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FEASIBILITY STUDY FOR IMPLEMENTATION OF A SOLAR–GEOTHERMAL HYBRID PLANT BASED ON AN ORGANIC RANKINE CYCLE IN LAKE ABHE GEOTHERMAL AREA, WITH A PARTICULAR HOT ARID CLIMATE, DJIBOUTI

Hamoud Souleiman Cheik
Office Djiboutien De Developpement De l'Energie Geothermique – ODDEG
PK 20, Rue d'Arta, P.O. Box 2025
Djibouti
REPUBLIC OF DJIBOUTI
hamoudsoulei@yahoo.fr

ABSTRACT

Lake Abhe, situated in southwestern part of Djibouti, is one of promising geothermal field and was recently the subject of a complete surface exploration. Djibouti possesses several medium-enthalpy resources distributed in different parts of the country and it is located in a hot arid climatic zone. This particular climate makes it necessary to find new ways in modelling common geothermal power plants. The objective here is to determine how the medium-enthalpy resource in Lake Abhe geothermal field would be best utilized, both technically and commercially. The backbone of this paper will be how to deal with the hot arid climate in order to improve the efficiency of the power plant. A thermodynamic model was developed using Engineering Equation Solver (EES) to evaluate the performance of ORC geothermal power plants standalone, and an ORC assisted by a parabolic trough solar concentrating collector field. Based on the results obtained in this study, the solar-geothermal hybrid scheme increases the power generation compared with geothermal-only power plants. Results of the basic model of the binary power plant with an air cooled condenser and hybrid modelling are presented. With a geothermal fluid mass flow of 443 kg/s and temperature of 145.7°C and under Djiboutian climatic conditions with an average ambient temperature of 31°C, two models have been proposed. The air cooled condenser basic binary model produces 11 706 kWe of gross power output with an auxiliary power consumption of 24.5% of the total gross output power where the fan power represents 58.5% of the latter. The cycle efficiency is 12%. For the hybrid solar-geothermal power plant, the net power output is 14 778 kWe where 23% go for the use of the auxiliary components. The hybrid outperforms the basic binary plant by 26.24%.

1. INTRODUCTION

The Republic of Djibouti is located in East Horn of Africa with an area of 23 000km^2. It is bordered by Ethiopia in the west and south, Eritrea in the north, and Somalia in the southeast. It is hence a strategic place between Africa and Arabia, the entrance of the Red Sea in the extreme West of the Aden Gulf, between latitudes 10° and 13°N and longitudes 41° and 44°E, within the Arabian plate.

The location of the Republic of Djibouti is unique in terms of geodynamics activity. It is situated at the eastern extreme of the Afar depression. The Afar depression is one of the most unique geological settings on the Earth today. It represents the only modern example of continental rifting at an active triple-junction, where two oceanic ridges, Gulf of Aden and Red Sea, meet with the East African Rift (Tazieff, et al., 1972). This unique geographical area is characterized by the presence of geothermal resources revealed by numerous hot springs and fumaroles found in different parts of the country. The total geothermal potential is believed to reach the amount of about 1000 MWe from approximately of 13 locations.

One of promising sites, Lake Abhe geothermal field (see Figure 1) was recently the subject of a complete surface exploration. This was conducted jointly by scientists of ODDEG and ISOR with a co-financing from MFA/ICEIDA. Electricity prices in Djibouti are among the highest in Africa per kWh. Currently, Djibouti depends on imported hydropower from Ethiopia to meet roughly two-thirds of its domestic energy needs, and the rest is generated by fuel (and the fuel's price fluctuates with the price of the market).

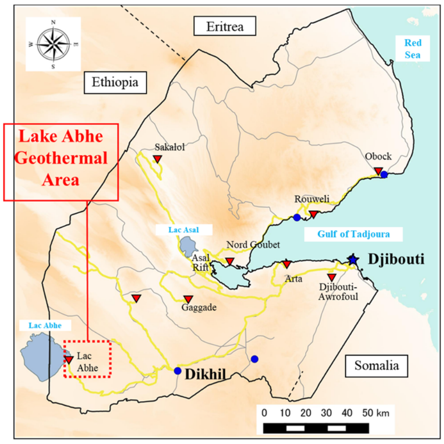

FIGURE 1: Lake Abhe geothermal project zone (JICA, 2014)

Developing geothermal potential is central to achieving the government's goal of relying entirely on clean energy by 2020, a key component of the country's Vision 2035 economic strategy. In response to this preoccupation, a new power plant planned to use steam resources from boreholes is underway. A financing agreement was signed on 27 March 2018 between the Government and the Kuwait Development Fund for 27 million dollars US funds, which will be used to finance a project to build a binary geothermal power plant at Lake Asal with a capacity of 15 Megawatts through 10 geothermal wells). It is well known that Djibouti has a hot arid climate. The variation of the ambient temperature can affect the power output of the plant. The coldest months have the highest net power output. This particular climate makes it necessary to introduce a new way in designing geothermal power plants. The backbone of this paper and my MSc thesis will be how to deal with the hot arid climate in order to improve the efficiency of a binary power plant.

2. RESSOURCE ASSESSMENT

2.1 Climate in Djibouti

Djibouti climate is qualified as hot and arid. There have two seasons in Djibouti, the cold season start from October to April and the hot season from May to September. The mean annual temperature at Djibouti Town is 30°C and occasional temperatures of 48°C have been recorded near Lake Asal (155 m b.s.l.). Total annual precipitation averages 163 mm which is equivalent to 163.5 L/m². The lowest monthly relative humidity is 43% in July and the maximum appear in April and attain 74%. The average annual relative humidity is 63.3%. Humidity is always high at the coast but decreases dramatically in passing inland. Figure 2 summarizes the climate data for one year in Djibouti.

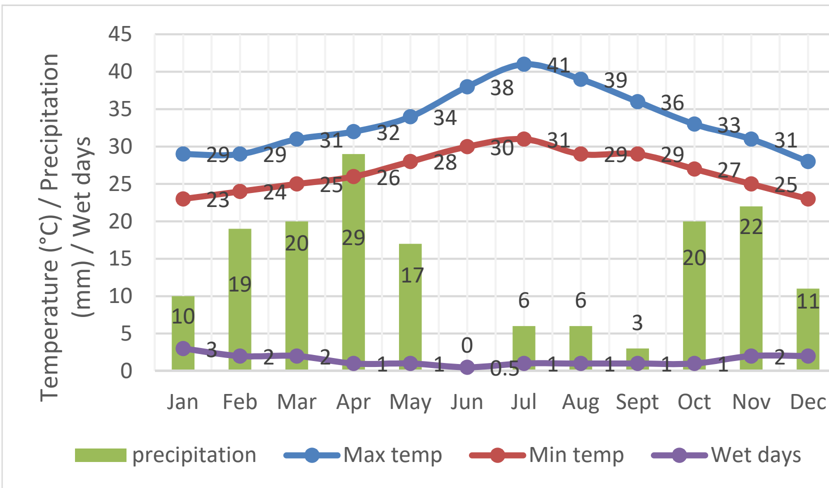

FIGURE 2: Djibouti climate graph (Climatemps, 2018)

The average maximum temperature is shown in July which is 41°C and the average minimum temperature appears in December/January at 23°C. The number of the wet days is less than 20 days over the year as shown in the Figure 2.

2.2 Geological features of Lake Abhe

Lake Abhe geothermal field is well known by the presence of many high chimneys of travertine; the highest one reaches 60 m and has a diameter of about 90 m. At the peak of these chimneys of travertine smoke of fumaroles escapes. Moreover, at their foot, most of the hot springs flow. These travertines were formed several thousands of years ago, before the Lake lost a significant amount of water at which time they were submerged. They result from the mixing of Ca-rich spring waters with saline, carbonate-rich lake water leading to immediate precipitation of calcium carbonate (Pentecost and Viles, 1994). The growth rate of modern travertines reaches a few centimetres per year. The growth of travertines is governed by the chemistry of parental solution and the rate of CO_2 degassing, which control the effective precipitation of calcium carbonates (Gradzinski et al., 2015).

The lake Abhe area is mainly composed of stratoïd basalts with a high plateaus limited by E-W faults configuring the Gobaad plain. Several rhyolitic intrusions-pyroclastics are distributed along the southeastern margin. The area is still in formation due to the ongoing movement of the divergent plate boundary. The travertines are aligned on the main fracture trends. Major west-northwesterly fracture systems are parallel to the graben and horst structures, while minor transversal north-northeasterly trending fractures are also recognized. Surface hydrothermal manifestations are numerous around the lake, a fumarole and rich variety hot springs and many travertine constructions. Geochemical data show that the lake does not recharge the geothermal reservoir. Based on the geochemical and geological data, the reservoir is mainly thought to be recharged from higher altitudes west-northwest of the geothermal field (Figure 3). Recharge may also occur along the WNW-ESE graben faults east of the lake.

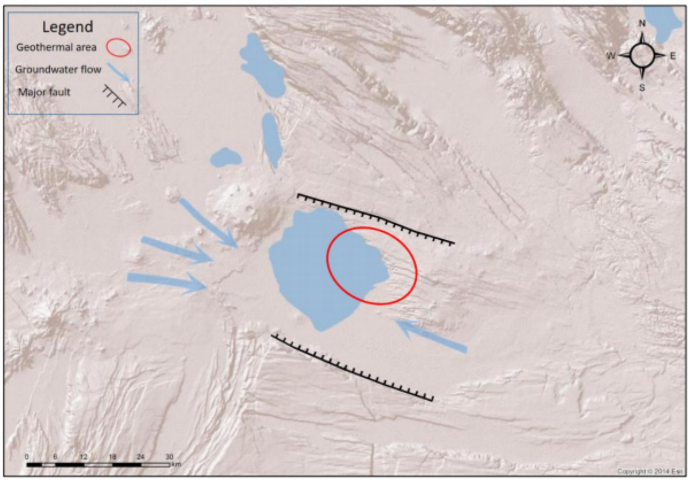

FIGURE 3: Estimated recharge of the geothermal system and the main faults orientation (ODDEG-ISOR, 2016).

2.3 Geochemistry of Lake Abhe

Geochemical study of thermal water from Abhe Lake area was carried out from 1975 to 2014 in order to investigate the origin and sources of solutes and estimate the subsurface reservoir temperature.

- The first geochemistry study done in 1980 by Aquater classified the water from Lake Abhe in two groups. Most of the hot springs are alkaline-chloride-sulphated and few of them present a bicarbonated type as a result of surface water mixing. And geothermometers indicated a temperature in the range of 137-176°C (Aquater, 1981).
- In 2009, CERD undertook surface exploration in Lake Abhe area. The geochemical team with its leader Dr. Houssein collected 21 water samples from cold and hot springs. They concluded that the hot springs in the Lake Abhe area are characterized by Na-Ca-Cl type of water with a temperature of the hot spring varying from 88.8 to 99.7°C. The total dissolved solids of this group ranges from 1700 to 3400 mg/l. The results of the geothermometers show that the reservoir temperature can be reach up to 150ºC (Bouh, 2010).
- In 2014, the CERD carried out another geochemical survey. Chemical (mainly Na/K and SiO2), isotope (bisulphate- and anhydrite- water), and multiple mineral equilibrium approaches were

applied to estimate the reservoir temperature of the hot springs in the Lake Abhe geothermal field. These different geothermometric approaches estimated a temperature range of the deep geothermal reservoir of 120–160°C. In spite of the relatively wide range, the three different approaches led to a same mean of about 135°C (Awaleh et al., 2015).

- Recently, a study done jointly by ODDEG and ISOR indicated a low-enthalpy geothermal system with reservoir temperatures in the range of 110–150°C. The estimated total water flow from the manifestations is around 20-25 L/s (ODDEG-ISOR, 2016).

TABLE 1: Sampling locations, T, pH, EC, TDS and hydro-chemical types of the sampled waters.

N°	Samples		Latitude 00°00′00″	Longitude 00°00′00″	T °C	pH	EC (µS/cm)	TDS (mg/l)	hydrochemical ty[pe]
1	**SHC1**	**Geothermal spring waters**	11°08′53.2″	041°52′51.9″	94.5	8.22	5495	3488	Na – Cl
2	**SHC2**		11°08′41.4″	041°52′54.1″	98.1	8.34	5576	3482	Na – Cl
3	**SHC3**		11°08′50.9″	041°52′52.8″	98.5	8.49	5610	3503	Na – Cl
4	**SHC4**		11°08′53.0″	041°52′50.2″	82.2	7.61	5866	3747	Na – Cl
5	**SHC5**		11°08′54.7″	041°52′44.9″	98.8	8.33	5332	3466	Na – Cl
6	**SHC6**		11°08′54.7″	041°52′44.7″	98.1	7.97	5409	3795	Na – Cl
7	**SHC7**		11°08′54.6″	041°52′44.4″	97.1	8.06	5411	3511	Na – Cl
8	**GHC1**		11°06′49.6″	041°52′30.1″	92.1	8.6	3224	2129	Na – Cl
9	**GHC2**		11°06′49.8″	041°52′13.2″	71	8.62	3191	1958	Na – Cl
10	**GHC3**		11°06′46.5″	041°52′12.7″	86	8.52	3192	2236	Na – Cl
11	**GHC4**		11°06′46.7″	041°52′11.9″	99.7	8.69	3124	2072	Na – Cl
12	**GHC5**		11°06′47.1″	041°52′10.6″	84.2	8.72	3138	2023	Na – Cl
13	**GHC6**		11°06′48.6″	041°52′09.5″	92.5	8.62	3105	2016	Na – Cl
14	**GHC7**		11°06′48.6″	041°52′09.6″	82.4	8.79	3124	1918	Na – Cl
15	**GHC8**		11°06′49.6″	041°52′10.0″	93	8.69	3095	2037	Na – Cl
16	**GHC9**		11°06′50.6″	041°52′39.0″	76.6	8.11	3314	2089	Na – Cl
17	**Lake Abhe**	**Lake water**	11°09′52.2″	041°53′24.2″	29	9.86	96084	92622	Na – Cl – HCO_3 – S

Temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), sampling locations, and hydro-chemical types of all water samples are listed in Table 1. This table is modified from (Awaleh et al., 2015). The temperatures of the geothermal water samples at Lake Abhe geothermal field ranged from 71 to 99.7 °C (Table 1). Geothermal waters are moderately alkaline (pH = 7.61–8.79) with TDS values of 1918–3795 mg/L. The geothermal waters contain Cl− and Na+ as the predominant anion and cation.

2.4 2D model and drilling target

The geothermal system in Lake Abhe is presumably fracture dominated with near vertical conductive fractures. Based on results from various geoscientific disciplines (Figure 4), it can be concluded that the hydrothermal fluids flow from the Ethiopian side (below the lake). The existence of the volcano Dama Ale and presence of the surface activities at the other side of the lake are consistent with ODDEG-ISOR hypothesis, and a possible magma body below the volcano may act as the heat source for the surface activity east of Lake Abhé (ODDEG-ISOR, 2016). The conductive zones are between 900 and up to 1500 m thick before showing higher resistivity. The major normal faults in the area are also thought to facilitate fair permeability. Based on this, future wells should be drilled to more than 1 000 m depth and targeting one of the major faults in the area (Khaireh et al., 2016).

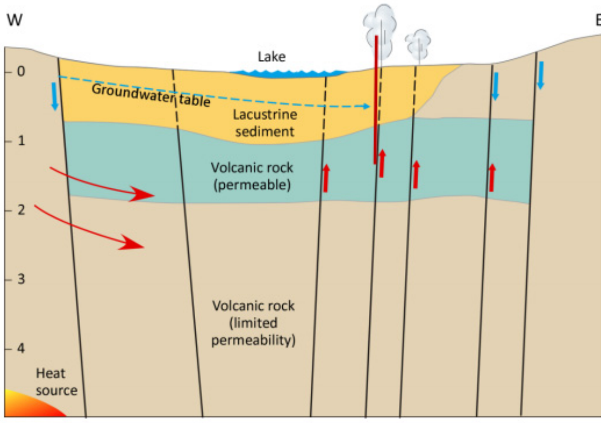

FIGURE 4: Geologic cross-section; a well drilled to more than 1000 m depth, intersecting one of the main permeable faults in the system is shown as a red vertical line on the cross section (ODDEG-ISOR, 2016).

2.5 Volumetric assessment

The uncertainty of reservoir parameters requires that they be estimated. For this reason, a Monte Carlo simulation was carried out. The Monte Carlo simulation program is embedded in MS Excel spreadsheet. Belonging to Reykjavik University. The simulation allows the input parameters to vary from a range of possible minimum to maximum values. Only, rock specific heat, average reservoir depth, rejection temperature, plant capacity factor and project lifetime have to be fixed (see Table 2). The values within the range are calculated at a random according to a beta or even probability distribution function. To obtain a good representation of the distribution, sampling is done through 2000 iterations with continuous calculation.

TABLE 2: Volumetric assessment parameters and their probability distribution for Lake Abhe

Parameter	Unit	Minimum	Most likely	Maximum	Distribution
Reservoir Area (A)	km²	70.0	75.0	88.0	Beta
Reservoir Thickness (H)	m	800	1000	1200	Beta
Reservoir Temperature (T)	°C	110	150	176	Beta
Recovery Factor (R)	%	5%	10%	20%	Beta
Utilization Factor (u)	%	35%	40%	45%	Beta
Porosity (fi)	%	5%		20%	Even
Specific Heat of Rock (CR)	kJ/m³/°C		950		Fixed
Average Reservoir Depth (D)	m		1500		Fixed
Rejection Temperature (Ta)	°C		90		Fixed
Plant Capacity Factor (F)	%		95%		Fixed
Project Lifetime	years		30		Fixed

2.5.2 Results of the volumetric method

The distributed frequency and the potential electrical power for Lake Abhe are shown in Figure 5. The results of the simulation show that the Lake Abhe reservoir has a most likely potential between 12.8 and 16.1 MWe for 30 years. The cumulative frequency distribution indicates that the most likely value for the reserve is 14.45 MWe. The cumulative frequency graph also illustrates that there is less than a 10% chance that the reserve will be above 33.9 MWe. On the other hand, there is a 90% chance that the reserve will yield 9 MWe. According to Monte Carlo volumetric resource assessment, the most probable range of generation is between 12,8 to 16,1 MWe. The total energy output of the power plant will the most likely power set after calculation by the previous method at 14,45 MWe (Table 3).

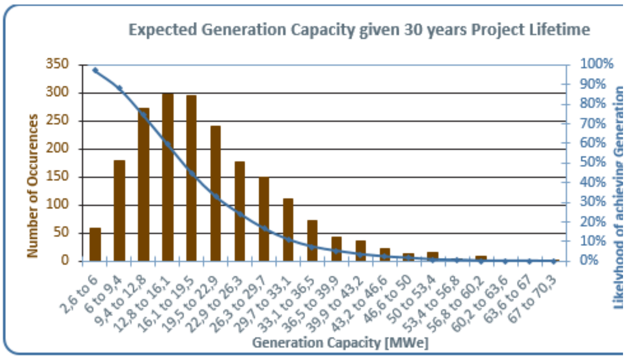

FIGURE 5: Frequency and cumulative frequency distributions for the reserve estimate of the Lake Abhe geothermal field

TABLE 3: The results of the thermal power estimation for the Lake Abhe reservoir by Monte Carlo volumetric assessment

Capacity (MWe)		
90%	**Most probable**	**10%**
8.8	14.45	33.9

Theoretically, the maximum amount of energy, which can be extracted from the reservoir is given by the energy balance equation (Çengel & Boles, 2015):

$$W = \dot{m} C_P (T_{Geo} - T_{Ret}) \eta \quad (1)$$

where $\dot{m}$ is the geothermal brine mass flow from the reservoir, C_P is the specific heat capacity of water, T_{Geo} is the temperature of the resource at extraction, and T_{Ret} is the rejection temperature and ε is thermal efficiency of binary unit (Binary cycle power plants have a thermal efficiency of 10-13%).

Deducted total mass flow of the wells is 443 kg/s to produce approximately 14.5 MWe. According to the study done by International Finance Corporation, member of World Bank Group, in June 2013 (IFC, 2013), the average capacity of 1087 geothermal wells is calculated to be 3 MWe. Hence, the deduced number of wells needed in Lake Abhe is 5 for a 14.45 MWe electricity production.

4. RESULTS

Solar and geothermal energy resources are of particular interest in Djibouti for hybridization due to their wide availability and enormous reserves. With its geographical position and generally clear skies, Djibouti benefits from an important solar energy resource. The annual duration of bright sunshine is 3240 hours and global solar average irradiation of 6.5 (kWh/m²/day) (Ahmed Aye, 2009). Binary power plant is chosen for the geothermal production, since that fits best with the medium-temperature range available and as it has a small scale of emission. The main environmental problems concerned are the release of gases and the disposal of some geothermal fluids (National Geographic, 2016). The location of the binary power plant is already decided, incl. five production wells and two reinjection wells. The geothermal power plant will work on ORC (Organic Rankine Cycle), using R245fa as a working fluid.

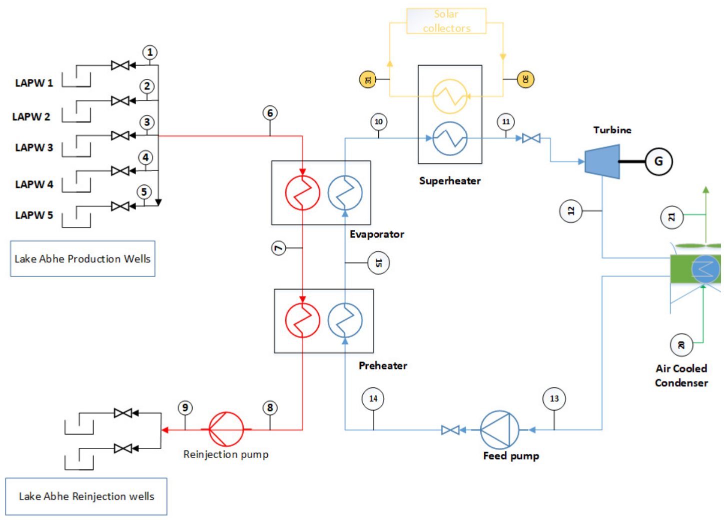

FIGURE 6: Process flow diagram

Overall power plant process flow diagram is shown in Figure 6. The process commences at the five productions wells LAPW1-LAPW5. Geothermal fluid exits the wells at conditions described by states 1 to 5, respectively. The fluid passes through the wellhead valves that are used to regulate mass flow and pressure if needed. After that, the five flows are collected to the common pipe reaching the same pressure and temperature (State 6). The geothermal brine enters the system through two stages in the heat exchanger, the first stage is the evaporator and the second is the preheater. The geothermal fluid cycle (red in Figure 6) and the working fluid cycle (blue in Figure 6) are separated, so only the heat transfer takes place through the heat exchangers. The preheater is a heat exchanger that heats the working fluid before it enters the evaporator. Heat is added to evaporate the working fluid to its saturated vapour state (State 10) in the evaporator. Saturated vapour is then transported through the valve, enters the turbine and expands to reach the set exhaust pressure. At State 12, the working fluid passes through the air-cooled condenser ACC and rejects the thermal energy to the open air cooling cycle (States 20-21) fed by the fans. Organic working fluid leaves the condenser at slightly sub-cooled state and passes through the feed pump (processes 13-14). The working fluid reaches its original vaporization pressure as it enters the heat exchangers, and the cycle restarts.

Results of the basic model of the binary power plant with an air cooled condenser and hybrid modelling are presented in Table 4. With a geothermal fluid mass flow of 443 kg/s and temperature of 145.7°C. The air cooled condenser binary model produces 11 706 kWe of gross power output with an auxiliary power of 24.5% of the total gross output power that the fan power represents 58.5% of the latter. The cycle efficiency is 12%. For the hybrid solar and geothermal power plant, the same conditions are set. The net power output is 14 778 kWe where 23% go for the use of the auxiliary components. With 0.11 as cycle efficiency, the hybrid specific power output is higher than of the basic one and it equals 25.69 kW/(kg/s).

TABLE 4: Results of the different scenarios

Parameters	Value for basic model ACC	Hybrid solar-geothermal	Units
Gross power output	11706	14778	kWe
Net power output	8805	11382	kWe
Auxiliary power	2902	3396	kWe
% of Auxiliary to Gross power	24.8	23	%
Power fan	1698	2193	kWe
% fan in Auxiliary	58.5	64.6	%
Efficiency	0.12	0.11	[-]
Specific Power Output (SPO)	19.87	25.69	kW/(kg/s)
Geothermal fluid flowrate	443	443	Kg/s
ORC WF mass flow (R245fa)	466.3	466.3	Kg/s
Solar WF mass flow (Benzene)	[-]	445.9	Kg/s

Figure 7 depicts the net power output of the hybrid solar –geothermal and binary power plant with an air cooled condenser in function for the ambient temperature ranging from 20 to 37°C. Both curves have the same trend with a gap between both which is reduced when the ambient temperature increases. The temperature at the condenser is kept fixed at 46°C. The hybrid doesn't solve the problem that the plant has with working over twelve months of the year dealing with the variation of the temperature.

5. CONCLUSIONS

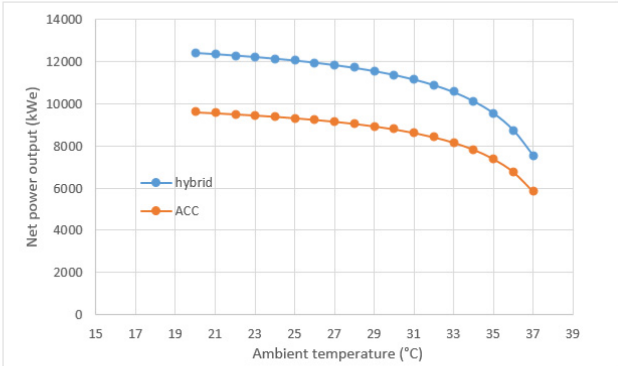

FIGURE 7: Comparison of the net power of the hybrid and ACC models.

The work presented in this report contributes to the modelling of a geothermal binary power plant in a hot and arid climate. Djibouti is classified as hydric stress water country and the water cooling system need a huge quantity of this white gold. Dry cooling system is best suited for areas where there is water stress or where strict water regulations prevail. The best fitted system is the hybrid solar-geothermal power plant which outperforms by 26.24% the basic binary plant. However, the major problem faced is the adverse effects of diurnal temperature change on the operation of air-cooled condensers which typically leads to fluctuations in the power output and degradation of thermal efficiency due to lack of detailed meteorological data.

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