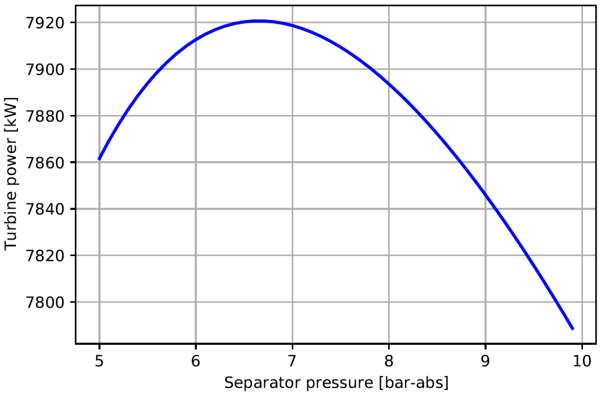

FIGURE 15: Turbine power vs Separator pressure curve for Single Flash power plant

Case 2: Single Flash with ORC power plant

Since two cases were analysed in this study, the question arose as to whether the combination of these cases could bring significant improvements in terms of electricity production, so the decision was made to make a model that could simulate the operating conditions of a single flash plant in conjunction with a binary cycle plant.

Figure 16 shows the model proposed for this case. In this model, the steam obtained from the cyclone separator is used to drive a single flash turbine and the brine from this process is used as a heat source for our binary cycle. The assumptions made for the previous models are maintained since this case is a mixture of the two previous ones with slight differences in terms of operation.

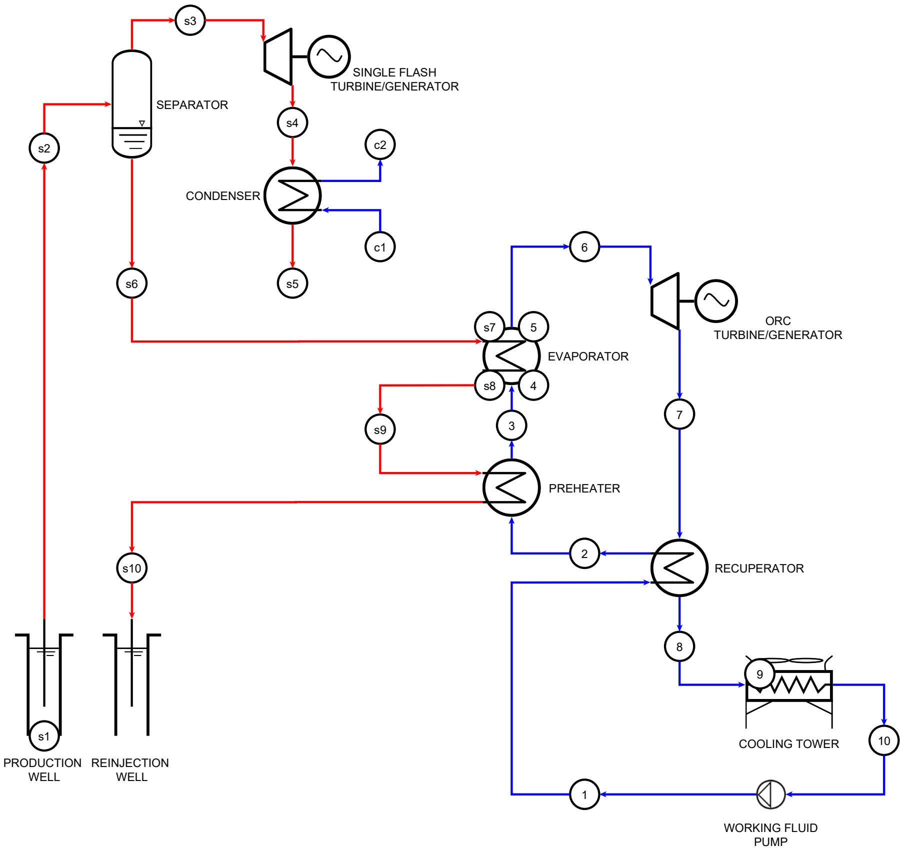

FIGURE 16: Case 2 basic Single Flash plant with ORC

Since we are dealing with a conventional binary cycle plant where the source fluid is always in a liquid state, it is unnecessary to add the steam preheater which we had in the model proposed at the beginning of this chapter. However, it is necessary to maintain the recuperator since the return temperature must be kept above 140°C. Likewise, the use of a dry tower as cooling equipment for the working fluid of the binary cycle plant is maintained.

The pressure in the cyclone separator for this case was selected using the production curve of the SV-5A well that was developed for the previous case. The previous model had an optimum pressure close to 6.7 bar-abs, but for this model, it is observed that the production of the single flash plant decreases with an increase in pressure in the cyclone separator, but the production of energy in the binary cycle plant increases due to the increase of geothermal fluid that can be destined to it. Table 14 shows operating conditions for our system in a range of values from 7.5 to 8.9 bar-abs.

TABLE 14: Flow and power conditions at different separation pressures

P	$\dot{m}$ Source	$\dot{m}$ Steam	$\dot{m}$ Brine	$\dot{W}$ Single Flash	$\dot{W}$ ORC	$\dot{W}$ Total
7.5	43.01	14.45	28.56	7909.38	560.28	8469.66
7.7	42.95	14.35	28.60	7903.77	585.60	8489.37
7.9	42.89	14.26	28.63	7897.19	610.65	8507.84
8.1	42.84	14.17	28.66	7889.69	635.43	8525.12
8.3	42.78	14.09	28.70	7881.33	659.96	8541.29
8.5	42.73	14.00	28.73	7872.16	684.23	8556.39
8.7	42.67	13.91	28.76	7862.22	708.14	8570.36
8.9	42.61	13.83	28.78	7851.56	731.92	8583.48

Figure 17 shows the generated power vs. separation pressure curves for the single flash plant and for the binary cycle plant attached to the system. A third curve is the total generation curve that the array can provide.

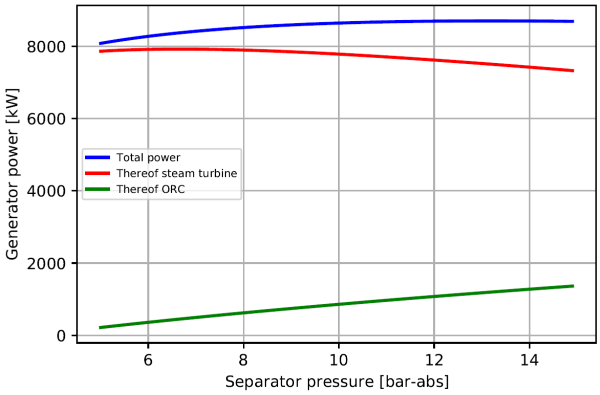

FIGURE 17: Case 2 Generator power vs. Separator pressure curve for Single Flash and ORC

Case 3: Hybrid power plant

Figure 18 shows the third case analysed for the San Vicente Geothermal Field. It takes up the idea proposed in the main model of this paper and proposes the use of steam and brine in the system but presents a different arrangement of exchangers.

As in Case 2, the steam coming from the cyclone separator is used in a backpressure turbine, but this time the condensate coming from the turbine is used in a pair of heat exchangers that transfer heat to our working fluid at two different points of the process. The brine from the cyclone separator is also utilized in the same way. The installation of the dry cooling tower and the recuperator are maintained for this case study as well as the condition for the return temperature which should not be less than 140°C.

Although the amount of gases in the San Vicente Geothermal Field is less than 1%, the installation of a gas separator is considered in the proposed scheme. The analysis of this component of the model was considered but was not carried out in detail, so the results presented for this case do not consider the use of this equipment and assume that the amount of gases is negligible.

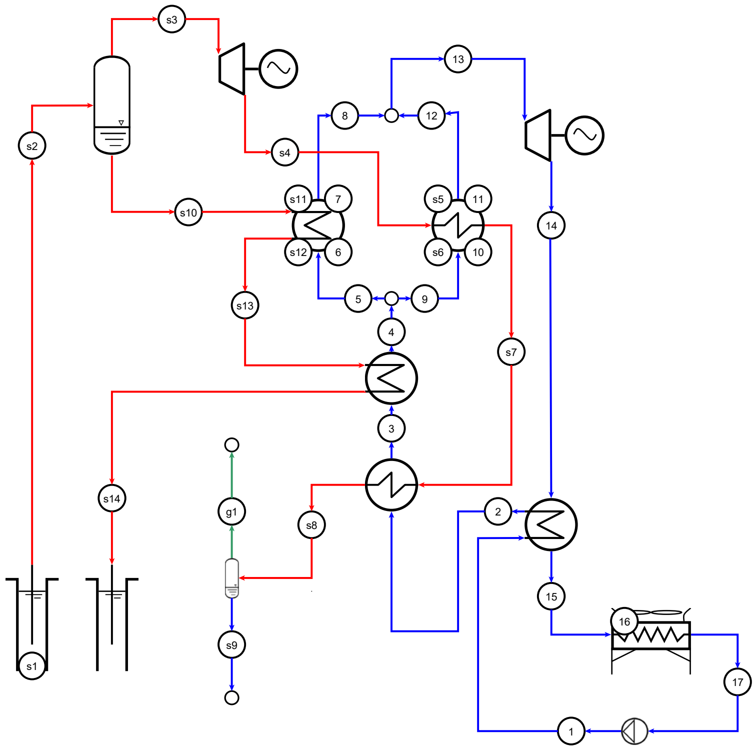

FIGURE 18: Proposed Hybrid model for the San Vicente Geothermal Field

The results obtained for this case are presented in Figure 19. As can be seen in this figure, the accumulated generation values using n-Pentane as working fluid at separation pressures of 9 bars and vaporizer pressures close to 16 bars are greater than 10 MWe.

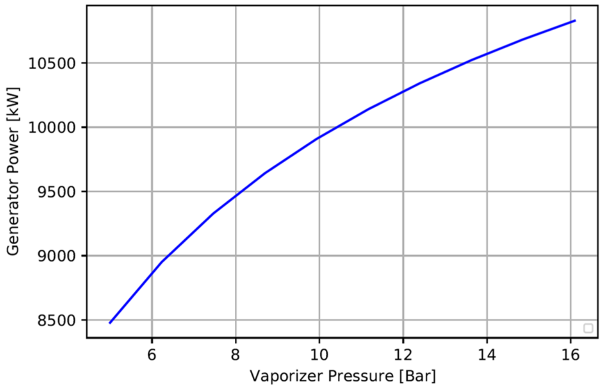

FIGURE 19: Case 3 Generator power vs Separator pressure curve for total production

8. CONCLUSIONS AND RECOMMENDATIONS

The San Vicente Geothermal Field has sufficient resources to begin commercial exploitation. The wells on the SV-5 platform have resources that can be used to generate electricity, but it is crucial to define the type of technology that is the most appropriate and efficient for this purpose. Four options have been evaluated in this document in order to meet this goal.

Of the four options evaluated, Case 3 would produce the highest amount of electric energy or above 10

MWe, so it could be considered the best option if only this aspect was evaluated. However, the problem of this case is the amount of main and auxiliary equipment required for its operation. Two sets of preheaters, two sets of evaporators, and two sets of turbines make this case the most expensive of the four proposed. Case 2 is in the same line since the costs are significantly increased by proposing two sets of turbines. For the base case, it has been demonstrated that it is feasible to use steam in the system, so the installation of a binary cycle plant with a steam preheater is a good option for the San Vicente Geothermal Field, which could start commercial exploitation at an early stage and produce about 6.69 MWe. However, there is the issue of the thermal efficiency of the plant, which would be lower than a simple flashing plant, so resource utilization comes into play.

Taking into account then the issue of generation and use of the resource, the installation of a simple flashing plant becomes then the best alternative for the beginning of the commercial exploitation of the San Vicente Geothermal Field. A total of 7.92 MWe could be produced with separation pressures close to 6.7 bars and without incrustation problems in the reinjection lines since the return temperatures of the geothermal fluid are much higher than the requested 140°C.

Although it is true that the four cases presented in this document are technically feasible, there are more factors that must be considered in the decision-making process for the installation of a geothermal power plant in the San Vicente Geothermal Field. The information provided in this document can be included along with other considerations and can serve as a comparison parameter and as a decision-making tool to choose the development plan that best suits the field.

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