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FEASIBILITY OF OPERATION OF THE EXISTING GEOTHERMAL RESOURCE OF THE SOUTH-EAST SECTOR OF THE MIRAVALLES GEOTHERMAL FIELD, COSTA RICA

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ABSTRACT

Due to increased fuel costs and the global energy crisis, geothermal energy plays a key role as a clean, renewable and cheap energy source to be considered a proper energy substitute for fossil fuels. The main objective of this report is to propose possible exploitation systems of the geothermal resource in the east-southeast sector of the Miravalles geothermal field by using data obtained from wells already drilled at this site. The wells already drilled show a non-condensible gas (NCG) content ranging from 1.52% to 13.09% (weight based). Several candidate power cycles were analyzed and their power output calculated. For each cycle, options regarding NCG extraction were studied. Finally, a preliminary technical and economical comparison was made between the candidate cycles to investigate feasibility of operation. The results show that the lowest cost in terms of capital cost per kW was achieved with a single-flash cycle with a binary bottoming cycle. Close in cost was a double-flash cycle with a binary bottoming cycle. The second system has the advantage of low sensitivity to NCG composition which is an important advantage in the field under consideration.

1. INTRODUCTION

Currently, geothermal energy provides 18% of the total electric generated energy in Costa Rica. To achieve this output, generating plants have to operate at full capacity. During the rainy season in Costa Rica hydropower production increases and contributes to increased energy given to the interconnected national network. This period is also suitable for maintenance work in the geothermal generating units in Costa Rica. During the dry season, the importance of geothermal energy for base load production increases due to reduced production in the hydropower stations.

1.1 General information about the Miravalles geothermal field

The Miravalles geothermal field was the first geothermal area to be exploited on a commercial basis by the Costa Rican Electricity Institute (ICE). It has been online, producing electricity continuously since March 1994. The field is an active hydrothermal area confined in a collapsed caldera type

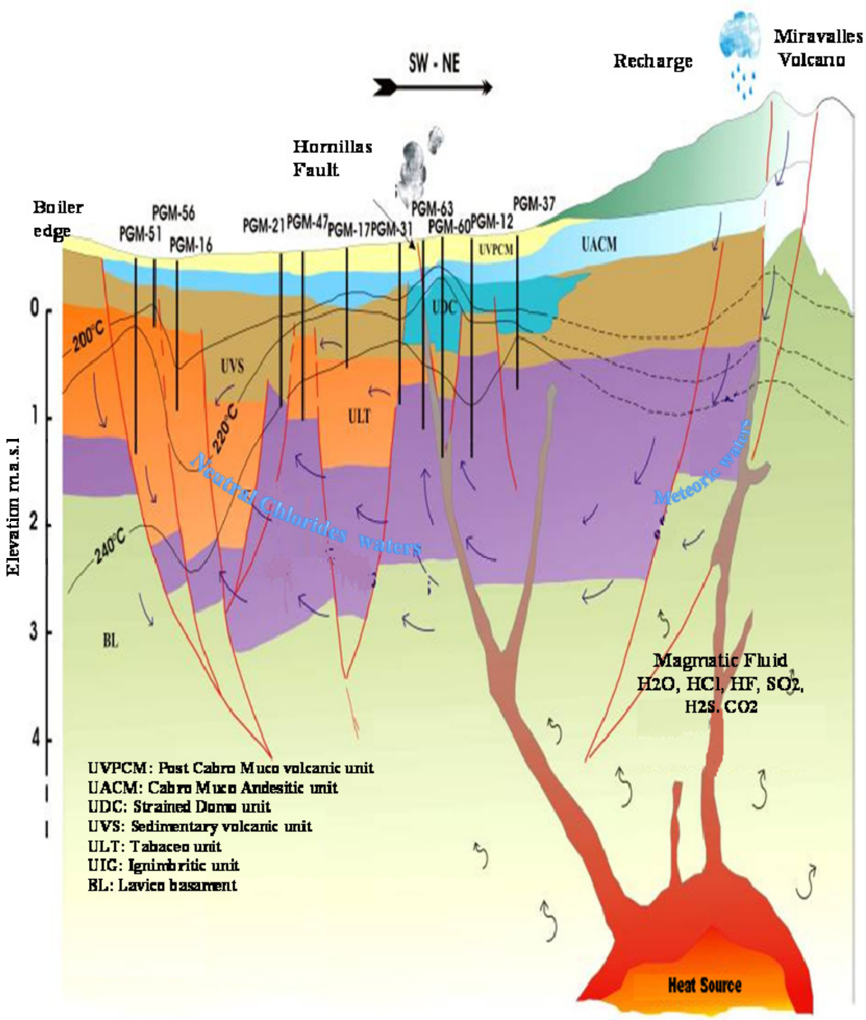

FIGURE 1: A conceptual model of the Miravalles geothermal field (Sanchez, et al., 2006)

structure, 15 km in diameter, characterized by its morphology and its soft-geological and structural complexity (Figure 1). The permeability in Miravalles is mainly secondary, a product of fractured rocks, caused by tectonic activity. The permeability in the geothermal system is not homogeneous, rising from north to the south and central parts of the field (Sanchez, et al., 2006).

The Miravalles geothermal field is a high-temperature liquid-dominated reservoir, located at a depth of approximately 700 m and has an estimated thickness of 800-1000 m. Highest temperatures have been identified in the northern sector, gradually declining southward and westward. The fluids are typically neutral sodium-chloride. In addition to the main aquifer, there is a sodium-chloride acid type aquifer in the northeast and central-east area and a chloride-type sodium bicarbonate reservoir in the area east and southeast of the field, the eastern boundary is not clearly defined. Both the acid and bicarbonate aquifers present temperatures close to 230ºC (Figure 2).

During operation, the Miravalles geothermal field has experienced unwanted side effects. The production wells from the main aquifer have a low to medium trend towards the formation of calcite (5-25 mg/kg of $CaCO_3$ fluid produced). On the other hand, the wells from the acid area produce a highly corrosive fluid and the production wells from the bicarbonate aquifer show a high tendency towards the formation of calcite (70-80 mg/kg of $CaCO_3$ fluid produced). Due to these tendencies, it is necessary to apply chemical treatment to the fluids at depth, to ensure continuous production.

Another unwanted factor is the increase in non-condensable gases (NCG) in the steam; in the main aquifer, these gases range from 0.2 to 1.8% by weight, in the acid aquifer from 0.9 to 1.75% by weight and approximately 3-7% by weight in the bicarbonate aquifer. This has caused problems. In the original design, due to a tight design capacity for gas extracting generating plants, the content of gases present in the steam delivered to the generating units was already near the maximum capacity of extraction (Sanchez, et al., 2006).

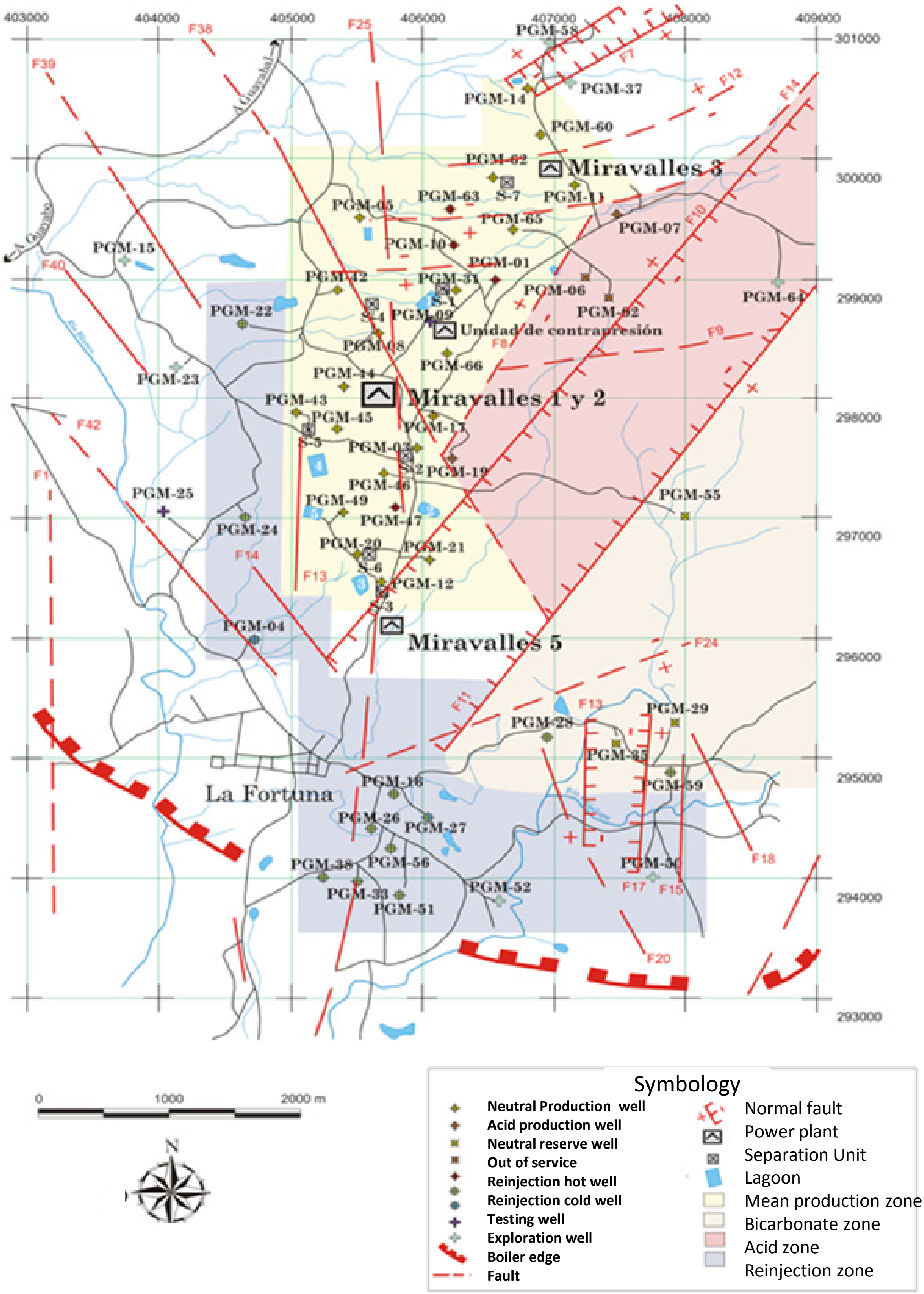

FIGURE 2: The Miravalles geothermal field and its division into production zones (Sanchez et al., 2006)

The field has now been under continuous exploitation for 14 years. During that period the reservoir has changed from being a liquid-dominated system to being steam-dominated. Consequently, the content of NCG present in the steam delivered to the generating units has increased a lot, and the capacity to extract NGC in the condenser has reached its maximum limits.

1.2 Objectives of this study

The 14 years of commercial exploitation of the Miravalles geothermal field, have led to an increase in NCG in some sectors of the field, and the generating units do not have sufficient capacity to extract it. This has caused a temporary closure of some producing wells, and backup wells are now needed to meet steam demand. The main objective of this report is to propose possible exploitation systems of the geothermal resource in the east-southeast sector of the Miravalles geothermal field by using data obtained from wells already drilled at this site. The technical difficulties will be pinpointed and possible solutions suggested. The aim is not to present an optimization of the resource but rather to explore and analyze possible solutions.

Economic aspects cannot be put aside when considering possible options for electricity generation. Some economic aspects are known in advance. Various reports exist as well as references for the costs of installing geothermal plants in Costa Rica (Radmehr, 2005) and these show well-marked differences in prices from one system to another. Therefore, an economic evaluation will be presented that should identify important tradeoffs between the solutions.

1.3 Literature

In March 2006, a panel of consultants conducted an inquiry into Costa Rica and a document was presented which cites the possibility of increased production in the Miravalles geothermal field and better use of the existing resource in the east / southeast sector (Sanchez et al., 2006). The document offers necessary information for developing a possible solution for the sector under study. Information was also obtained on the production curves of the wells. To calculate power outputs of cycles as well as for other modelling, the program ESS (Engineering Equation Solver) was used. Most equations and models were taken from books and lectures (Pálsson, 2008; DiPippo, 2007). Data on the necessary steam flow needed to remove distinct NCG content was obtained from a study performed by the National Renewable Energy Laboratory, Colorado, USA (Vorun and Fritzler, 2000). Also used were reports by Fellows of the UNU Geothermal Training Programme in Iceland.

The economic analysis was based on information of geothermal generation plant costs in Costa Rica, documents from the world congresses on geothermal energy, and reports recently done by UNU Fellows in Iceland.

1.4 Overview of the geothermal resource in the east-southeast sector

1.4.1 Resource available for exploitation

The east-southeast sector of Miravalles geothermal field has high-pressure wells and enthalpy values appropriate for electricity generation (Table 1). Currently there are 4 wells drilled in this field: PGM-28, PGM-29, PGM-35 and PGM-55. The following summarises the main information from the wells:

PGM-28: Drilling operations began 20/12/94 and ended 03/02/95, a duration of 45 days reaching a depth of 1315 m. The well was planned as a reinjection well. It was connected to the Miravalles unit II in 1998, and in the beginning it was used as a reinjection well connected to the field's collector 1, accepting reinjection water from various separation units (01, 04 and 07). It is currently closed and awaiting production assessment testing for a feasibility study.

PGM-29: Drilling operations began 02/06/94, lasting 55 days and reaching a depth of 1388 m. It was also planned as a reinjection well, interconnected with well PGM-28. However, due to its great potential, it was decided to use it for steam production for a back-pressure turbine which was rented from the Mexican Confederation of Electricity. It remained in operation about 18 months. Generation was stopped when the back pressure turbine was returned to Mexico at the expiration of the contract.

After a report was submitted to the panel of consultants in 2006, a series of recommendations were made by the Department of Geothermal Resources for the administrative part of ICE. Installation of a pit mouth (steam direct) unit commenced at this site. Since the beginning of 2007, the well has generated an average of 5 MW. The well has generated a large content of non-condensable gases, mainly CO_2; the rate at the time was around 70% by weight. Today it maintains a percentage of non-condensable gases of less than 25% by weight and it seems to be declining. It remained constant throughout 2007 and into 2008. Due to the high content of bicarbonates in the liquid phase, inhibitors were used at a higher concentration than that used for other geothermal wells in the field.

PGM-35: Drilling operations began 10/05/2000, lasting 85 days and reaching a depth of 1050 m. It was proposed as an exploratory well but it was impossible to make an assessment deep enough to characterize the well. At present, the well is connected with well PGM-29, for reinjection of hot water from a separate zone. On average, 30 to 40 l/s are re-injected. In conjunction with well PGM-28, it is awaiting production assessment tests.

PGM-55: Drilling operations began 03/10/2002, lasting 120 days, reaching a depth of 1790 m. This well is sited farther away, located at the northern boundary of the east-southeast area. This well is similar to PGM-29 but failed production tests of longer duration for a better characterization.

At present only well PGM-29 has being evaluated long term in terms of production and stabilization of its gas content. Other wells have been tested for short periods which served to provide data on temperature, and enthalpy flows, among others.

1.4.2 Geochemical characteristics associated with the east-southeast sector

In Table 1, characteristic geochemistry is presented from one well for each reservoir sector (neutral and acid) along with the 4 wells in this study from the east-southeast sector of the Miravalles geothermal field. Note that there is a big difference between the reservoirs, especially characterized by the presence of a high concentration of bicarbonates in the reservoir area of the east-southeast sector. The inhibition system needed would require a higher dose than that used in the neutral zone's central area. Also, the high CO_2 content is responsible for non-condensable gases in the steam. Notice the large percentage of NCG in the wells in the east/southeast area. This area presents several geochemical differences when compared with the rest of the main reservoir and the acid reservoir.

Recent data from the wells in the study has established some estimates to assess the amount of power possible to obtain either by steam or hot water from a separate binary or dual-flashed system. Using the experience in the Miravalles geothermal field using a single-flash and binary cycle, the potential megawatts of all wells can be calculated, taking into account that there are several constraints such as the type of cycle and the efficiency of the same cycle. The turbine’s input and output are both primarily influenced by temperatures and enthalpy. The needed steam for each MW for a single-flash cycle is 2.2 kg/MW. For a binary cycle, in the best case a flow of 820 l/s is needed for generation from a 19 MW plant. These numbers are based on results from the Miravalles I and II single-flash cycles and Miravalles V binary plant.

Table 2 presents assessed flows from the wells and their possible generation upon separation of steam and liquid fractions for a pressure of 12 bar. Table 1 in Appendix I presents data from the 4 different wells at different separation pressures, and Tables 2 and 3 the design conditions and the equipment in the Miravalles geothermal plant.

TABLE 1: Chemical composition of different aquifers in the Miravalles geothermal field

Reservoir	Central neutral PGM-21	Acid PGM-19	East-southeast Bicarbonate PGM-29	East-southeast Bicarbonate PGM-55	East-southeast Bicarbonate PGM-28	East-southeast Bicarbonate PGM-35
Date	14-oct-05	13-oct-05	16-dec-03	38106	18-oct-95	38004
Sep. pressure (bar-a)	0.94	0.94	0.94	0.94	0.94	0.94
pH	7.87	5.76*	7.44	8.26	8.09	8.05
Cond. (μS/cm)	15860	12630	13320	12615	11700	12205
Na (ppm)	3068	2505	2616	2534	2323	2479
K (ppm)	321	300	222	214	207	214
Ca (ppm)	126	37	72	67	41	34
Mg (ppm)	0.11	7.13	0.42	0.37	0.55	0.44
Fe (ppm)	Nd	nd	nd	nd	Nd	nd
Cl (ppm)	5086	3973	4316	4114	3783	4005
SO_4 (ppm)	53	326	71	73	68	74
HCO_3 (ppm)	31	2	216	158	95	110
B (ppm)	77	67	66			60
SiO_2 total (ppm)	549	576	561	555	532	546
SiO_2 monomeric (ppm)	507	544	559	559		550
TDS (ppm)	8040	7470	8395	7900	7293	7830
CO_2 (mmol/kg)	145.16	117.77	2966.54	899.69	354.29	343.36
H_2S (mmol/kg)	1.17	1.79	1.79	0.98	0.69	0.86
N_2 (mmol/kg)	1.35	0.67	10.51	5.52	1.37	3.4
H_2 (mmol/kg)	0.08	0.10	0.31	0.04	0.06	0.05
Total	147.81	120.41	2979.14	906.39	356.41	347.68
NCG-% in the steam	0.65	0.53	13.09	3.98	1.57	1.52
$T_{Na/K}$ (°C)	221	233	203	203	207	205
$T_{Na/K/Ca}$ (°C)	222	240	211	211	218	219
T_{Quartz} mpv (°C)	227	232	234	234	230	233
$T_{measured}$ (°C)	233	230	230	230	229	230
Enthalpy (kJ/kg)	994	1140	999	989	988	985
Total flow (kg/s)	140	104	190	77	158	208

*pH neutralized (Sanchez et al., 2006)

TABLE 2: Total flow of the wells, 12 bar separation pressure

Well	Pressure separation (bar)	Flow mass (kg/s)	Flow steam (kg/s)	Flow liquid (kg/s)	H liquid (kJ/kg)	H steam (kJ/kg)	Power liquid (MW)	Power steam (MW)	Total power (MW)
PGM-28	12.0	158	15.10	143.0	988	2803	3.31	6.86	10.17
PGM-29	12.0	190	20.01	170.0	1008	2803	3.93	9.12	13.05
PGM-35	12.0	208	19.56	188.44	985	2803	4.36	8.89	13.25
PGM-55	12.0	77	7.40	69.60	989	2803	1.61	3.36	4.97
Total		**633**	**62.12**	**570.88**	**993**	**2803**	**13.21**	**28.24**	**41.45**

2. POWER CONVERSION TECHNOLOGIES

With the characteristics of the geothermal field in the study known, i.e. mass flow and enthalpy, both the size and type of geothermal power plant can be selected. The possible generating capacity of a plant is determined based on the current productivity of the reservoir, considering wells already drilled. The power conversion cycle for the exploitation of resources can depend on the chemical characteristics of the fluid as well as the economic and environmental conditions of the project. Three basic cycles are used to produce electricity from geothermal reservoirs:

- Flash cycle based on a back-pressure turbine or direct steam cycle;
- Flash cycle with a condensing unit;
- Organic Rankin cycle (ORC) or binary plant.

2.1 Flash cycle with a back-pressure turbine

The fluids may contain high-enthalpy dry steam or a mixture of steam and water; in this case, water and steam are divided by a cyclonic separator. The steam is directed to the turbine and the water reinjected. Such turbines have a low cost; their size is commonly small, usually between 1 and 10 MW and they can be installed near the wellhead. The consumption of steam is about 5 kg/MW, which is nearly double the amount used by the turbines to condense efficiently, with reference taken from the Miravalles geothermal field.

In this cycle, the exhaust steam is discharged into the atmosphere after performing its work in the turbine. Therefore it can be used in geothermal systems with a high content of NCG. Such cycles are also commonly used to measure the potential of a well for exploitation.

The back-pressure units can be installed and implemented for a few months and then moved from one place to another. They are therefore suitable for installing on a provisional basis at any stage in the development of the field. This phase is recommended because it anticipates field exploitation, allowing efficient monitoring of field behaviour before the installation of permanent generation plants. Figure 3 shows a simplified diagram of a back-pressure-type plant

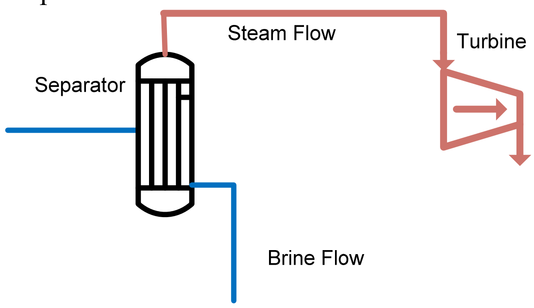

FIGURE 3: Flow chart of back-pressure power plant

2.2 Single-flash condensing cycle

In this cycle, steam is condensed out of the turbine, with a pressure vacuum of around 0.10-0.12 bar, which increases the enthalpy differential and hence the efficiency of the cycle. The consumption of steam is on the order of 1.8-2.8 kg/s flow per megawatt steam as is the case in Miravalles, taking into account the content of NCG, and the pressure of separation. Production, in areas where fluids are dominated by water, requires the use of steam/water separator systems; in single-flash type cycles, the pressure of separation can be selected, and the turbine pressure optimized (usually between 5 and 7 bars). Under these conditions, the water separator maintains a temperature between 150 and 170ºC. Figure 4 shows a diagram of simplified single-flash type plants.

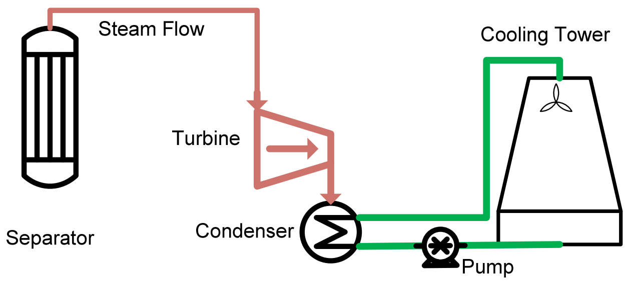

FIGURE 4: Flow chart of single-flash power plant

2.3 Double-flash cycle

With this technique, various appropriate configurations can be devised. Different configurations can use a single turbine with double entries of steam at different pressures or use 2 turbines in order to obtain greater power production. Back-pressure turbines can therefore be combined with a single-flash cycle with a condenser to form a double-flash cycle. Often an increase in power production of 20-25% can be achieved.

A double-flash cycle is not always recommended for two main reasons. The first is that the final temperature of the separated water (about 120ºC) generally increases the fouling in the reinjection wells. Secondly, the cost of equipment may not necessarily result in a sufficient increase in energy production which offsets the additional investment, especially when the contents of water in a geothermal fluid decrease over time, as often happens in high-enthalpy reservoirs. A simplified diagram of a plant of this kind is shown in Figure 5.

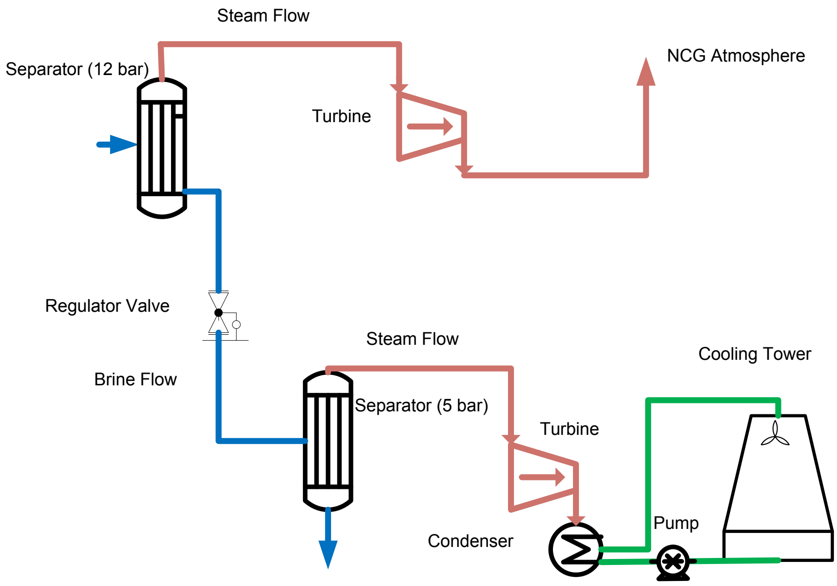

FIGURE 5: Flow chart of a double-flash power plant

2.4 Binary cycle

In this cycle, the geothermal fluid travels through a heat exchanger, where a secondary fluid (chloride, fluoric, carbon, ammonia, isopentane) with a low boiling point evaporates and then drives a turbine. It is then condensed and recycled within a closed system. Such units are generally used for the production of electrical energy using resources with low or medium temperature.

Binary units have high cost per unit of installed capacity compared with conventional flash cycles, but in many cases they are the most suitable alternative for geothermal development and can be more economical without worrying about the NCG content in the well. Binary cycles can be highly flexible and allow optimization of the geothermal resource through a combination of systems. For example, a common practice is to bottom flash cycles with binary cycles if the chemistry of the liquid allows it.

A diagram of this type of plant is presented in Figure 6; the cycle consists of a pre-heater, an evaporator, control valves, turbine generator set, capacitor and a feed pump. Water is used for cooling, depending on site conditions. If using wet cooling, the water must be replenished. Due to chemical impurities from the brine, waste is not generally suitable for use in the cooling tower. There is a wide range of fluids working for the power cycle; for their selection, you should try to achieve better use of the thermo-dynamic characteristics of the geofluid, especially its temperature. Hydro-carbons such as isobutene, isopentane and propane are good candidates for use as working fluids, as well as certain refrigerants. The fluid is selected to provide higher efficiency and safe and economical operation. The binary type plants are particularly suitable for shaping modular packages in a wide range of megawatt units.

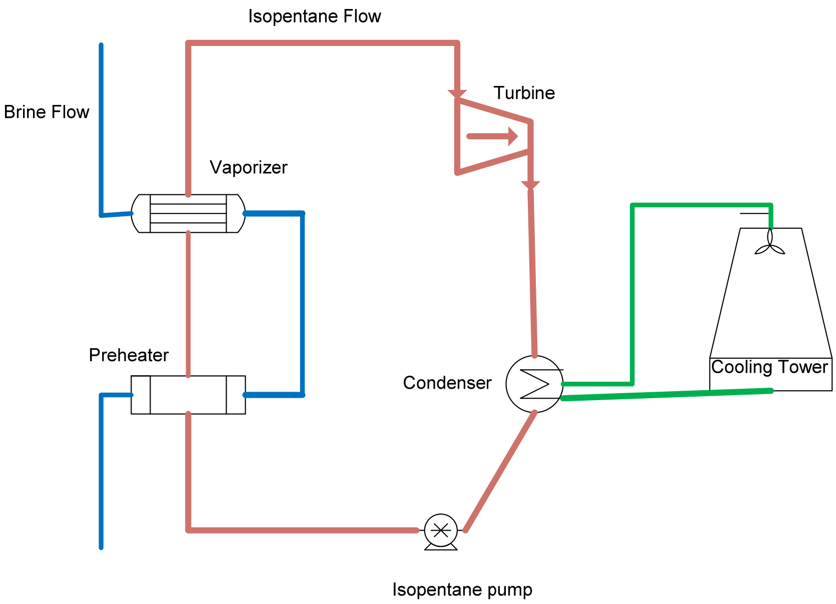

FIGURE 6: Flow chart of a binary power plant

3. TECHNICAL ASSESSMENT OF PRODUCTION CYCLES

Each cycle has advantages and disadvantages associated with it. The main characteristic of the east-southeast area is the high NCG content; therefore, the effects of this needs to be carefully modelled.

According to the data obtained in terms of generation based on the different phases (liquid/steam), a model can be made of various types of plants. The cycles considered were:

- A single-flash cycle in parallel with a binary cycle,
- Double-flash cycle with a back-pressure turbine working at a high pressure and a single-flash cycle with a condenser and finally with a binary bottoming cycle
- A binary cycle with two-phase flow into evaporator and pre-heater

Using the EES program type (F-Chart Software, 2002), all calculations were made associated with enthalpy and power flows, based on data from the wells in the study area. For comparison, the obtained power (MW) is compared with experience in the Miravalles geothermal field, as demonstrated in Table 2. The EES programs are shown in Appendix II.

3.1 Field installations required

In the current section the required field installation for a power plant in the east-southeast sector will be reviewed. There are not many differences in the installations between plant types. For example it is expected that a separator station will be in place even if a binary plant is the chosen cycle. For all cycles a separation station is required and a system for carrying fluids, as well as a cooling tower.

3.1.1 Separation station

There is a lot of experience in Miravalles with the use of stations with vertical separators, which carry out the disengagement process in a centrifuge. The Miravalles geothermal field has 7 separator units that receive two-phase flow of 4 producing wells. These units are fully automated and operate without need for personnel in the area. They are monitored 24 hours a day and can be operated from the checkpoint. They possess a dual electric backup system (diesel-batteries bank) so that a single failure does not disrupt operation; they can also be operated by hand by the Operation Field staff. There are also separation systems for the acid wells, 3 in total and a unit for PGM-29 in which the steam is diverted to a back-pressure cycle. With all this experience in separation units, no problems are expected in implementing a similar system to separate fluids from wells in the east-southeast area.

3.1.2 Inhibitor system

As mentioned earlier, the area east of the Miravalles geothermal field has a high bicarbonate content which favours the formation of $CaCO_3$, thus clogging the wells. To eliminate this effect, a system of inhibiting $CaCO_3$ has been used in Miravalles. This consists of a pumping system to which there is a tank connected in which a liquid inhibitor (polyacrylate acid) is stored; this substance is injected into the well through a capillary tube (ø ¼ – ⅜") to a depth of about 100 m just before the flash point of the well. Several years of operation in this field has given experience to find the optimal dose of the inhibitor to inject, depending on the mass flow of the well and the concentration of HCO^-_3 and Ca^{+2}. For example, a well in the normal pH neutral sector consumes around 0.5 ppm of inhibitor while a well such as PGM-29 in the east-southeast sector consumes 2.5 ppm. Well PGM-29 is currently operating with a back-pressure unit. Here, a completely automated inhibition system (monitored 24 hours) was installed. This well also has an emergency backup system that operates during a blackout. This is necessary as the well would be totally occluded in six days, if the inhibition system is not working. As there is already experience in the use of inhibitors in the east-southeast area, no technical problems are expected on exploitation of the rest of the resource.

3.1.3 Pipelines

The wells in the east-southeast sector, with the exception of PGM-55, are interconnected through a two-phase flow pipeline (ø 28"). There is a reinjection collector in the centre of the field which connects all the wells previously used for this purpose. To carry out the project in this area, it would be necessary to build several sections of relatively short pipes and a longer section joining well PGM-55 with all the others.

Figure 7 shows the location of wells 28, 29, 35 and 55 as well as the planned pipe lines (heavy line) for connecting them. The dotted lines show the connection of existing reinjection wells. The separation unit and the generation unit are to be located at an altitude of 500 m a.s.l. Placing the separation unit at a site at this elevation favours obtaining optimum pressure for use in a binary plant at a lower elevation. Note that this figure is an approximation and has no dimensions, as the goal of the report was not to perform a detailed design of the piping system.

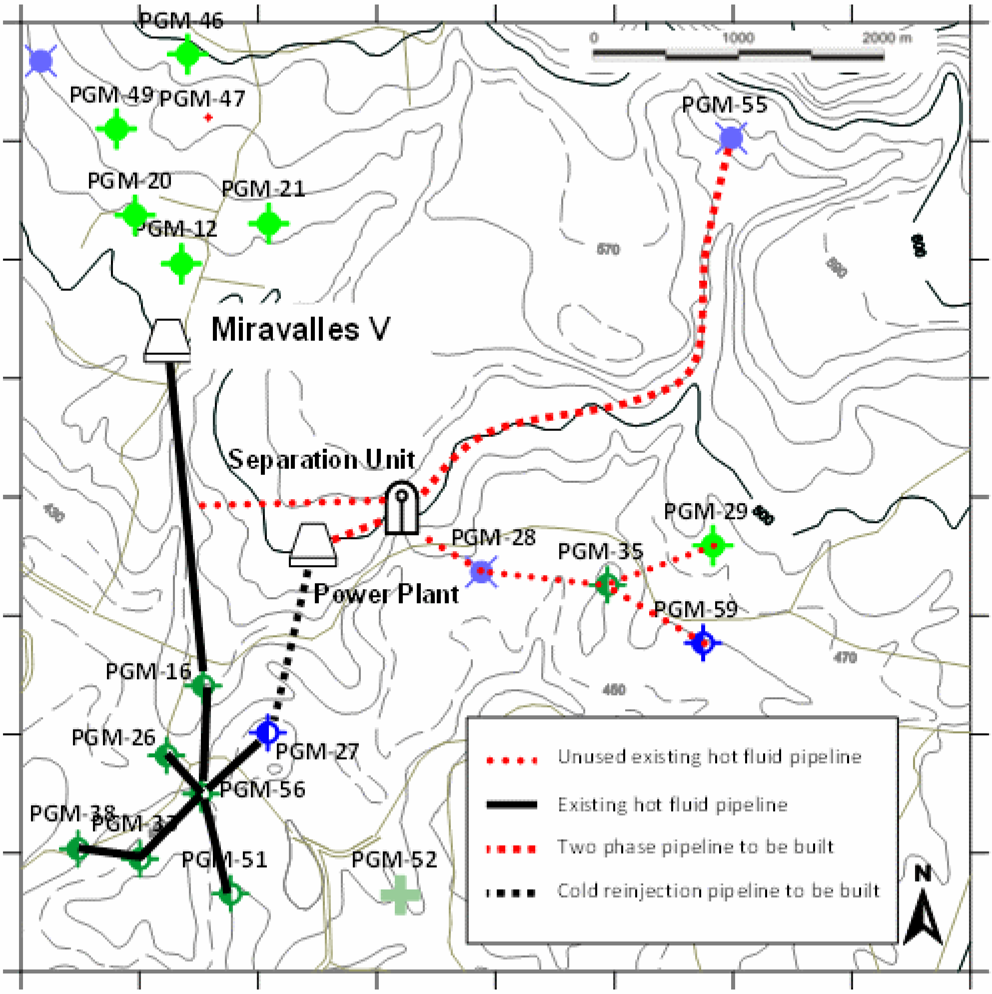

FIGURE 7: Map of the east-southeast zone of the Miravalles geothermal field

3.1.4 Reinjection

Existing collectors can be used for reinjection. They have sufficient capacity to absorb the possible 525 l/s that the wells under study generate, on average. These collectors are connected to 7 re-injection wells, as shown in Figure 7. The existing reinjection wells are quite good, the worst one is capable of receiving 200 l/s without pumping.

In this sector there should also be built small sections of pipes to connect the proposed plant and the separation unit. The cold re-injection system which should be directed to well PGM-27, could be used for this purpose, although a pipeline would have to be constructed as shown in Figure 7. An alternative would be to send the fluid for reinjection to well PGM-59, but then the needed pipeline would be somewhat longer.

The geography of the geothermal field, gives the advantage of being able to locate the re-injector wells at a lower elevation than the producing wells; thus, gravity can be used instead of pumps. The proposed east-southeast sector has the same advantage; it is possible to find a favourable location for both the separation unit and the power plant. In Figure 7 it can be seen that both the separation unit and power plant could be located at approximately 500 m a.s.l. and connected with the re-injection wells at 430 m a.s.l.

3.1.5 Cold end installations

The field also has 4 cooling towers located with different units. The area has a cold water source from the river Cabro Muco with enough water to supply these systems with makeup water. The existing connection pipeline will be enlarged in the near future. Currently, the average water circulation in the 4 cooling towers is around 12,000 l/s. Makeup water for a new cooling tower in the east-southeast area, with a circulation of about 4,500 l/s, will not be a problem for the planned infrastructure, since water is abundant.

3.2 NCG removal system

A good NCG extraction system depends on the ability of the ejectors, vacuum pump and compressors to extract the NCG from the condenser in a reliable manner while using little power. After years of exploitation in the Miravalles geothermal field, an increase in NCG in the steam flow has been observed. The plant units I and II were originally designed with an extraction system to extract at a rate of 0.68 and 0.82% mass fraction of NCG, respectively. The installed extraction system uses compressors and ejectors for a maximum extraction at a level of 1.2% of NCG. At present, production from the field exceeds that level and both ejectors are working at peak capacity, resulting in high power consumption of steam, over 8 MW, in order to maintain production at both 55 MW units.

With increasing NCG, and taking into account that the existing resource in the east-southeast area currently has a percentage average of 3% of NCG, a feasible option for extracting NCG with small power consumption for the cycle design in the East-Southeast area is needed. Taking into account that the history of the central part of the field could repeat itself and the NCG content could increase over time, 4 different types of gas extraction systems will be analyzed simultaneously, using NCG values of 3% and 5% to simulate the effects of an increase of NCG in each system. Note that all systems extract NCG as well as steam from the condenser, which means the actual mass flow from the condenser will be higher than the expected NCG content (3-5%).

The NCG in the steam brings about a reduction of the condenser's vacuum, reducing the efficiency of the turbine's generation. At present, several non-condensable gas extraction systems exist. In the present study, five types of systems will be evaluated:

- Systems with a vacuum pump;
- Systems with ejectors;
- The 3ST-turbo system, and
- The hybrid system.

The first system, based on using a vacuum pump, is shown in Figure 8. For a single-flash cycle, the estimated power required to operate the extraction system is given with the following formula (Radmehr, 2005):

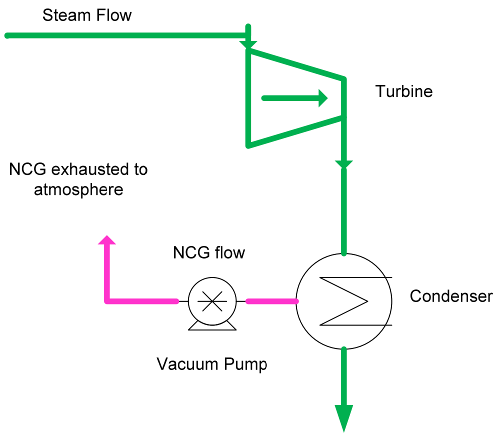

FIGURE 8: Flow chart of a vacuum pump extraction system

$$P_{vpump} = \left(\frac{\gamma}{\gamma-1}\right)\frac{m_g R_u T_{cond}}{\eta_{vpump} M_{gas}}\left[\left(\frac{P_{atm}}{P_{cond}}\right)\right]^{\left(1-\frac{1}{\gamma}\right)} - 1 \quad (1)$$

where P_{vpump} = Power of the pump (kW);
γ = Cp-gas/Cv-gas (value 0.7);
m_g = Mass flow rate of the extracted NCG and steam (kg/s);
R_u = 8.314 kJ/(kmol °C), the universal gas constant;
T_{cond} = Temperature of the condensate (°C);
η_{vpump} = Efficiency of the pump;
M_{gas} = Molar mass of the gas;
P_{atm} and P_{cond} = Atmospheric and condenser pressures (bar-a), respectively.

With data from the cycle obtained in the ESS simulation, the necessary power of the vacuum pump driven NCG extraction system was 1,071 kW to extract a flow of 5.52 kg/s of NCG, equivalent to 3% NCG plus 3 % steam flow. The reason steam is added is that the NCG is never found in the condenser in a pure state but is always mixed with steam. The NCG flow is sent to the top of the cooling tower, to be carried away by the ascending air flow. This is a common practice to minimize the presence of H_2S around the power plant.

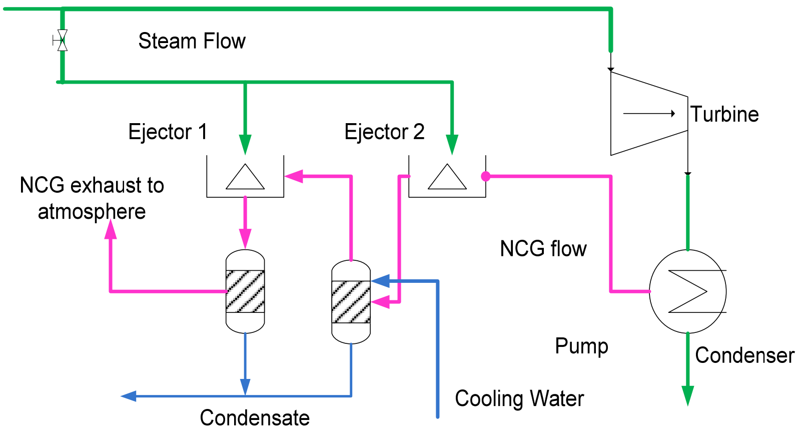

FIGURE 9: Flow chart of a two-ejector extraction system

In the second option, a system of ejectors is used as shown in Figure 9. For this system, under the same conditions of NCG (3%), 2540 kW power is needed.

The other options are two alternative systems in which processes combining new technology and maximum efficiency are used. These systems are the 3ST-turbo system, and the hybrid system (Vorun and Fritzler, 2000). Through the EES program, the values (ppmV) are obtained for the different percentages of NCG present in the reservoir under study; these are graphically presented in Figure 10 including the two-ejector system, showing the steam flow (kg/s) and resulting energy consumption (kW). In Table 3, the results for each of the different systems are given for two NCG percentages, 3 and 5%.

TABLE 3: Efficiency of three non-condensable (NGC) gas removal systems

System	2-ejector system	2-ejector system	3ST-turbo	3ST-turbo	Hybrid	Hybrid
NCG (%)	3	5	3	5	3	5
Gas level (ppmV)	13136	31146	13136	31143	13136	31146
Steam flow (kg/s)	5.6	14.6	3.7	9.2	3.6	10.8
Power required (kW)	2540	6635	1690	4150	1640	4920

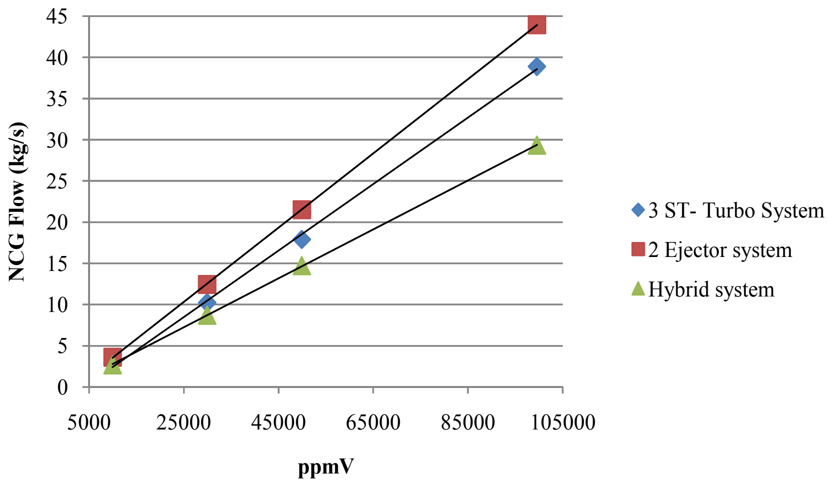

FIGURE 10: NCG flow vs. gas level (ppmV) diagram for three extraction systems (Vorun and Fritzler, 2000)

The following equation, gives the required steam flow Y (kg/s) to remove concentration X (ppmV) of NCG in the vapour stream for the 2-ejector system:

$$Y = 0.0005X - 0.976 \quad (2)$$

For the 3ST-turbo system this can be calculated in a similar way. The equation for obtaining the kg/s of steam is:

$$Y = 0.0003X - 0.2136 \quad (3)$$

Finally for the hybrid system and the same conditions, the equation for obtaining the kg/s of steam is:

$$Y = 0.0004X - 1.636 \quad (4)$$

Comparison of the different options shows that the one which offers the least power consumption (1071 kW) is the vacuum pump. What is lacking is an assessment of the cost associated with these options, which is outside the scope of this document. It is also difficult to obtain such information from suppliers.

3.3 Evaluation of cycles

3.3.1 Single-flash plant with binary bottoming

In the Miravalles geothermal field, there is about 14 years of experience using single-flash type generating plants, and in parallel with a binary plant for the last 5 years. With the experience in handling these types of production cycles in Miravalles, it is considered feasible to install a similar system in the east-southeast sector of the field, but careful consideration should be given to the costs associated with the gas extraction system and the complications involved.

The main design values were considered similar as in the rest of the Miravalles field, with the exception of the NCG content. These are summarized in Table 4:

TABLE 4: Design parameters

Separation pressure (bar-a)	6.8
Vacuum pressure (bar-a)	0.10
Efficiency of turbine	0.85
Temperature of cooling water (°C)	20
% NCG	3

With the ESS program, the calculations were performed based on data from the wells, and Tables 1 and 2 (Sanchez et al., 2006). The power of the cycle, with NCG set at a similar value as in the rest of the Miravalles geothermal field, is 39 MW.

In order to evaluate the process with a NCG extraction system, calculations were done for the four different gas extraction systems applying EES with NCG concentrations of 3% and 5% in the steam. Table 5 shows the calculated power consumption results for the NCG gas extraction systems. For comparison, the motor of the cooling tower pump consumes 250 kW for a cooling water flow of 3044 kg/s; and the tower fans consume around 350 kW. In summary, the final power of the cycle is calculated as 35.7 MW.

TABLE 5: Power consumption of the NCG system (kW) with a single-flash system

	NCG conc. 3%	NCG conc. 5%
Single-flash with vacuum pump	1071	1784
Single-flash with 2-ejector system	2540	6635
Single-flash with 3ST-turbo	1690	4150
Single-flash with hybrid system	1640	4920

The binary system takes the brine fluids from the separation of the single-flash cycle analysis to a pressure of 6.8 bar of separation and to a brine temperature of 163.8°C in order to do its job with the caloric exchange with isopentane. The brine surrenders its heat in the vaporiser, is preheated and then returned to be re-injected into the hot pool (Figure 6). The essential thing is to maintain a temperature of 130°C output to avoid embedding with both silica and vibration problems in the pipes due to reinjection flash caused by the exchange of temperature and pressure. The EES program estimated that the total power needed for a binary plant, with regard to steam generation and producing a heat exchange with isopentane, is 11.8 MW.

3.3.2 Double-flash plant (direct steam with single flash)

The version of a double-flash cycle considered in this report is one where the steam from the first separator is led to a back-pressure turbine. This is done to get rid of as much of the NCG content in the water as possible. The brine is then flashed a second time and passed to a turbine with the outlet guided to a condenser. As the brine has already flashed once, the NCG concentration in the second flash will be considerably smaller. Finally, the brine from the second flash is carried to a binary cycle for further usage (Figure 11).

As a result of the whole process, the following results were obtained through the EES program. An initial separation pressure of 12 bar obtained an output of 22.2 MW in the back-pressure unit. The second separation (5 bar) obtained an output of 25 MW in the single-flash unit. If the power consumption of a vacuum pump (115 kW), the cooling tower's pump motor (229 kW) and the fans (185 kW) is subtracted, the final power output is 24.5 MW.

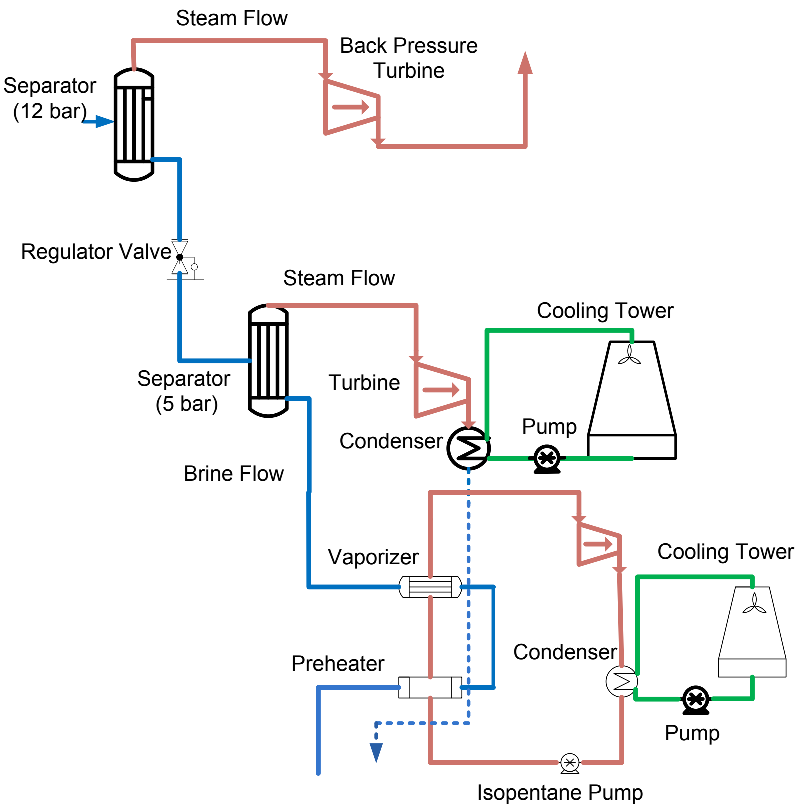

FIGURE 11: Flow chart of a double-flash cycle combined with a binary cycle

The water temperature from the separated brine is 151.8°C. For a binary system with an output of 10.1 MW, the isopentane pump requires 256 kW, 52 kW are necessary for the motor of the tower pump and 42 kW for the fans. Hence the total generated is 9.8 MW. The final temperature of the brine to be reinjected is 135.4°C. Hence the total power produced by the double-flash cycle, including direct steam, single-flash and binary cycles, is 56.5 MW.

The power quoted rests on the assumption that the NCG concentration will be small in the steam flow from the second separation station. To support this assumption, Figure 1 in Appendix I shows CO_2 evolved to flashed steam. For a temperature and separation pressure of 188°C and 12 bar, respectively, it can be estimated that 90% of NCG evaporates and leaves the brine in the first separator (2.7%) and the rest (0.3%) in the second flashing for 3% NCG in the full steam flow. Similar numbers are seen when the NCG is 5%.

Finally, it should be noted that experimental data was collected from well PGM-29 regarding the NCG content after flashing, and it supports these estimations (Miravalles data bank).

3.3.3 Binary plant using two-phase fluid

As an alternative to trying to minimize losses to generation due to consumption in the NCG system, there is the possibility of incorporating the steam flow with the flow of brine to a binary system in exchange with isopentane. The steam flow is divided into two equal branches with mass flow, the first going directly to the vaporiser, delivered to the fluid from the heat exchange of pentane with brine, and then diverted to a second exchanger, given that it still has enough temperature to carry out work in the form of delivering heat. The second stream goes directly to the second steam vaporizer and the output of this joins with the output of the first spray of steam to perform work as well as provide heat in the second vaporiser. This second vaporiser gives off enough heat to the steam condensate until it is ready to leave and be re-injected into the cold system.

The flow of brine goes directly to the first preheated exchanger and hence to the reinjection system as hot fluid; a final temperature at the exit should not exceed 130°C in order to avoid fouling wells and vibration problems in collecting reinjection fluid (Figure 12).

The results obtained through the EES program give an output of 37.4 MW with the temperature for the brine output at 135.5°C. The separation pressure is 8.0 bar, with a total brine fluid flow of 164 kg/s at 171°C; the total steam flow is 62 kg/s at 185°C.

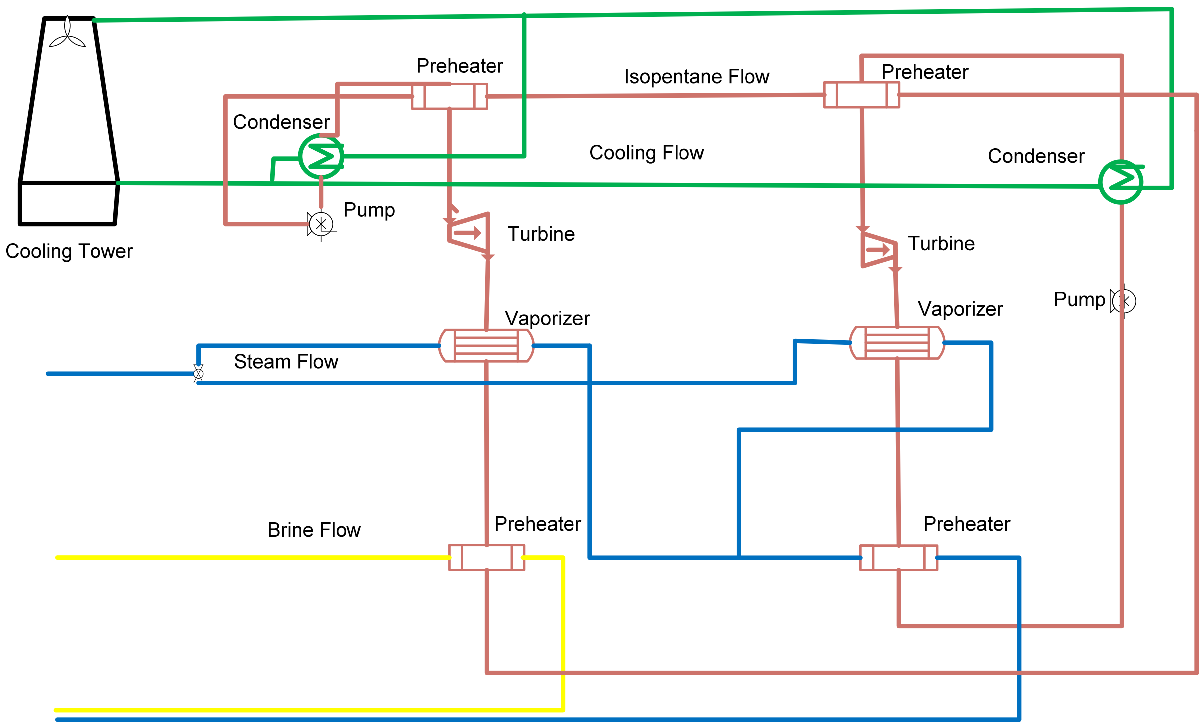

FIGURE 12: The flow chart of the binary system using brine and steam

3.4 Summary of technical assessment

An analysis for the various schemes was applied to the generation of the geothermal wells in the east-southeast sector; the following conclusions were drawn (Table 6):

In Table 7, the advantages and disadvantages in each cycle can easily be seen.

TABLE 6: Summary of cycle power

Power cycle	Generation (MW)*
Single-flash cycle with vacuum pump	37.7
Binary cycle with brine	11.3
Total	49.0
Double-flash cycle (back-pressure/single-flash)	45.5
Binary cycle with brine	9.8
Total	55.3
Binary cycle with two phases	36.9

*The output for the power plant is found by deducting the power required for the vacuum pump, motorized pump and motorized fan.

TABLE 7: Advantages and disadvantages of the analysed cycles

Power cycle	Advantages	Disadvantages
Single flash with hybrid system	New technology, low power required	Uses references
Double-flash cycle	More power for installation capacity, little sensitivity to NCG content.	Maintenance
Binary cycle with two phases	Low NCG effect	Scaling, dangerous liquid handling

4. ECONOMICAL ANALYSIS OF GEOTHERMAL POWER PLANTS

4.1 Economic factors of the geothermal plants

Geothermal power development consists of successive developmental phases that aim at locating the resources, confirm the power generating capacity of the reservoir and build the power plant and associated structures. Various kinds of parameters will influence the length, difficulty and material required for these phases, thereby affecting their cost.

The steam gathering system is the network of pipes connecting the power plant with all production and injection wells. The cost for these facilities varies widely depending on the distance from the production and injection wells to the power plant, pressure of the flow and chemistry of the produced fluids.

Power plant design is a complex activity that aims at minimizing both construction and operation & maintenance costs in a long-term perspective. It, thus, consists of defining the optimal size of power plant equipment and choosing the best suited technologies and construction materials to deal with site and resource particularities (Cédric, 2005). The costs associated with the construction and operation of a geothermal plant depend on the following factors (UPME, 2003):

- Type of resource (steam or hot water);
- Temperature of the resource;
- Productivity of the plant (volume);
- Type of plant (single flash, binary…);
- Environmental regulations;
- Cost of the investment; and
- Cost of manpower.

The three first factors are indicative of the number of wells that are necessary to drill and support the plant capacity. Using typical costs and generation potential of the deposits, the average value of drilling a well in Costa Rica is up to around \$1,000,000. The next three factors determine the cost of the system while the last affects the cost of plant operation (O&M). Table 8 presents the installation costs for power plants in Costa Rica, expressed in (USD/kW).

TABLE 8: Installation cost of geothermal power plants in Costa Rica

Power plant	Power (MW)	Starting time	Installation cost (USD/kW)
Miravalles I	55	March 1994	4525
Miravalles II	55	Aug. 1998	3027
UBP-direct steam	5	Nov. 1994	1147
Miravalles V	19	Jan. 2004	1330

4.2 Indicators of geothermal power plant efficiency

As a way to demonstrate the efficiency of a cycle's production of geothermal energy, an analysis related to the generating units of the Miravalles geothermal field is presented. The data obtained are based on the operation of the units during the year 2007. Three indicators exist to describe the yield of a geothermal plant with all dimensions being expressed in percentages. These are (UPME, 2003):

- Capacity factor;
- Load factor;
- Factor of availability.

The definitions of the technical indicators are:

$$Capacity\ factor\ (\%) = \frac{Total\ of\ MWh\ generated\ in\ the\ period}{Installed\ capacity\ (MWe) \times period\ (hours)} \times 100 \tag{5}$$

$$Load\ factor\ (\%) = \frac{Total\ of\ MWh\ generated\ in\ the\ period}{Fully\ factored\ load\ (MWe) \times period\ (hours)} \times 100 \tag{6}$$

$$Factor\ of\ availability\ (\%) = \frac{Total\ hours\ of\ plant\ operation\ during\ the\ period}{Total\ duration\ of\ the\ period\ (hours)} \times 100 \tag{7}$$

The availability factor (%) is depends on the maintenance needs. Here, programmed annual maintenance is important. An established date must be set to carry out maintenance, taking into account the type of maintenance and the duration. The time needed for maintenance may also depend on the magnitude of a problem. Both the capacity and the load factor are necessary to describe the technical yield of the plant; additional indicators partially describe the yield and the operating conditions. Table 10 gives typical data for generating plants in Costa Rica.

TABLE 10: Base data for production at the Miravalles geothermal power plants

Unit	MW-hr	Hours	Installed capacity (MW)	Maximum load (MW)	Capacity factor (%)	Load factor (%)	Availability factor (%)
Mira I	465,086	8546	55.0	59.2	99.0	92.0	97.6
Mira II	415,172	8371	55.0	54.5	90.2	91.0	95.6
Mira V	93,388	7347	19.0	13.7	67.0	92.6	84.0
UBP	36,164	8120	5.0	4.8	89.1	92.8	92.7

From the above analysis, it can be seen that the binary cycle has the lowest efficiency, mainly affected by off-duty time, compared with the UBP which, despite needing a high steam flow for operation efficiency, is quite acceptable.

4.3 Cost analysis

Capital costs of geothermal projects are very site and resource specific. The resource temperature, depth, chemistry and permeability has a major effect on the cost of the power project. The resource temperature will determine the power conversion technology (steam & brine) as well as the overall efficiency of the power system. Site accessibility and topography, local weather conditions, land type and ownership are additional parameters affecting the cost and time required to bring the power plant online. Power plant and steam field operation and maintenance costs correspond to all expenses needed to keep the power system in good working status (Cédric, 2005).

TABLE 11: Capital cost of power facilities for different technologies (Tiangco et al., 2004)

Cycle of generation	USD / kW
Back pressure	1476
Single flash	1237
Binary ORC	2259

After making the calculations related to the generation of each type of cycle and their possible combinations and taking benchmark data from Table 9, Table 11 shows the costs have been associated with each cycle.

According to the scenarios raised and the data obtained with different production cycles, the installation costs can be offset against the ultimate power delivered (Table 12), at the same time providing the most feasible option in each process, simulated with the EES program. Because the costs are very different for a binary plant in tandem with a single- or double-flash process, their graphs were developed separately. Table 12 presents the costs associated with plant generation cycles.

TABLE 12: Cost of different power cycles

Cycle	Power (MW)	Cost (USD)	(USD/ kW)
Single flash (6.8 bar)	39	48,243,000	1237
Binary with brine	12	27,108,000	2259
Total	51	75,351,000	1478
Double flash			
Back pressure (12 bar)	22.2	32,767,200	1476
Single flash (5 bar)	25.0	30,925,000	1237
Binary with brine	10.1	22,815,900	2259
Total	57.3	86,508,100	1510
Binary with two phases	37.4	84,486,600	2259

Generation through the single-flash cycle with binary for 51 MW would cost USD 75,351,000, while a double-flash plant with a binary cycle would cost USD 86,508,100.

This demonstrates that the combination obtained from the double-flash cycle is the most profitable, with the highest generation. The NCG has no effect on the process and the total generation is higher. Both the double- and the single-flash cycles are combined at the end with a binary cycle. The modelling cycle of a plant using two phases binary (steam and brine) has the highest cost and also the smallest generation.

5. CONCLUSIONS AND RECOMMENDATIONS

- According to the cycles evaluated, the double-flash cycle is more economical and fastest in obtaining the greatest generation (with low sensitivity to NCG).
- Through innovation and technological development, it is good to seek a production cycle that provides better returns on investment and replacement.
- Due to the high NCG content present in the study area, for an average of 45 MW electricity generation, the necessary gas extracting process could result in a very high cost for a single-flash plant.
- Investing in geothermal energy is very relevant as fuel prices are high. For example, in Costa Rica the cost of thermal kW is 9.5 times higher than kW geothermal.

The following recommendations can be given:

- Having only 4 wells to supply the system poses a limiting factor; it is recommended to add 2 more wells. There is plenty of space and locations that have not yet been used for drilling.
- The facility (separation unit, cooling tower and plant) should be located at an elevation so that there is no need for a pumping system for reinjection.

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APPENDIX I: Wells and equipment for the Miravalles power plants

TABLE 1: Production wells data at different separation pressures

Well	PGM-28	PGM-29	PGM-35	PGM-55	MW	MW	MW
P bar-a	12	12	12	12	Steam	Brine	Total
T °C	187.96	179.88	170.41	158.84			
HT kJ/kg	988	1008	985	989	992.5		
HV kJ/kg	2782.7	2782.7	2782.7	2782.7			
HL kJ/kg	798.4	798.4	798.4	798.4			
Fraction steam	0.096	0.106	0.094	0.096			
Fraction brine	0.904	0.894	0.906	0.904			
Total flow kg/s	158	190	208	77			
Steam flow kg/s	15.10	20.07	19.56	7.40	62.1		
Brine flow kg/s	142.90	169.93	188.44	69.60	570.9		
Steam MW	6.86	9.12	8.89	3.36	28.2		
Brine MW	3.31	3.93	4.36	1.61		13.2	
Total MW	10.17	13.06	13.25	4.97			41.5
P bar-a	10	10	10	10			
HV kJ/kg	2776.2	2776.2	2776.2	2776.2			
HL kJ/kg	762.8	762.8	762.8	762.8			
Fraction steam	0.112	0.122	0.110	0.112			
Fraction brine	0.888	0.878	0.890	0.888			
Total flow kg/s	158	190	208	77			
Steam flow kg/s	17.67	23.14	22.96	8.65	72.4		
Brine flow kg/s	140.33	166.86	185.04	68.35	560.6		
Steam MW	8.03	10.52	10.43	3.93	32.9		
Brine MW	3.25	3.86	4.28	1.58		13.0	
Total MW	11.28	14.38	14.72	5.51			45.9
P bar-a	8	8	8	8			
HV kJ/kg	2767.5	2767.5	2767.5	2767.5			
HL kJ/kg	720.9	720.9	720.9	720.9			
Fraction steam	0.131	0.140	0.129	0.131			
Fraction brine	0.869	0.860	0.871	0.869			
Total flow kg/s	158	190	208	77			
Steam flow kg/s	20.62	26.65	26.84	10.09	84.2		
Brine flow kg/s	137.38	163.35	181.16	66.91	548.8		
Steam MW	9.37	12.12	12.20	4.58	38.3		
Brine MW	3.18	3.78	4.19	1.55		12.7	
Total MW	12.55	15.90	16.39	6.13			51.0
P bar-a	6	6	6	6			
HV kJ/kg	2755.5	2755.5	2755.5	2755.5			
HL kJ/kg	670.4	670.4	670.4	670.4			
Fraction steam	0.152	0.162	0.151	0.153			
Fraction brine	0.848	0.838	0.849	0.847			
Total flow kg/s	158	190	208	77			
Steam flow kKg/s	24.07	30.76	31.38	11.77	98.0		
Brine flow kg/s	133.93	159.24	176.62	65.23	535.0		
Steam MW	10.94	13.98	14.27	5.35	44.5		
Brine MW	3.10	3.69	4.09	1.51		12.4	
Total MW	14.04	17.67	18.35	6.86			56.9

TABLE 2: Design conditions for the Miravalles geothermal power plants

Power plant	**Unit I**	**Unit II**	**Unit III**	**Unit V**	**UHW**
Location	Miravalles	Miravalles	Miravalles	Miravalles	Miravalles
Began operations	1994	1998	2000	2003	1994
Type	Single flash	Single flash	Single flash	Binary	Back press.
Power MW	60	60	29.5	21	5
Power output. MW	55	55	27.5	19	5
Geothermal flow. kg/s	132 steam	132 steam	65.1steam	418-brine	22 steam
Resource temperature. °C	228	228	228	228	228
Input pressure turbine	5.5	5.5	4.5	8.2	7.2
Input temperature turbine	168	168	168	168	168
Vacuum pressure bar	0.1	0.1	0.1	n.a.	n.a.
Turbine blades height mm	584	584			n.a.
Velocity rpm	3600	3600	3600		3000
Condenser type	DC	DC	DC	n.a.	n.a.
Heat required MWth	243	243			
Cooling water flow kg/s	4234	4234			
NCG steam ejector	yes	yes	yes	no	No
Step	2	2	2	n.a.	n.a.
Min. steam flow for ejectors kg/s	4.06	4.06	2.0		
Compressor	yes	yes	yes		
Step	4	4			
Min. power for compressor MW	0.4	0.4	0.2		
Vacuum pump					

TABLE 3: Main equipment of the Miravalles geothermal power plants

Equipment and type	**Single flash**	**Double flash**	**Binary**	**Dry steam**
Pumps	yes	yes	yes	no
Heatwell valve	yes	yes	yes	yes
Silencer	yes	yes	yes	yes
Grit chamber	yes	yes	yes	yes
Steam pipe	yes	yes	yes	yes
Steam separator	yes	yes	yes	yes
Storage tank	No	No	yes	no
Brine pipe	yes	yes	yes	yes
Humidity separator	yes	yes	no	no
Preheated condensate	no	no	yes	no
Vaporizer	no	no	yes	no
Condenser	no	no	yes	no
Steam turbine	yes	yes	no	yes
Organic turbine	No	No	yes	No
Duo admission turbine	No	yes	No	No
Control system	yes	yes	yes	yes
Condenser pump	yes	yes	yes	No
Cooling water pump	yes	yes	yes	No
Steam ejector	yes	yes	yes	No
Compressor	yes	yes	yes	No
Vacuum pump	yes	yes	yes	No
Cooling tower	yes	yes	yes	No

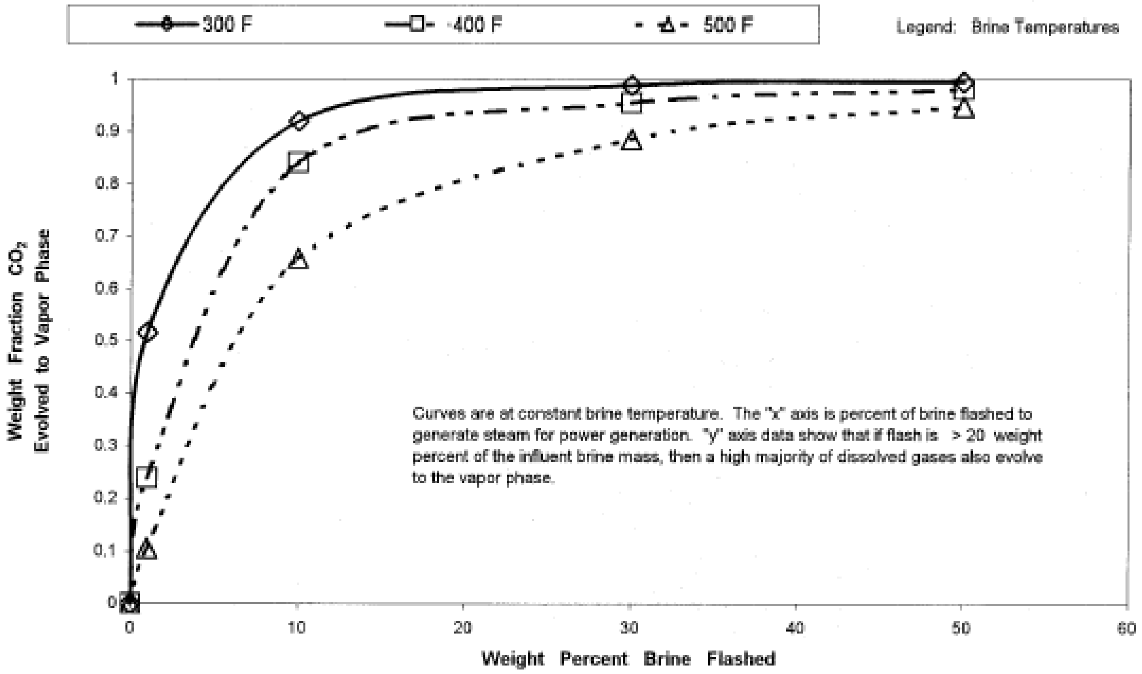

FIGURE 1: CO_2 evolved to flashed steam (Vorun and Fritzler. 2000)

Appendix II: EES programs

Binary plant:

```
T_A=164
P_A=6. 8
h_A=Enthalpy (Water; T=T_A; x=0)
cp_A=Cp (Water; T=T_A; P=P_A)

"Balance of mass"
m_dot_A=541
m_dot_A*cp_A*(T_A-T_B) =m_dot_iso*(h_1-h_6)
T_B=T_6+5
T_C=T_A-(T_A-T_B)*((h_1-h_5)/ (h_1-h_6))
Q_vap=m_dot_A*cp_A*(T_A-T_B)
Q_vapiso=m_dot_iso*(h_1-h_6)

"Turbine flow"
"Node 1"
eta_t=0. 85
P_1=20
h_1=Enthalpy (Isopentane; P=P_1; x=1)
s_1=Entropy (Isopentane; P=P_1; x=1)
"Node 2"
P_2=1.866
s_2s=s_1
h_2s=Enthalpy (Isopentane; T=T_3; x=1)
h_2=h_1-eta_t*(h_1-h_2s)
"Node 3"
P_3=1.866
T_3=46
h_3=Enthalpy (Isopentane; T=T_3; x=0)
```

```
s_3=Entropy (Isopentane; T=T_3; x=0)

"Condenser"
T_4=46
P_4=1.866
h_4=Enthalpy (Isopentane; T=T_4; x=0)
v_4=Volume (Isopentane; T=T_4; P=P_4)*100

P_5=P_1
P_5s=20
h_5s=h_4+v_4*(P_5s-P_4)
h_5=h_4+ ((h_5s-h_4)/eta_pump)
eta_pump=0.75

P_6=P_1
T_6=144
h_6=Enthalpy (Isopentane; T=T_6; P=P_6)

w_t=h_1-h_2
q_c=h_2-h_4
w_p= (h_5s-h_4)
q_IN=h_1-h_5
eta_th= (w_t-w_p)/q_IN
W_dot_net=m_dot_iso*(w_t-w_p)
```

Single-flash plant:

```
" Node 1 "
m_dot_1=633
 h_1=993
T_1=230

h_1*m_dot_1=h_2*m_dot_2+h_3*m_dot_3
m_dot_1=m_dot_2+m_dot_3

"Node 2"
"Steam Flow"
h_2=enthalpy(Water;x=1;P=P_sep)
T_2=Temperature(Steam;P=P_2;v=v_2)
P_2=P_sep
s_2=Entropy(Water;h=h_2;x=1)
v_2=Volume(Water;h=h_2;x=1)

"Node 3"
"Brine flow "
h_3=enthalpy(Water;x=0;P=P_sep)
T_3=Temperature(Water;x=0;P=P_sep)
P_3=P_sep
s_3=Entropy(Water;h=h_3;x=0)
v_3=Volume(Water;h=h_3;x=0)

"Node 4"
"Steam flow after drop pressure"
h_4=h_2
P_4=P_2-dP24
s_4=entropy(Water;h=h_4;P=P_4)
T_4=Temperature(Water;h=h_4;P=P_4)

"Steam flow for NCG"
m_dot_CO2= m_dot_2*NCG_p/100
v_dot_CO2=Volume(CO2;T=T_4;P=P_4)
v_dot_H2O=Volume(Water;T=T_4;P=P_4)
Vv_dot_CO2=m_dot_CO2*v_dot_CO2
```

```
Vv_dot_H2O=(m_dot_2-m_dot_CO2)*v_dot_H2O

PPMV=Vv_dot_CO2/(Vv_dot_CO2+Vv_dot_H2O)*1000000
m_dot_ncg=0.001*PPMV

"Node 5 "
"Steam flow for turbine"
h_5=h_4
P_5=P_4
s_5=s_4
T_5=T_4
m_dot_5=m_dot_2-m_dot_ncg

"Node 6"
"Steam flow out side turbine"
h_6s=enthalpy(Water;P=P_cond;s=s_5)
eta_t=0.80
eta_t=(h_5-h_6)/(h_5-h_6s)
P_6=P_cond
W_turb=m_dot_5*(h_5-h_6)

P_7=0.1
h_7=Enthalpy(Water;P=P_7;x=0)

"Extraction system NCG"
cp_6=Cp(CO2;T=T_2)
cv_6=Cv(CO2;T=T_2)
MW_6=MolarMass(CO2)/1000
lamda_6=cp_6/cv_6
mg_1=5.52
Ru=2.28
P_atm=1
P_conda=0.9
T_conda=46
E_vp=(lamda_6/(lamda_6-1))*(mg_1*Ru*T_conda)/(0.95*MW_6)*((P_atm/P_conda)^(1-1/lamda_6)-1)
mg_2=2.76
E_ncg=mg_2*(h_2-h_amb)-T_amb*(s_2-s_amb)
T_amb=24
h_amb=Enthalpy(Air;T=T_amb)
s_amb=Entropy(Air;T=T_amb;P=P_atm)

"Cooling system"
T_c2=35
T_c1=20
cp_cw=Cp(Water;T=T_c1;x=0)

m_cw*cp_cw*(T_c2-T_c1)=m_dot_2*(h_6-h_7)
delta_p=0.08
eta_pump=0.9
eta_motor_pump=0.95
P_pump=m_cw*delta_p/eta_pump
P_motor_pump=P_pump/eta_motor_pump
```

Binary plant (steam and brine):

```
"Initial data of reservoir"
T_0=Temperature (Water; h=h_0; x=0)
P_0=Pressure (Water; h=h_0; x=0)
s_0=Entropy (Water; h=h_0; x=0)
v_0=Volume (Water; h=h_0; x=0)
m_0=633
 h_0=993
```

```
"Steam flow (input/exit) of Vaporizer I"
h_2=Enthalpy (Steam; T=T_0; P=P_0)
T_2=Temperature (Steam; h=h_2; P=P_2)
P_2=8
s_2=Entropy (Steam; h=h_2; x=1)
v_2=Volume (Steam; h=h_2; x=1)
m_2=15. 5
Q_vap1=m_2*(h_2-h_4)
T_4=146
P_4=6
h_4=Enthalpy (Steam; T=T_4; P=P_4)
m_4=m_2

"Brine flow (input/exit) of preheater I"
h_1=720. 9
T_1=Temperature (Water; h=h_1; P=P_1)
P_1=8
s_1=Entropy (Water; h=h_1; x=0)
v_1=Volume (Water; h=h_1; x=0)
m_1=m_6*cp_6*(T_7-T_6)/ (h_1-h_5)
Q_pre1=m_1*(h_1-h_5)
h_5=Enthalpy (Water; T=T_5; P=P_5)
T_5=135
P_5=6

"Isopentane flow (input and exit) of Vaporizer I for 15.5 Kg/s of Steam"
T_6=71. 5
P_6=15. 5
h_6=Enthalpy (Isopentane; T=T_6; P=P_6)
cp_6=Cp (Isopentane; T=T_6; P=P_6)
m_6=m_7
T_7=117
P_7=13. 5
m_7=m_2*(h_2-h_4)/ (cp_7*(T_sat_7-T_7) + (h_sat_7s-h_sat_7l) +cp_sat_7*(T_8-T_sat_7))
h_7=Enthalpy (Isopentane; T=T_7; P=P_7)
cp_7=Cp (Isopentane; T=T_7; P=P_7)
P_sat_7=14. 5
T_sat_7=T_sat (Isopentane; P=P_sat_7)
h_sat_7s=Enthalpy (Isopentane; T=T_sat_7; x=1)
h_sat_7l=Enthalpy (Isopentane; T=T_sat_7; x=0)
cp_sat_7=Cp (Isopentane; T=T_sat_7; x=1)
m_8=m_7
T_8=148. 1
h_8=Enthalpy (Isopentane; T=T_8; P=P_8)
P_8=15. 5
cp_8=Cp (Isopentane; T=T_8; P=P_8)

"Area of preheater I and Vaporizer I"
A_pre1=Q_pre1/ (U_pre1*LMTD_pre1)*1000
U_pre1=150
LMTD_pre1= ((T_1-T_6)-(T_5-T_7))/ln ((T_1-T_6)/ (T_5-T_7))

A_vap1=Q_vap1/ (U_vap1*LMTD_vap1)*1000
U_vap1=900
LMTD_vap1= ((T_2-T_8)-(T_4-T_7))/ln ((T_2-T_8)/ (T_4-T_7))

"Steam flow (input/exit) to preheater II and Vaporizer II"
T_3=T_2
P_3=P_2
h_3=h_2
m_3=m_2

m_12=m_3
```

```
T_12=T_4
P_12=P_4
h_12=h_4

m_13=31
T_13=T_12
P_13=P_12
h_13=h_12

T_14=45. 4
P_14=6
h_14=Enthalpy (Steam; T=T_14; P=P_14)
Q_pre2=m_13*(h_13-h_14)
Q_vap2=m_3*(h_3-h_12)

 "Isopentane flow (input/exit) of preheater II"
T_9=38. 3
P_9=11. 5
h_9=Enthalpy (Isopentane; T=T_9; P=P_9)
cp_9=Cp (Isopentane; T=T_9; P=P_9)
s_9=Entropy (Isopentane; T=T_9; P=P_9)
T_10=97
P_10=13. 5
cp_10=Cp (Isopentane; T=T_10; P=P_10)
h_10=Enthalpy (Isopentane; T=T_10; P=P_10)
s_10=Entropy (Isopentane; T=T_10; P=P_10)
P_sat_10=14. 5
cp_sat_10=Cp (Isopentane; T=T_sat_10; x=1)
T_sat_10=T_sat (Isopentane; P=P_sat_10)
s_sat_10=Entropy (Isopentane; T=T_sat_10; x=1)
h_sat_10s=Enthalpy (Isopentane; T=T_sat_10; x=1)
h_sat_10l=Enthalpy (Isopentane; T=T_sat_10; x=0)
m_10=m_3*(h_3-h_12)/ (cp_10*(T_sat_10-T_10) + (h_sat_10s-h_sat_10l) +cp_sat_10*(T_11-T_sat_10))

T_11=150. 1
P_11=15. 5
h_11=Enthalpy (Isopentane; T=T_11; P=P_11)
cp_11=Cp (Isopentane; T=T_11; P=P_11)
s_11=Entropy (Isopentane; T=T_11; P=P_11)

"Area of preheater II and Vaporizer II"
A_pre2=Q_pre2/ (U_pre2*LMTD_pre2)*1000
U_pre2=900
LMTD_pre2= ((T_13-T_10)-(T_14-T_9))/ln ((T_13-T_10)/ (T_14-T_9))

A_vap2=Q_vap2/ (U_vap2*LMTD_vap2)*1000
U_vap2=900
LMTD_vap2= ((T_3-T_11)-(T_12-T_10))/ln ((T_3-T_11)/ (T_12-T_10))

"Power plant for unit"
T_15=87. 5
P_15=1. 5
h_15=Enthalpy (Isopentane; T=T_15; P=P_15)
T_16=82
P_16=1. 3
h_16=Enthalpy (Isopentane; T=T_16; P=P_16)

W_1=m_7*(h_8-h_15)/1000

W_2=m_10*(h_11-h_16)/1000
```