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# HYBRID POWER PLANT USING THREE ENERGY RESOURCES AT THE SAN VICENTE GEOTHERMAL FIELD, EL SALVADOR

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## ABSTRACT

A conceptual design of a 10 MW power plant (3HS+ORC), where energy comes from hybridization of geothermal water, solar irradiation and biomass heat sources (3HS), is proposed to generate electricity by a conventional organic Rankine cycle (ORC) with isopentane as a working fluid. The power plant performance is preliminarily assessed by integrating the amount of these renewable energies available in the northern boundary of the San Vicente geothermal field.

## 1. INTRODUCTION

Global energy crisis demands many countries to change or diversify their energy matrix. This is done mainly by reducing fossil consumption and opening up to technologies that use renewable energy as indigenous energy resources. During the 70's and this century's worldwide crisis, El Salvador began to assess solar, small hydro, wind and biomass renewable energies to add them to its energy matrix, which is composed mainly of imported oil, large hydro from Lempa River and high enthalpy geothermal resources.

A political frame to develop electricity generation projects based on renewable energy has existed since 2009 in El Salvador. For instance, tax incentives for projects up to 20 MW size and a long term strategy (2015-2025) are applied to meet electrical demand considering natural gas and renewable energy such as geothermal, photovoltaic, small hydro, wind and biogas technologies.

Power plant technology based on hybrid systems like geothermal-thermosolar or geothermal-thermosolar-biomass should be developed by the generator sector to take advantage of the cheaper indigenous energy, and therefore the country should be ready for the electricity demand and environmental obligations beyond 2020.

In Ahuachapán (Alvarenga, et al. 2008) and Berlin (Handal and Alvarenga, 2010) geothermal fields, LaGeo has demonstrated that thermosolar concentration and geothermal residual water can be combined to produce saturated steam to drive steam turbines, without scaling or corrosion problems in the solar field, however, low availability factor was an issue because of the duration of the solar day.

To improve the availability and capacity factors of an ORC power plant using isopentane as a working fluid as well taking advantages of low to medium geothermal resources existing in El Salvador became the reasons to assess and discuss the 3HS+ORC hybrid power plant concept.

## 2. 3HS+ORC POWER PLANT CONCEPT

Figure 1 shows a diagram of the 3HS+ORC power plant concept. It consists of a thermosolar field including thermal storage tanks, a biomass boiler, heat exchangers and a power block.

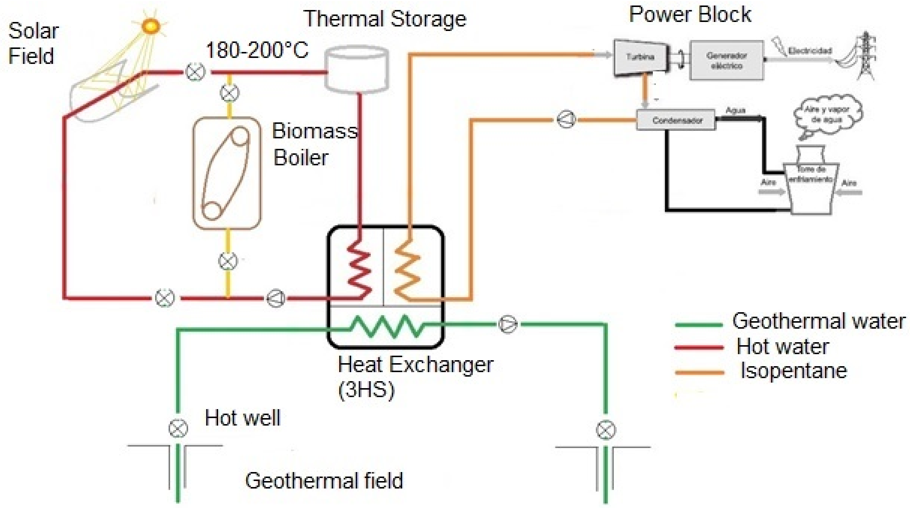

FIGURE 1: 3HS+ORC hybrid power plant concept

The organic Rankine cycle uses isopentane as a working fluid for driving the turbine in the power block side. The heat to process the isopentane is supplied by hotter water flowing through the heat exchangers.

The hot water flow can be originated in a liquid dominated and low to medium enthalpy geothermal reservoir or can be conducted from separated liquid into a flash process of a high temperature geothermal field, which feeds steam power plants. Also, water flow can gain heat into a thermosolar field that during sun's peak hours can save energy in the thermal storage tanks. This stored energy can be utilized during cloud coverage or some hours after sunset. In the case of low or lack of solar irradiation, water can be heated through the boiler that can generate hot water by forestry biomass combustion.

The nominal capacity of the hybrid power plant depends on the amount of energy resource on the site and governmental regulations to make use of the tax incentives, which in El Salvador establishes an upper limit of 20 MWe.

## 3. SITE PROPOSAL FOR THE POWER PLANT

As can be seen in Figure 2, both the sites for the 3HS+ORC hybrid power plant and the solar field are proposed to be located at the northern part of the San Vicente Geothermal production wells. Pipelines for less hot reinjection water would cross the border of solar field supplying separated water to the 3HS+ORC system. The terrain, currently used for sugar cane plantation with 13.5% S-N slope is appropriate for deploying the solar field of 1 $km^2$ size and has access to unpaved roads to transport forestry biomass from nearby plantations.

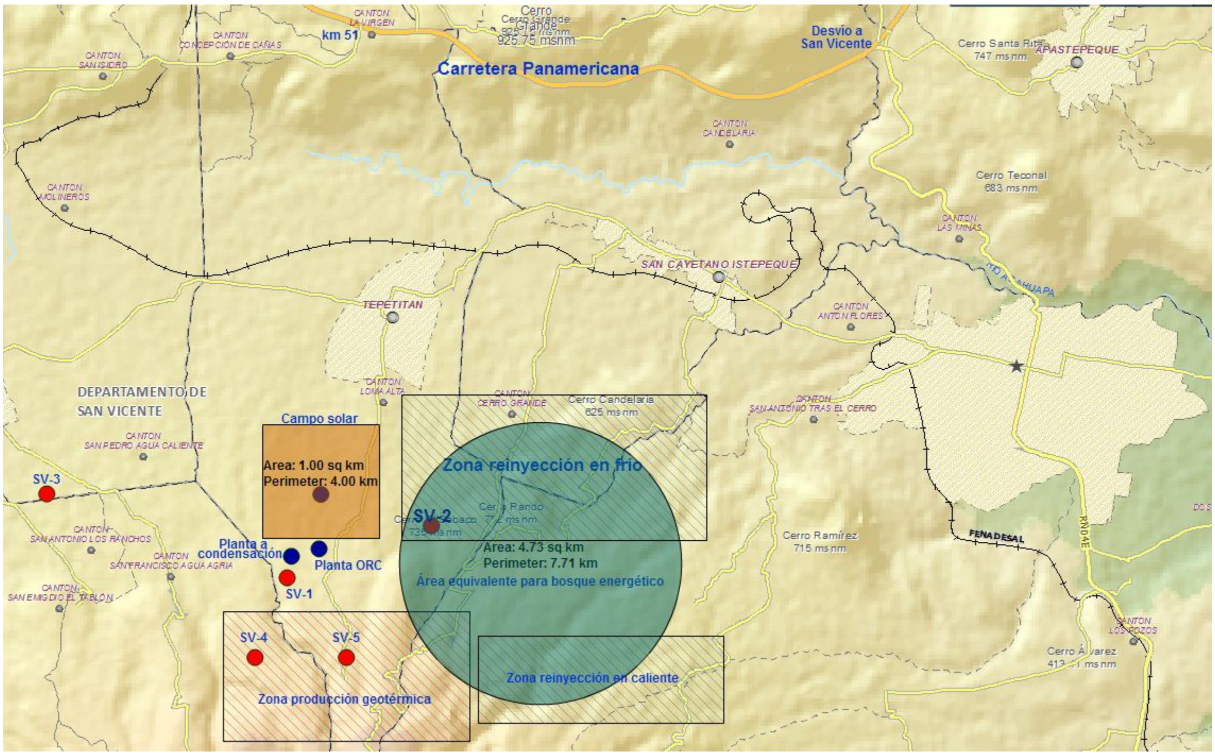

FIGURE 2: Site proposal for developing the 3HS+ORC hybrid power plant and solar field

## 4. OUTPUT

The power output of the 3HS+ORC hybrid power plant is based on the ORC efficiency and assessment of the renewable energy resources, which is available in the surroundings and also considered in this proposal, i.e. geothermal, solar and biomass.

## 5. GEOTHERMAL POTENTIAL

The geothermal energy that will supply a portion to drive the 3HS+ORC hybrid power plant would come from the enthalpy in the mass flow of the separated water in the process to get steam for the planned single flash power plant in the San Vicente geothermal field.

The available water mass flow can be derived from the size of the single flash power plant, steam fraction of 25% and a consumption factor of (2.0 kg/s)/MW. The installed capacity for the single flash power plant is estimated by applying the well-known volumetric calculation method with Monte Carlo simulation. According to Sarmiento and Steingrímsson (2011), the volumetric method calculates the thermal energy in the rock and the fluid that could be extracted based on volume and temperature reservoir as well as in the final or abandonment temperature, which is 170-180 ºC for steam power plants. Considering that San Vicente geothermal reservoir is a liquid dominated type, the total thermal energy stored in that reservoir is:

$$Q_t = A\, h\, [\, \rho_r\, C_r\, (1-\varphi) + \rho_w\, C_w\, \varphi\, ]\, (\, T_i - T_f\, ) \qquad (1)$$

The power plant size (P) to be supported by that resource results as:

$$P = \frac{Q_t \, R_f \, C_e}{t \, P_f} \tag{2}$$

As shown in Table 1, all the quantities in the above equations are in IS units. Besides, area (A), thickness (h), porosity (φ) and reservoir temperature (Ti) are considered here as random variables with triangle and normal log probability distributions. Some properties as density (ρr) and heat capacity (Cr) of the reservoir rocks are taken as uniform or constant distributions. Additional properties like abandonment temperature (Tf), recovery factor (Rf), conversion efficiency (Ce), economic life in years (t) of the project and power plant factor (Pf) are of a reasonable constant value.

TABLE 1: Values and probability distributions for the variables of the volumetric method

| Variable | Symbol | SI units | Min | Most likely | Max | Probability distribution |
|---|---|---|---|---|---|---|
| Area | A | km$^2$ | 4 | 6 | 12 | Triangle |
| Thickness | h | m | 700 | 1500 | 2000 | Triangle |
| Temperature | Ti | °C | 230 | 240 | 250 | Triangle |
| Abandonment temperature | Tf | °C |  | 180 |  | Constant |
| Porosity | φ |  |  | 0.06 |  | Normal Log SD=0.02 |
| Rock specific heat | Cr | kJ/kg °C |  | 0.85 |  | Constant |
| Water specific heat | Cw | kJ/kg °C |  | 4.6 |  | Constant |
| Rock density | ρr | kg/m$^3$ |  | 2500 |  | Constant |
| Water density | ρw | kg/m$^3$ |  | 806 |  | Constant |
| Recovery factor | Rf |  |  | 0.20 |  | Constant |
| Conversion efficiency | Ce |  |  | 0.12 |  | Constant |
| Plant factor | Pf |  |  | 0.95 |  | Constant |
| Economic life | Years |  |  | 30 |  | Constant |

Figure 3 shows the results of 100,000 iterations using the Monte Carlo simulation. The available geothermal potential, with 90% of certainty, is between 21 and 58 MWe. The cumulative probability curve indicates that there is 80 to 90% of probability for extracting about 27 MWe of reserves existing in the San Vicente geothermal area.

If 27 MWe are going to be developed in a single flash power plant, the total steam consumption would reach 54 kg/s and therefore hot separated water at 180 ºC available for the 3HS+ORC hybrid power plant would be 162 kg/s.

## 6. FORESTRY BIOMASS

The thermal energy that will be the second portion to drive the 3HS+ORC hybrid power plant, would be heat obtained through water, while both native Gliricidia Sepium (locally known as Madre Cacao) and imported Eucaliptus Camaldulensis trees will be used to burn into a conventional boiler.

The chemical energy (Bridwater, A., 1996 and Nogués et al., 2010) contained in this biomass forestry type depends on their chemical constituents and moisture present in these trees. Table 2 summarizes the chemical composition of each tree as well as their higher heating value (HHV) dry base and lower heating value (LHV), with 30% wet base.

Those heating values are related with the following equation and the plot in the Figure 4 indicating that the LHV decreases linearly with the moisture content.

$$LHV_{(wet)} = HHV_{(dry)}\left(1-\frac{w}{100}\right) - 24.49\,(w+9H)\left(1-\frac{w}{100}\right) \tag{3}$$

where w and H are the moisture ratio and dry base hydrogen fraction, respectively.

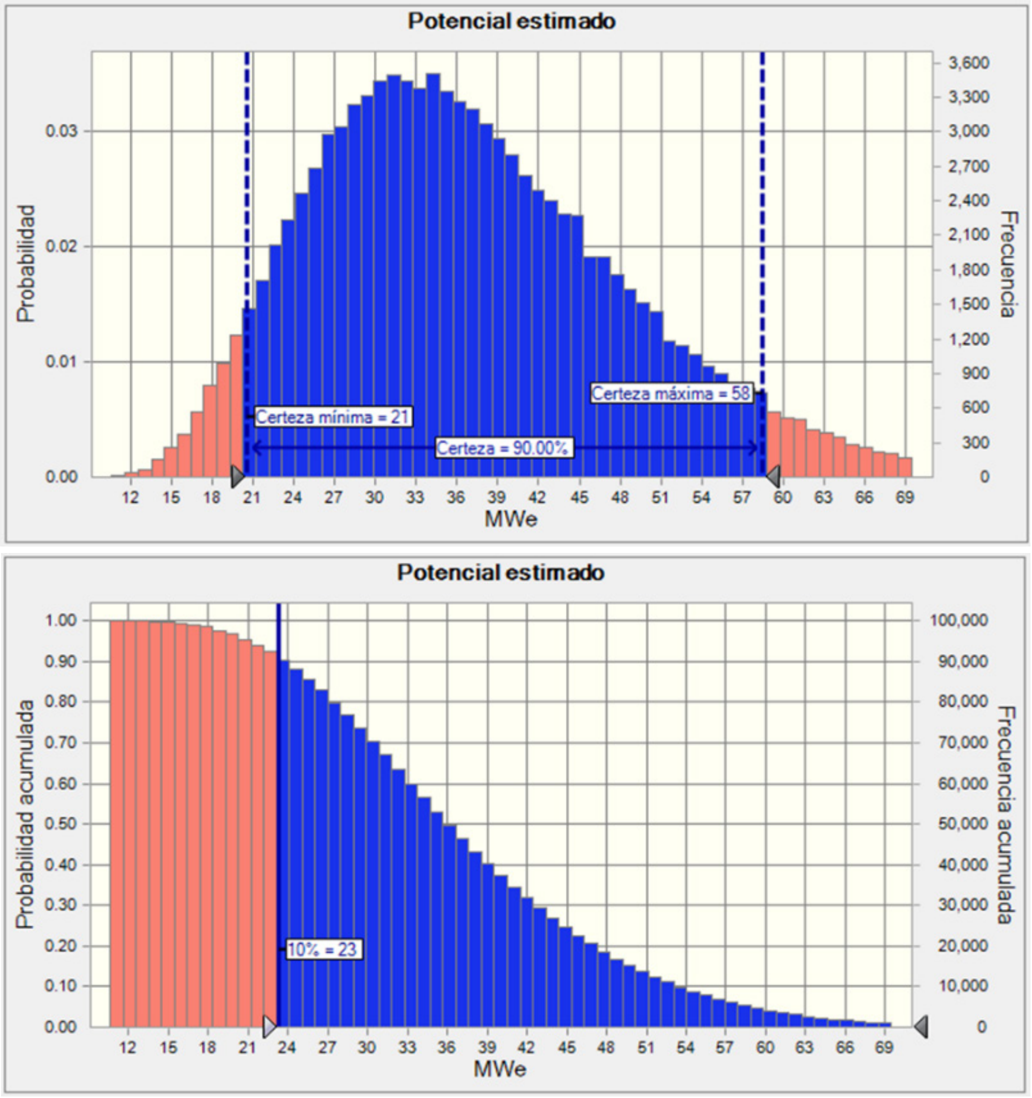

FIGURE 3: Relative frequency histogram and cumulative probability curve of the volumetric reserves estimation for the San Vicente geothermal field

TABLE 2: Chemical content and heating values for the Gliricidia Sepium and the Eucaliptus Camaldulensis biomass forestry type.

| **Chemical content and physical properties** | **Gliricidia Sepium** | **Eucalyptus Camaldulensis** |
|---|---|---|
| | **% weight** | |
| C | 45.22 | 48.68 |
| H | 5.91 | 6.20 |
| N | 1.06 | 0.24 |
| S | 0.00 | 0.00 |
| O | 46.26 | 44.86 |
| CL | 0.03 | 0.03 |
| ASH | 1.52 | 0.00 |
| $\text{HHV}_{(dry)}$ (kJ/kg) | 18380.00 | 20100.00 |
| $\text{LHV}_{(wet)}$ (kJ/kg) | 11219.46 | 12378.72 |

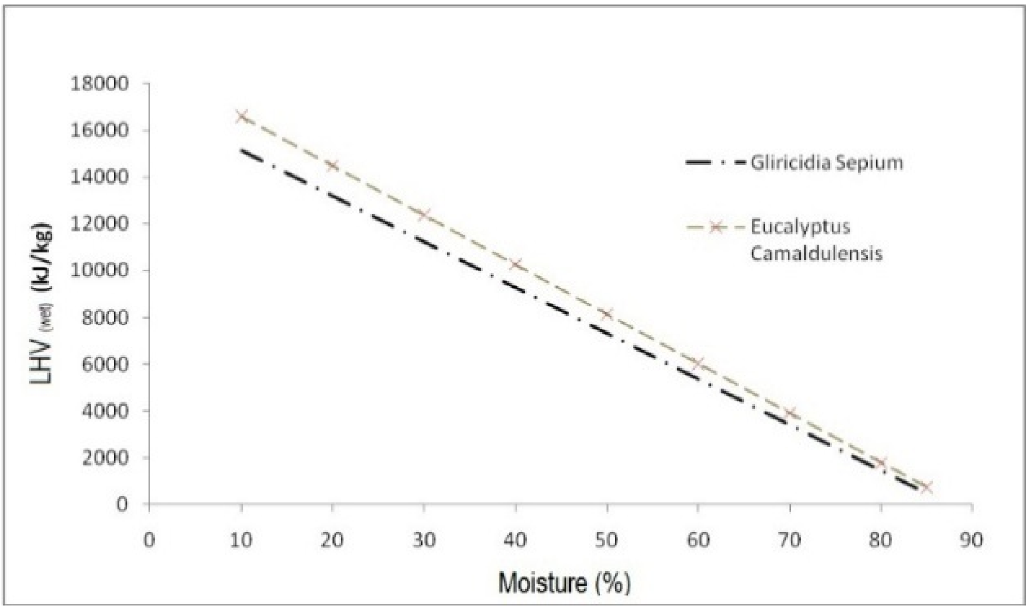

FIGURE 4: Low Heating Value versus moisture content

If "M" ton/year of biomass, 30% wet, is transformed into thermal energy by biomass combustion in the boiler, with thermal efficiency $\eta_{th}$, during "t" hours per year, the available thermal power ($P_{wet}$ in $MW_{th}$) is calculated as follows:

$$P_{wet} = \frac{M(LHV_{wet})}{3600\ t}\ \eta_{th} \qquad (4)$$

If the total amount of biomass is 1000 ton/month and the thermal efficiency of the boiler, working 8000 hours/year is 70%, the thermal power $P_{wet}$ becomes 3.40 MW as it can be easily deduced from Table 3.

TABLE 3: Available thermal power from biomass

| Forestry biomass | M (ton/month) | M (ton/year) | LHV wet (kJ/kg) | P wet (MW) |
|---|---|---|---|---|
| Gliricidia Sepium | 600 | 7200 | 11219.46 | 2.80 |
| Eucalyptus Camaldulensis | 400 | 4800 | 12378.72 | 2.06 |
| Total | 1000 | 12000 | | 3.40 |

Hence, if water temperature flowing into the boiler changes from 140 to 200°C, then 13.5 kg/s of water flow will obtain sensible heat caused by the available 3.40 MW thermal power.

## 7. SOLAR ENERGY

The last portion of thermal energy to drive the 3HS+ORC hybrid power plant would be heat gained by water circulating into a concentrated solar power field.

For IEA-ETSAP and IRENA (2013) and Kalogirou, (2009), concentrating solar power (CSP) plants use mirrors to concentrate sunlight onto a receiver, which then collects and transfers the solar energy to a heat transfer fluid that can be used to supply heat to generate electricity through conventional steam turbines. CSP plants can be equipped with a heat storage system for electricity generation at night or when it's cloudy.

There are four CSP variants: Parabolic trough, Fresnel reflector, solar tower and solar dish, which differ depending on the design, configuration of mirrors and receivers, heat transfer fluid used and whether or not heat storage is involved (Kalogirou, 2009 and Chen, 2011). Despite of the parabolic trough which is commercially the most developed technology, the solar tower mode with a heat storage system seems to be appropriate to deploy in the San Vicente area mainly because of its adaptability to non-flat terrain, neglected thermal losses, ability to operate at high pressure to heat water and its cost will be competitive by the years 2020-2025 to the conventional power plants.

The solar tower configuration, shown in Figure 5, is estimated to consist of 400 heliostats deployed in a circular shape to optimize 1 km$^2$ land size. Because of the terrain topography, the southern semicircle of the solar field will have more heliostats than the northern semicircle. Thus, considering 12m x10m per heliostat size, the total aperture area will be 48,000 m$^2$. Each heliostat will track the sun along the azimuthal and elevation solar position, resulting on continuous solar concentration.

At 100 m height, above the center of the heliostat circle, a tubular cylinder type boiler will receive concentrated sunlight to heat deionized water. This boiler or heat receiver should be installed next to the 3HS+ORC hybrid power plant to reduce energy consumption when pumping hot water to the heat exchanger of the hybrid power plant.

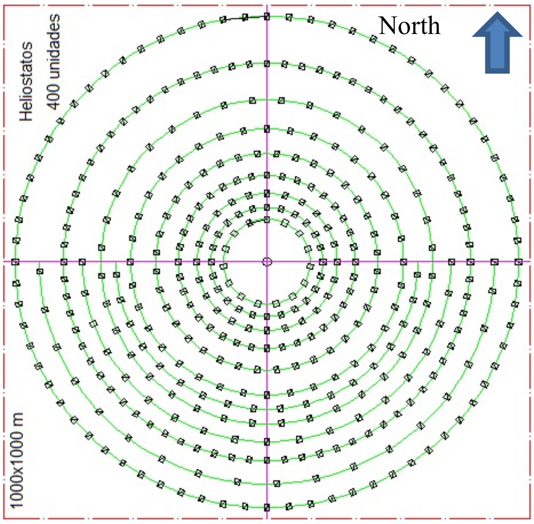

FIGURE 5: Heliostat solar field

The lower elevation land to the north of the San Vicente geothermal production wells could have an annual global irradiation, characteristic of the world solar belt, which according to LaGeo solar monitoring in "15 de Septiembre" hydropower dump, is almost 2000 KWh/m$^2$.year equivalent to 5.0 to 5.5 kWh/m2 day.

If design irradiance is taken as 800 W/m$^2$ during 7 hours/day and solar field global efficiency is 44%, the solar power input would reach almost 38 MW and the water flowing into the receiver would gain approximately 17 MWth. These quantities are summarized in Table 4.

TABLE 4: Thermal power from the solar field

| **Solar power input, efficiency and thermal power output** | **Value** |
|---|---|
| Solar irradiance (W/m$^2$) | 800 |
| Solar power input (MW) | 38.4 |
| Solar field global efficiency | 44% |
| Thermal power absorbed by water (MW) | 16.9 |

Therefore, if the working pressure in the receiver is 20 bar-g, the water mass flow that changes temperature from 140 to 200ºC when it has absorbed 17 MWth, results on about 68 kg/s.

## 8. INTEGRATING THREE HEAT SOURCES AND THE ORC CYCLE (3HS+ORC)

From the three previous analysis, the available water mass flow in the hot water/isopentane heat exchanger is around 243 Kg/s, which is the result of 162 kg/s separated geothermal water at 180ºC/10 bar, 13 kg/s biomass at 200ºC/20 bar and 68 kg/s thermosolar at 200ºC/20 bar.

Because of heat and pressure losses along the hot water transportation, the 243 kg/s hot water side of the water/isopentane heat exchanger would flow at least at 10 bar and 180ºC, respectively.

Figure 6 shows a linear correlation (Estevez (2012) among ORC turbine gross power output and both geothermal water at 184ºC and isopentane mass flow rates. This linear tendency matches data for a 9 MW binary cycle power plant installed in the Berlin geothermal field.

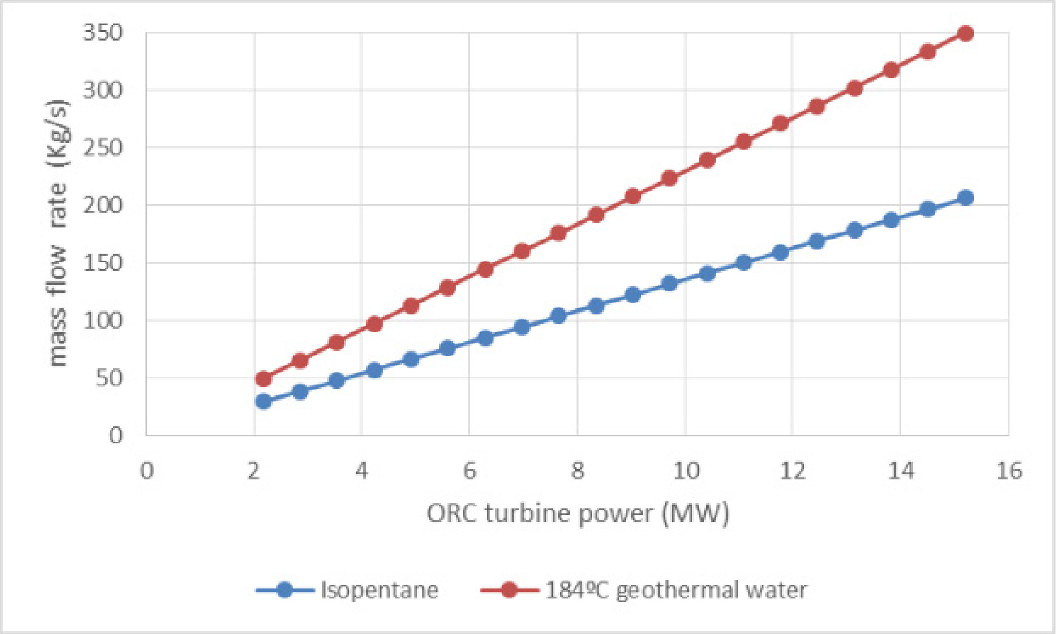

FIGURE 6: ORC turbine gross power output versus mass flow rates (Estevez, 2012)

If that approach is conservatively applied not to the available 243 kg/s but to 231 kg/s hot water at 180ºC, results presented in Table 5 come close to 10 MWe install capacity.

The geothermal hot water flow ensures the highest contribution to the 10 MW ORC gross electrical power, hence, the geothermal portion should be taken as basis source of energy while the rest sources should be on line according they are either naturally available or stored in the synthetic oil, which conveniently can be use later to generate electricity.

TABLE 5: Water flow and heat source breakdown for 10 MWe 3HS+ORC hybrid power plant

| **Heat source (3HC)** | **Water flow (kg/s)** | **ORC power (MWe)** |
|---|---|---|
| Geothermal | 158 | 6.9 |
| Solar | 63 | 2.7 |
| Biomass | 10 | 0.4 |
| Total | 231 | 10.0 |

The breakdown heat source contribution to generate 10 MWe during sunny and cloudy days is outlined in Figure 7. For days with clear sky or dry season, input thermal energy from 7 to 17 hours will be of the three types of resources, utilizing them for electrical generation and stored heat in the synthetic oil tank. During cloud coverage or wet season, the solar irradiance decreases partially or totally allowing the biomass boiler balances the reduction of hot water mass flow. In both scenarios, from 17 to 21 hours, sensible heat stored in the synthetic oil will be released to supply heat to hot water/isopentane heat exchanger. The subsequent 10 hours, the 3HC + ORC hybrid power plant will operates to very low demand.

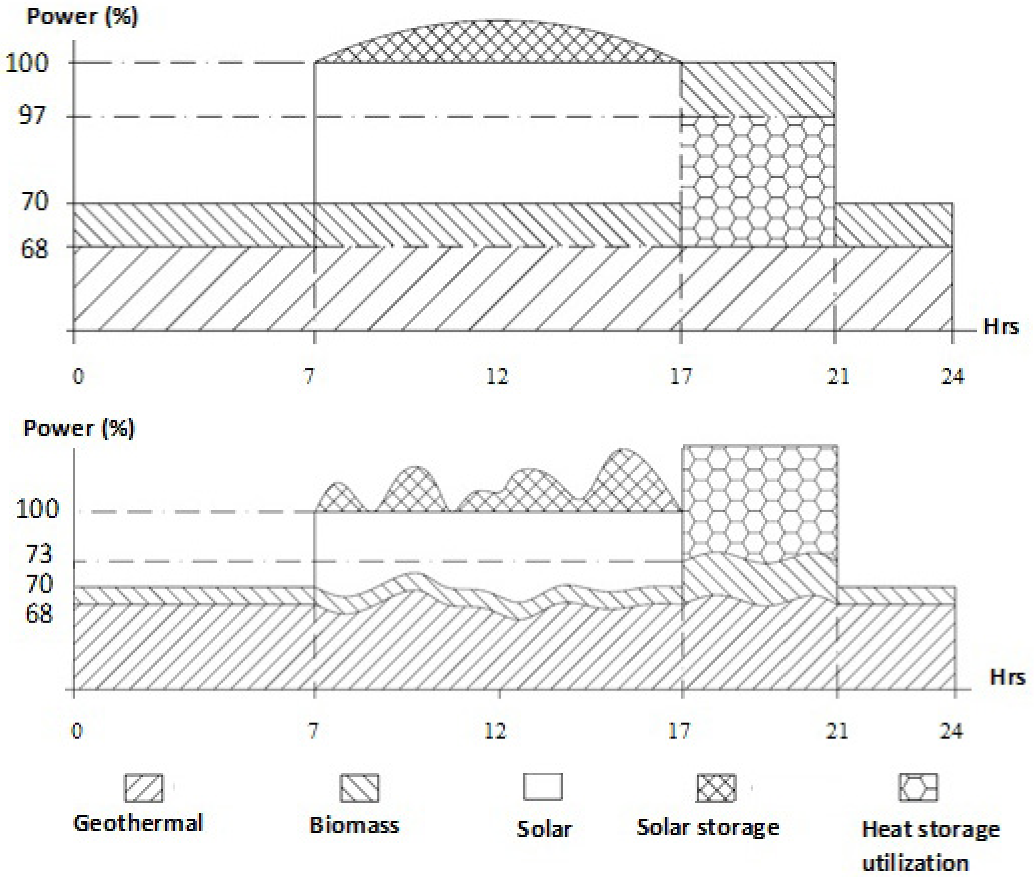

FIGURE 7: Heat sources input breakdown for 10 MWe ORC gross power generation. On the top sunny days and below cloudy days.

## 9. HIGHLIGHTS

It seems that the 3HS + ORC hybrid electrical power plant conceptual approach offers an alternative to take advantage of the coexistence in a particular area of geothermal, solar and biomass energy renewable resources. Nevertheless, site solar monitoring, direct lab measurement of biomass heat content and determining available geothermal power should be completed to demonstrate whether or not the project is viable to be implemented by 2020-2030.

The thermodynamic conditions needed to drive the ORC hybrid electrical power plant can be those of either separated hot geothermal water from flash geothermal fields or hot geothermal water from low to medium temperature geothermal wells. In any case, scaling chemical potential studies should be included to define the optimum temperature to cool down the geothermal water.

Solar energy concentration and biomass combustion are well known methods to produce hot water or steam at thermodynamic conditions to drive any Rankine cycle and so they can be used for running the 3HS + ORC hybrid electrical power plant concept.

It seems that San Vicente geothermal area is suitable to develop at least 10 MWe of the 3HS + ORC hybrid electrical power plant type. That electrical power could be higher because:

a) Separated hot geothermal water mass flow could be increased if the flash geothermal plant becomes larger than 27 MWe;
b) Hot water mass flow from biomass combustion could be larger if a forest of Gliricidia Sepium (locally known as Madre Cacao) or Eucalyptus Camaldulensis can be planted in nearby zones to exceed 1000 ton/month of biomass feedstock; and
c) Additional plantation of biomass near the San Vicente geothermal field with similar or higher heat content than the Gliricidia Sepium or Eucaliptus Camaldulensis could exist there to increase hot water mass flow.

Design of the solar field still needs a topographic, soil property, ground water, geological risk and environmental studies to optimize civil works, risk management and water supply for thermosolar field and biomass boiler.

The logistics of transport, chips manufacturing, dry process and other costs need to be studied to determine biomass feasibility.

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