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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

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ABSTRACT

With a total area of 23,200 km^2, the Republic of Djibouti is located in East horn of Africa. It is bordered by Ethiopia in the west and south, Eretria in the north, and Somalia in the southeast. Unique in terms of geodynamics activity, it is situated at the only modern example of continental rifting at an active triple-junction, where two oceanic ridges, Gulf of Aden and Red Sea, meet with East African Rift. 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. One of them, Lake Abhe geothermal field was recently the subject of a complete surface exploration. This is conducted by the scientists of ODDEG and ISOR conjointly with a co-financing of ICEIDA. The objective of this paper is to determine how the medium enthalpy resource in Lake Abhe geothermal field would be best utilized, both technically and commercially. Djibouti possess several medium enthalpy resources for different part of the country and it is situated in a hot arid zone. The backbone of this paper will be how to deal with the hot, arid climate in order to maximize the net power output of the plant. A thermodynamic model was developed using Engineering Equation Solver (EES) to evaluate the performance of ORC geothermal power plants standalone with different cooling system, and an ORC assisted by a parabolic trough solar concentrating collector field. The ACC and hybrid solar-geothermal designs were selected and the NPV and IRR of these designs was modelled to allow an economic comparison. This study estimates a geothermal fluid mass flow of 443 kg/s and temperature of 145.7°C. Under Djiboutian climatic conditions with an average ambient temperature of 30.04°C, the air-cooled condenser basic binary model produces 10924 kWe of gross power output with an auxiliary power consumption of 22.6% of the total gross output power. The fan power represents 51.8% of the parasitic power. For the hybrid solar-geothermal power plant, the net power output is 13865 kWe with 20.6% for the use of the auxiliary components. The hybrid system shows higher power output (up to 21.24% difference) compared to ACC. This study finds the hybrid system to be a better option than individual geothermal system at all ambient temperatures. It is demonstrated that the hybrid is most economically attractive scenario, providing the highest NPV and the fastest payback period of 18 years with the highest IRR of 13%.

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, Eretria 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 East African Rift (Tazieff, Varet, Barberi, & Giglia, 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 potentials are believed to reach the amount of about 1000 MWe from approximately of 22 locations.

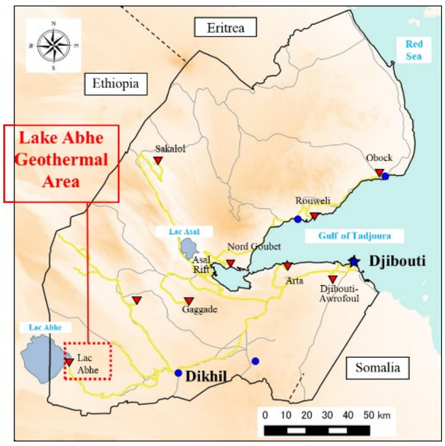

Figure 1: Lake Abhe geothermal Project zone (source: JICA, 2014)

One of promising site, Lake Abhe geothermal field was recently the subject of a complete surface exploration (see figure 1). This is conducted by the scientists of ODDEG and ISOR conjointly with a co-financing of ICEIDA. The electricity in Djibouti is one of the more expensive prices per kWh in Africa. 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).

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 by using the steam resources from the wells are underway (a financing agreement was signed on 27 March 2018 between the Government of Djibouti and the Kuwait Development Fund, 27 million dollars US will be used to finance a project to build a binary geothermal power plant at Lake Asal from a capacity of 15 Megawatts through 10 geothermal wells). As known Djibouti is situated in a hot arid zone. The variation of the ambient temperature affects the power output of the plant. The coldest months have the highest net power output. This particular climate force us a new way to remodel the common geothermal power plant.

The objective here is to determine how the medium-enthalpy resource in Lake Abhe geothermal field would be best utilized The backbone of the paper will be how to deal with the hot arid climate in order to improve the efficiency of the binary Power plant. The selection of the working fluid will be evaluated; the suitable working fluids should be taken in the consideration on the system performance analysis with a screening criteria based on the maximum net power output, thermal efficiency and specific power output SPO. Finally, economic analysis will be performed in order to assess the cost of developing the binary power plant in Lake Abhe geothermal field according of the best two scenarios.

2. RESOURCE 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 (155m bsl). Total annual precipitation averages 163 mm which is equivalent to 163.5 Litres/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. The figure 2 summarize the climate data for one year in Djibouti. 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.

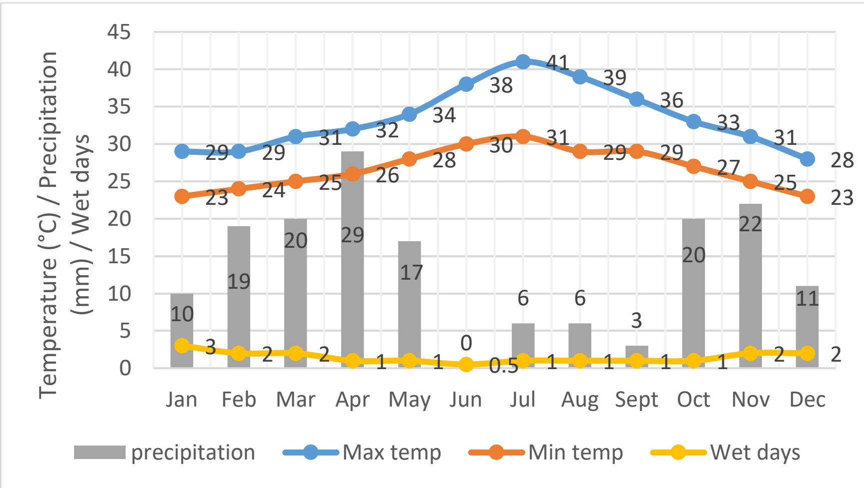

Figure 2: Djibouti climate graph

2.2 Geological Features of Lake Abhe

Lake Abhe zone is well known by the presence of a lot high chimneys of travertine; the highest one reaches 60 meters high and has a diameter of about 90 m. The peak of these chimneys of travertines escapes the smoke of fumaroles. Moreover, to them foots flow most of the hot springs. These travertines were formed several thousands of years before the Lake lose a significant water and they were immerged. These result from the mixing of Ca-rich spring waters with saline, carbonate-rich lake water leading to immediate precipitation of calcium carbonate (Pentecost & Viles, 1994). The growth rate of modern travertines reaches a few centimeters per year. The growth of travertines is governed by chemistry of parental solution and the rate of CO2 degassing, which decide upon effective precipitation of calcium carbonates (Gradzinski, Wrobblewski, & Bella, 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 WNW fracture systems are parallel to graben and horst structures, while minor transversal NNE trend 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 WNW of the geothermal field (Figure 3). Recharge may also occur along the WNW-ESE graben faults east of the lake.

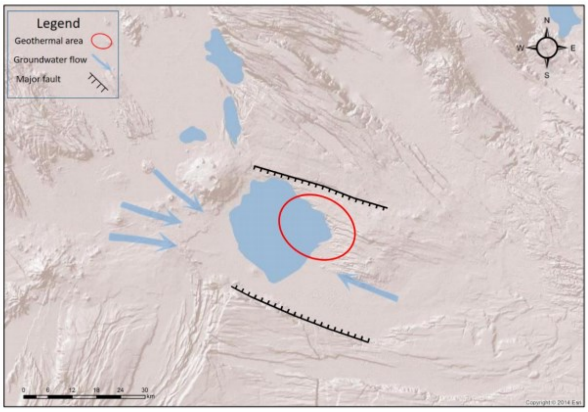

Figure 3: Estimated recharge of the geothermal system and the main faults orientation (ODDEG-ISOR, 2016).

2.3 Geochemistry of Lake Abhe

Geochemical study of thermal water from Abhe Lake area is 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 the geothermometer indicated a temperature in the range of 137°C and 176°C (Aquater, 1981).
- The CERD undertaken in 2009 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 from the Lake Abhe area are characterized by Na-Ca-Cl type of water with a temperature of the hot spring varies from 88,8 to 99,7°C. The total dissolved solids of this group range from 1700 to 3400 mg/l. The result of the geothermometer shows that the reservoir temperature can be reach up to 150 ºC (Bouh, 2010).
- In 2014, the CERD redid another geochemical survey. Chemical (mainly Na/K and SiO2), isotope (bisulfate- 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, Hoch, Boschetti, Soubaneh, & Egueh, 2015).
- Recently the study done by ODDEG and ISOR jointly indicate a low enthalpy geothermal system with reservoir within a range of 110–150° C. The estimated total water flow from the manifestations is around 20-25 L/s (ODDEG-ISOR, 2016).

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, Hoch, Boschetti, Soubaneh, & Egueh, 2015). The temperatures of the geothermal water samples at Lake Abhe geothermal field ranged from 71 to 99.7 °C (Table 3). 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.

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 types
1	**SHC1**		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**	**Geothermal spring waters**	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 – SO_4

2.4 Drilling Target and 2D Model

The geothermal system in Lake Abhe is presumably fracture dominated with near vertical conductive fractures. Based on results from various geoscientific disciplines, 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 surfaces 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 go from 900 m up to 1500 meters 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, Moussa, & Magareh, 2016).

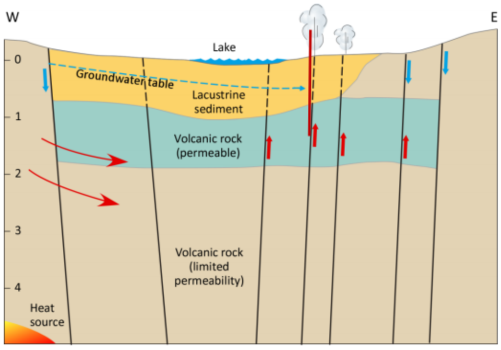

Figure 4: Cross section. A well drilled to more than 1000 m depth, intersecting one of the main permeable fault in the system is shown as a red vertical line on the cross section (ODDEG-ISOR, 2016).

2.5 Volumetric Assessment

The uncertainty of reservoir parameters requires that they be estimated. For this reason, a Monte Carlo simulation is carried out. The Monte Carlo Simulation program is embedded in MS Excel spreadsheet. This spreadsheet for volumetric reserves estimation belongs to the Reykjavik University. The simulation allows the inputs parameters to vary from a range of possible minimum to maximum values. Rock specific heat, average reservoir depth, rejection temperature, plant capacity factor and project lifetime have been only fixed. The values within the range are calculated at 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 Volumetric Method

The distributed frequency and the potential electrical power for Lake Abhe are shown in Figure 3. 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.

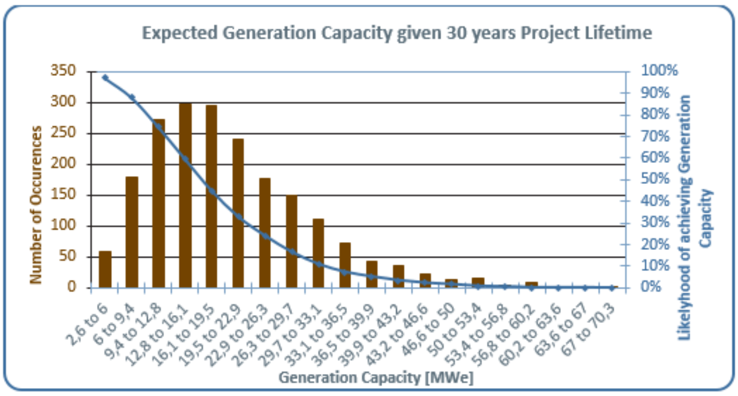

Figure 5: Frequency and cumulative frequency distributions for the reserve estimate of the Lake Abhe geothermal field.

The results of the simulation show that the Lake Abhe reservoir has 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: The results of the thermal power estimation for the Lake Abhe reservoir by the Monte Carlo volumetric assessment

Capacity (MW)		
90%	Most Probable	10%
8.8	**14.45**	33.9

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

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

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 MW_e. According the study done by International Finance Corporation, member of World bank Group, in June 2013 (IFC, 2013), the average capacity of 1087 wells is 3 MWe. The deducted number of wells is 5 with a 14,45 MWe electricity production.

3. TECHNICAL ANALYSIS

3.1 Scaling consideration

The silica mineral deposition from geothermal brine within steam-field and generating equipment is a common problem in geothermal power production. During the flash process to generate additional steam from the geothermal fluid, an increase in the silica concentration of the remaining fluid (brine) appear. This silica can build up a layer of solid deposit on the internal surfaces of pipelines, flash plants and turbines, impeding the flow of the fluid and leading to a drop in conversion efficiency and high maintenance cost.

In a binary system, the geothermal fluid cools down by passing through the heat exchangers. Thereby, silica is inclined to precipitate and form a scale on the inside of the pipes. This is a basic mechanism by which scale might form in any heat exchanger. The scale that forms by this process in the heat exchangers at Wairakei is remarkable in its extreme roughness (Woodhurst, 2011).

Hence, there are two major operational impacts of this scaling process; it imposes the need for frequent cleanings of the heat exchanger tube system and - because of the decrease in flow through the system - it decreases the amount of power that can be generated (Woodhurst, 2011).

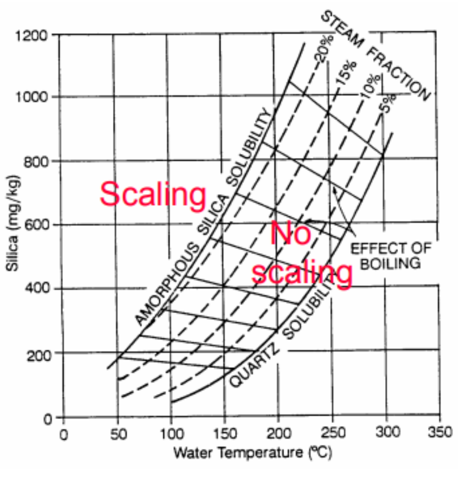

Figure 6: Solubility of silica in water (Gunnlaugsson, Armanson, Thorhalsson, & Steingrimsson, 2014).

According to (Gunnlaugsson, Armanson, Thorhalsson, & Steingrimsson, 2014) a silica "rule of thumb" may say that it is only possible to cool the geothermal water by some 100°C without the risk of scaling for any given geothermal reservoir temperature. The geothermometer indicates a reservoir temperature of 176°C in LAGF. The reinjection temperature should be above of 76°C. The best choice is not be too close to this limit of scaling potential temperature. In that consideration, the reinjection temperature in our case is set at 90°C.

3.2 Working fluid selection

Many papers have treated the choice of the working fluids using simulations of the thermodynamic models. A review of the scientific literature in the field of working fluid selection was proposed by the authors in (Quoilin, Declaye, Tchanche, & Lemort, 2011). Despite the multiplicity of the working fluid studies, no single fluid has been identified as optimal for the ORC. The performance of a binary-cycle geothermal power plant obviously depends upon the thermodynamic properties of the secondary working fluid used in the binary circuit. The working fluid must be carefully selected based on the thermodynamic specifications, safety, environmental and economy aspects (DiPippo, 2008).

In our case, the pre-screening criteria is based on well-known fluids that are used in the operating ORC plants or that has been studied on the literature. Hydrocarbons such as pentanes or butanes and refrigerants such as R245fa are good candidates for moderate and low temperatures typically lower than 200 °C (Quoilin, Declaye, Tchanche, & Lemort, 2011).

The final selection of working fluid candidates is described in Table 4; where their relevant thermodynamic properties is shown and pure water is included for comparison. These include flammability, ozone depletion potential (ODP) and global warming potential (GWP). The GWP is considered to be relative to the amount of heat that can be trapped by similar mass of carbon dioxide as the working fluid being analyzed (DiPippo, 2008). All of the candidate fluids have critical temperatures and pressures far lower than water. The suitable working fluids should be taken in the consideration on the system performance analysis. The screening criteria are maximum net power output, thermal efficiency and specific power output SPO.

Table 4: List of considered working fluids

Fluids	Critical temperature (°C)	Critical pressure (bar)	Flammability	ODP	GWP	Molecular weight (g/mol)
R245fa	154.1	36.51	Non-flammable	0	950	134
Isobutane	134.7	36.4	Very high	0	3	58.12
Isobutene	144.9	40.1	Very high	0	3	56.11
Isopentane	187.2	33.7	Very high	0	3	72.15
N-pentane	196.5	33.64	Very high	0	3	72.15
Toluene	318.6	41.26	Very high	0		92.14
Water	374	220.6	Non-flammable	0	-	18.02

In the present case of the ORC, the thermodynamic optimization aims at maximizing the net power output. This is equivalent to maximizing the overall efficiency since the flow rate and the temperature of the heat source are fixed. This analysis was conducted for each candidate working fluid in order to define maximum net power output, thermal efficiency and SPO of the ORC as well as the optimum evaporation temperature. The results of this optimization are presented in Table 5. Isobutane is the fluid showing the highest overall efficiency, followed by Isobutene and R245fa. These two hydrocarbons have the maximum parasite load. The evaporating temperature of the latter are close to their critical point. It is therefore obvious that these two fluids are not suitable for the present heat source temperature. R245fa has the maximum power output and specific power output (SPO). R245fa is best fit to our model.

Table 5: Performance of the different working fluids

Fluids	T of HX (°C) (at State 10)	Efficiency [%]	Net power (kWe)	SPO (kWe/ (kg/s))	Parasite load (kWe)
Isopentane	107.7	11.81	7740	17.54	4619
Isobutane	118.7	13.01	7908	17.85	5702
N-pentane	106.4	11.71	7711	17.41	4536
R245fa	111.5	12.28	7979	18.01	4873
Toluene	98.05	11.49	7735	17.46	4286
Isobutene	112	12.64	7952	17.95	5276

3.3 Air Cooled Condenser

Implementation of an air-cooled binary geothermal power plant in southern Djibouti is studied. The current performance of the plant is analysed with an emphasis on the effects of seasonal climate changes. The table 6 summarizes the common boundary of the basic binary plant with air-cooled condenser simulation.

Table 6: Common boundary conditions for the models

Parameters	Value	Units
Working fluid	R245fa	
Geothermal fluid temperature	145.7	°C
Average temperature of LAGF	30.04	°C
Geothermal fluid pressure	5	bar
Geothermal fluid flowrate	443	Kg/s
ΔPfan	150	Pa
Fan Efficiency	70	%
Motor efficiency	95	%
Turbine efficiency	85	%
Generator efficiency	98	%
Preheater heat transfer coefficient	1000	$W/m^2.°C$
Evaporator heat transfer coefficient	1600	$W/m^2.°C$
Condenser heat transfer coefficient	800	$W/m^2.°C$

Dry cooled binary plants highly depend on local ambient temperature hence subjected to efficiency fluctuations as the temperature changes both daily and seasonal. On a hot summer day, production can drop down to 50% because of insufficient cooling (Verkis Consulting Engineers, 2014). When this type of cooling system is preferred, the fluctuations in ambient temperature need to be considered.

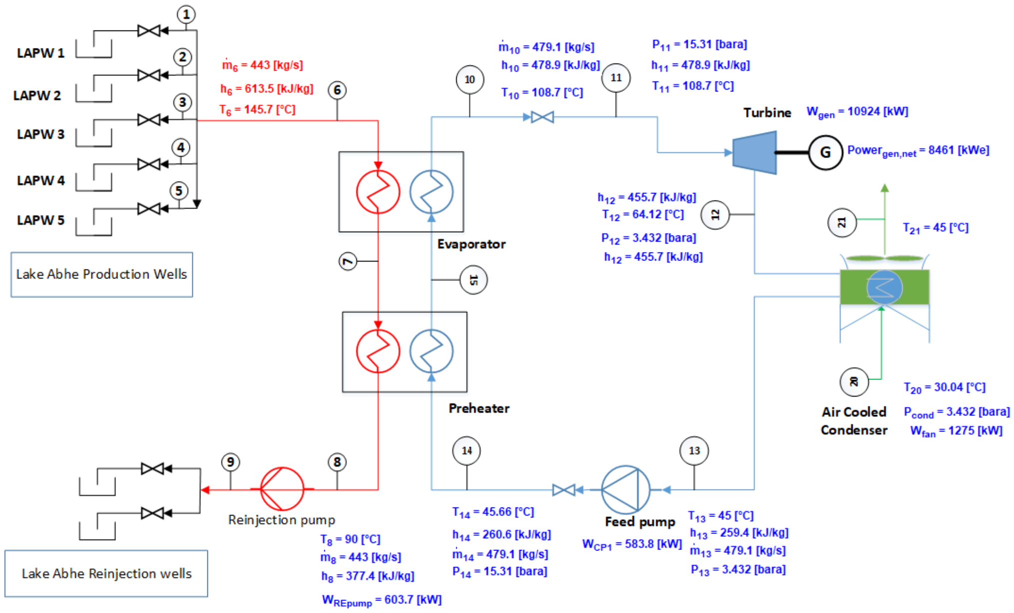

Figure 7: Schematic of the power plant with ACC

Dry cooling system is best suitable for areas where there is water stress or where strict water regulations prevail. However, the major problem faced by many standalone geothermal power plants, particularly in hot and arid climates such as Djibouti, is the adverse effects of temperature change on the operation of air-cooled condensers, which typically leads to fluctuation in the power output, and degradation of thermal efficiency. In the summer, the production drops down to 42% because of insufficient cooling.

3.4 Solar-geothermal hybrid

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 (ISERST, 1984). Djibouti is among the countries with a very high annual sunshine rate, citing France as its comparison, its sunstroke rate is between 1750 and 2750 hours depending on the region (Aye, 2011).

Table 7: Average annual irradiation of Djibouti's districts (KWh /m²/day)

Districts	Ali-Sabieh	Dikhil	Djibouti-ville	Obock	Tadjourah	Moyenne
KWh/m²/an	2219,6	2380,9	2330,3	2268,6	2078,5	2255,6

Table 8: Average monthly daily sunshine duration

Months	Jan	Fev	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sunshine (Hours/day)	8	7.5	8.5	9	10	9.5	8.5	9	9.5	9.5	9.5	8.5

In Djibouti, the sun could provide daily more than 45 times the annual electricity needs of the country, taking into account the current technology that can recover only 13% of this energy. The country has an area of 23,200Km², the energy received daily is then 142680GWh (E=6,15 (kWh/m²/day)*2.32.10[10] (m²)=142680 GWh). The average daily sunshine duration is around 8 hours.

3.4.1 Technical analysis of the hybrid Solar-Geothermal plant

The hybrid plant consists of two parts. The first part is a geothermal ORC power cycle configured in a binary arrangement. The second is composed of a solar heating system comprising a superheater, a solar pump, and solar collectors. The figure 8 describes the hybrid plant combined the geothermal and solar plant together. As described in the paragraph 1.3, the solar heating system is installed between evaporator and the turbine. Before the ORC working fluid enter the turbine, it passes through the solar superheater unit where its temperature is further increased by the solar energy. The heat is then converted into mechanical work and ultimately electricity as the working fluid expands in the turbine unit. The air-cooled condenser (ACC) condenses the working fluid from the turbine and then a new cycle begins again. The total heat input to the hybrid solar–geothermal power plant (Qtot) was defined as the sum of the solar heat input (Q_{solar}) and the geothermal heat input (Q_{geo}).

$$Q_{tot} = Q_{geo} + Q_{solar} = m_6 \times (h_6 - h_8) + A_{solar} \times DNI \qquad 2$$

where A_{solar} is the solar aperture area, DNI is the effective solar irradiance for the solar collectors (i.e. solar direct normal irradiance).

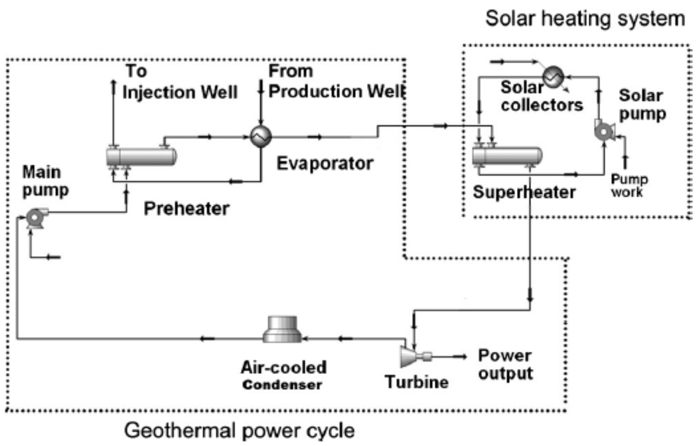

Figure 88: Schematic diagram of the hybrid solar–geothermal power plant (Zhou, Doroodchi, & Moghtaderi, 2013).

The heat losses in the solar field largely depend on the heat loss behaviour of the Heat Collection Elements (HCEs) within the solar collectors. (Zhou, Doroodchi, & Moghtaderi, 2013) developed a general correlation by performing a polynomial regression of all the existing data reported in the literature on HCEs heat losses of low to high efficiency solar collectors. This correlation provides the average HCEs heat loss as a function of the temperature gradient between the ambient temperature and the solar heat transfer fluid temperature, ΔT:

$$Q_{loss} = -0.04162 \times \Delta T + 0.00448 \times \Delta T^2 - 1.43426 \times 10^{-5} \times \Delta T^3 + 2.32022 \times 10^{-8} \times \Delta T^4 \qquad (3)$$

Other types of parasitic penalties in the solar field were also considered, including solar piping heat losses ($Q_{loss,piping}$), power consumption of the solar pump ($W_{pump,solar}$), and the power required to drive the collectors and electronics (W_{drive}).

$$Q_{loss,piping} = 0.01693 \times \Delta T - 1.683 \times 10^{-4} \times \Delta T^2 + 6.78 \times 10^{-7} \times \Delta T^3 \qquad (4)$$

$$Q_{pump,solar} = 1.052 \times 10^{-5} MWe/m^2 \qquad (5)$$

$$Q_{drive} = 2.66 \times 10^{-7} MWe/m^2 \qquad (6)$$

The chosen solar heat transfer fluid in our case is Benzene with a critical temperature and pressure of 288.9°C and 48.94°C respectively. The ambient temperature range is 23-41°C as reported in the table 1. The nominal DNI is assumed to be 1000W/m².

3.5 Results and Discussions

Results of the basic model of the binary power plant with an air-cooled condenser and hybrid modelling are presented in Table 9. With a geothermal fluid mass flow of 443 kg/s and temperature of 145.7°C. The air-cooled condenser binary model produces 10924 kWe of gross power output with an auxiliary power of 22.6% of the total gross output power that the fan power represents 51.8% of the latter. The cycle efficiency is 10.44%. For the hybrid solar and geothermal power plant, the same conditions are set. The power output is 13865 kWe where 20.6% go for the use of the auxiliary components. With 10.18 as cycle efficiency, the hybrid specific power output is 12.13 kW/(kg/s).

Table 9 : Results of the different scenarios

Parameters	Value for basic model	Hybrid solar-geothermal	Units
	ACC		
Gross power output	10924	13865	kWe
Net power output	8461	11014	kWe
Auxiliary power	2463	2851	kWe
% of Auxiliary to Gross power	22.6	20.6	%
Power fan	1275	1663	kWe
% fan in Auxiliary	51.8	58.3	%
Efficiency	10.44	10.18	%
Specific Power Output (SPO)	19.1	12.13	kW/(kg/s)
Geothermal fluid flowrate	443	443	Kg/s
ORC WF mass flow (R245fa)	479.1	479.1	Kg/s
Solar WF mass flow (Benzene)	[-]	465.3	Kg/s

The figure 9 depicts the net power output of the hybrid solar –geothermal and binary power plant with an air cooled condenser in function of the ambient temperature ranging from 20°C to 37°C. The both curves have the same trend with a gap between the both which is reduced when the ambient temperature increases. The temperature at the condenser is kept fix to 50°C. The ambient temperature is set at 30.04°C that represents the average temperature in Djibouti.

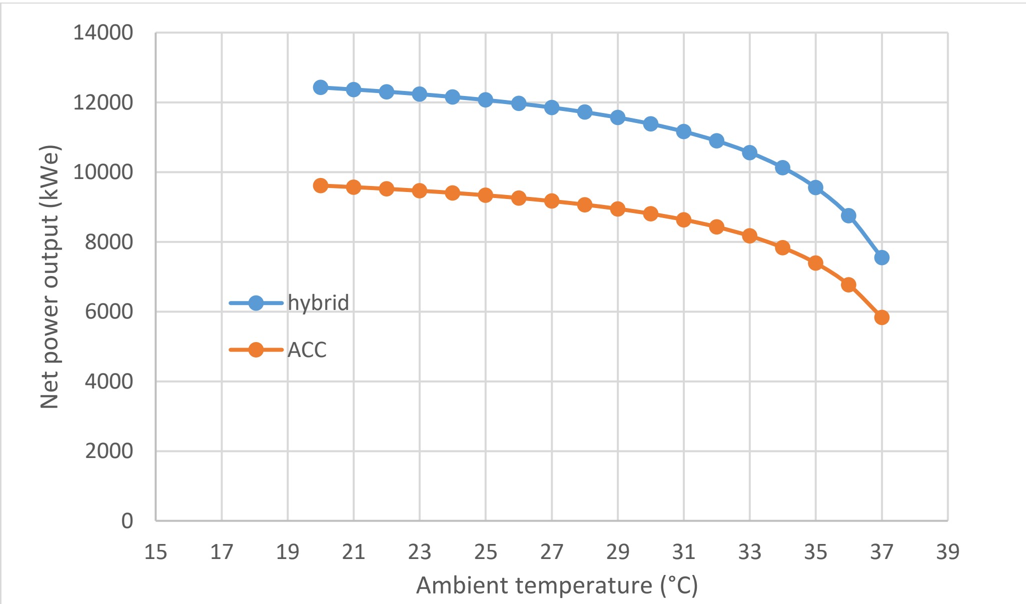

Figure 9: Comparison of the net power of the hybrid and ACC models.

4. ECONOMIC ANALYSIS

The thermodynamic analysis on its own is not sufficient to determine the viability and implementation of a particular technology. Economic consideration plays a very important role in the decision making process that govern the design of a system. Economic analysis will be performing in this section in order to assess the cost of developing the binary power plant in Lake Abhe geothermal field according of two scenarios. The scenario one is the binary power plant with air cooled condenser (ACC) and the second scenario is the concentrated solar power (CSP) combine by geothermal binary plant with ACC. The costs consist of the capital cost, operation and maintenance costs and the financial cost. The table 10 summarizes the main parameter for economic analysis.

Table 10: Main parameters for economic analysis

	Scenario 1 Binary geothermal plant	Scenario 2 Hybrid solar-geothermal
Net power output	8461 kW	9406 kW
Capacity factor	95%	95%
Cost development field	US$ 28 million	US $34,556,161
Cost of the plant	US $44,615,035	US$ 45,115,035
O&M	US $0.025/kWh	US $0.025/kWh
Equity	30%	30%
Selling price of electricity	13 cents USD	13 cents USD
Interest rate	6%	6%
Loan duration	15 years	15 years

In our case, the hybrid doesn't possess a thermal energy storage that means the CSP can add its thermal energy to the system only 8.9 hours according to the table 10. It is equivalent to 37% of a day. The plant produces a daily the sum of 37% of 11014 kW and 63%of 8461kW which means 9406 kW.

4.1 Results and discussions

The return of investment and the profit achieved are among the important indicators of the success of an engineering enterprise (Bandoro & Palson, 2010). It is estimated that annual energy production is 70.412 GWh with 1% of degradation, and by assuming that electricity costs procured by the project are US $0.013/kWh, US $9,153,617 is generated annually with 1% of escalation. Furthermore, assuming that the project has a 30 year operating life, and discount rate of 10%, the NPV has been calculated at US $2,770,609. Figure 10 presents the cash flow and NPV for geothermal binary plant scenario of the resource under these assumptions, where the project has an IRR of 11.0%, and 24 year discounted payback period.

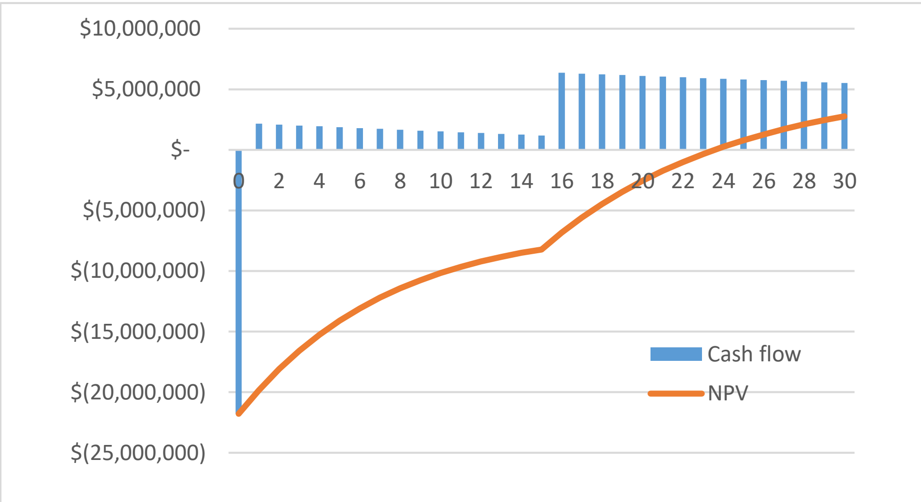

Figure 10: Net cash flow and NPV for scenario 1

<u>Scenario 2</u>

It is estimated that annual energy production is 78.277 GWh without degradation, and by assuming that electricity costs procured by the project are US $0.013/kWh, US $9,153,617 is generated annually. Furthermore, assuming that the project has a 30 year operating life, and discount rate of 10%, the NPV has been calculated at US $9,903,231. Figure 11 presents the cash flow and NPV for geothermal binary plant scenario of the resource under these assumptions, where the project has an IRR of 13.0%, and 18 year discounted payback period.

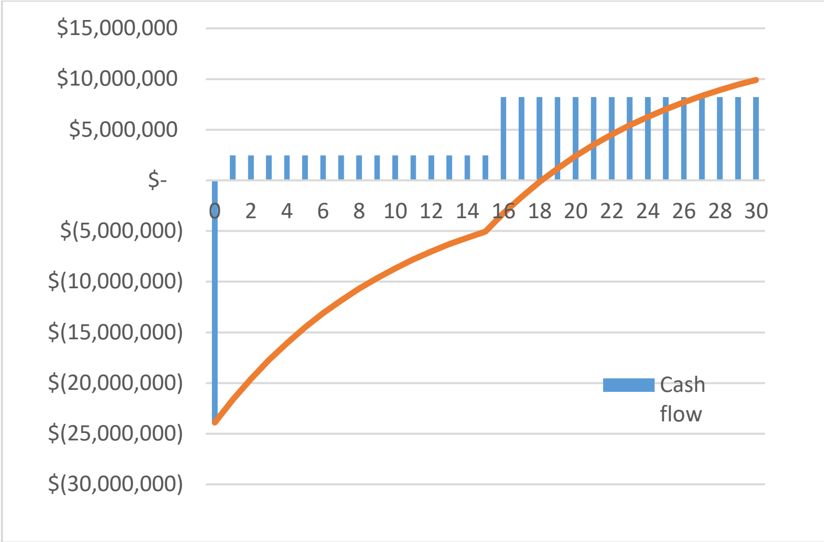

Figure 11: Net cash flow and NPV over lifespan

4.2 Sensitivity analysis

4.2.1 For Geothermal Binary Power Plant Standalone

Effect of various inputs on NPV as a main profitability measure for this project has been also analysed. Figure 12**Error! Reference source not found.** presents a sensitivity analysis in a graph with electricity prices, capital cost, reservoir depletion rate and interest rate. Each of these inputs have been varied from -50 % to +50 % of its value. Electricity prices and capital costs have the steepest lines and thus have the greatest impact on overall NPV.

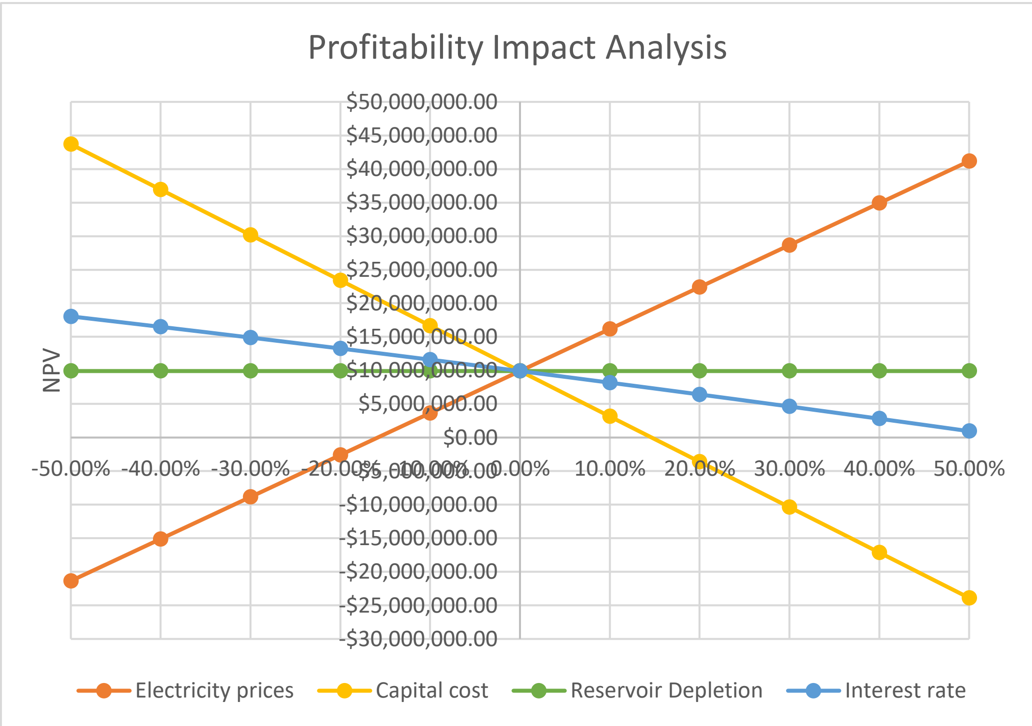

Figure 12: Sensitivity analysis of the NPV in scenario 1

4.2.2 For Hybrid Solar-Geothermal Plant

The impact of different parameters on the NPV was analyzed in the case of hybrid plant. Figure 13 presents a sensitivity analysis in a graph with electricity prices, capital cost, reservoir depletion rate and interest rate. Each of these inputs have been varied from -50 % to +50 % of its value. The same as the scenario 1, electricity prices and capital costs have the steepest lines and thus have the greatest impact on overall NPV.

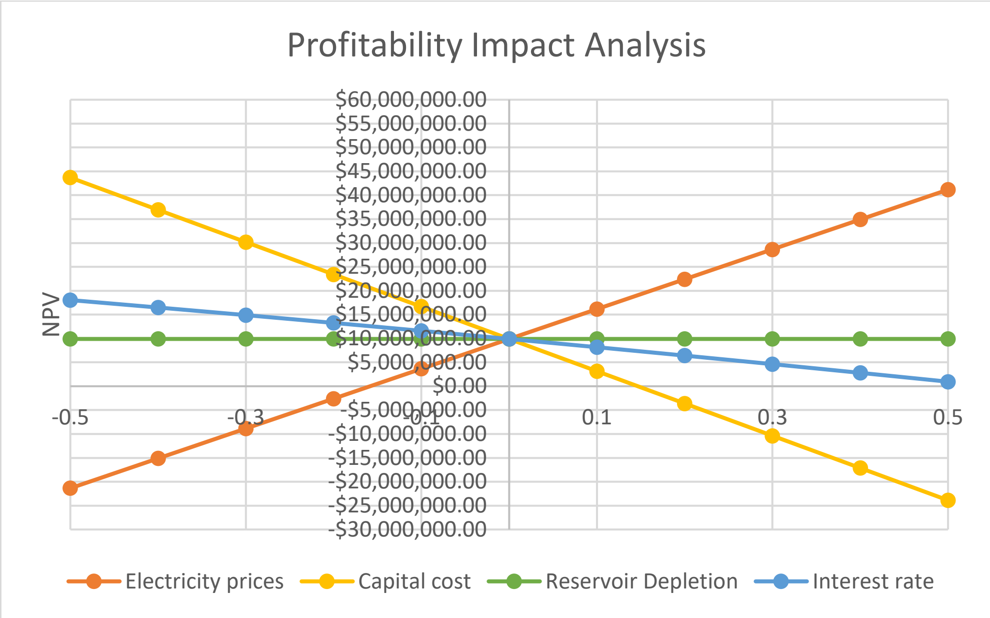

Figure 13: Net Cash flow and NPV for the scenario 2

The hybrid plant has a bigger IRR than the binary plant as advise the higher a project's internal rate of return, the more desirable it is to undertake the project. The hybrid solar-geothermal plant is the most economical use for the project, as it generates the highest NPV of the two proposed options ($9.9 m). It also has the highest IRR and quickest payback period on investment, of 13.0% and 18 years, respectively.

5. CONCLUSION

Djibouti possesses several medium enthalpy resources for different part of the country and it is situated in a hot arid zone. One of them, Lake Abhe geothermal field was recently the subject of a complete surface exploration. This is conducted by the scientists of ODDEG and ISOR conjointly with a co-financing of ICEIDA.

The objective of this paper is to determine how the medium enthalpy resource in Lake Abhe geothermal field would be best utilized, both technically and commercially. Four scenarios, namely binary power plant with air cooled condenser, binary power plant with water cooled condenser, binary power plant with wet type cooling tower and a combined Concentrated Solar power and binary power plant with air cooled condenser, were examined and categorized according to their respective viability, taking into account both positive and negative external effects.

The binary power plant with water cooled condenser and binary power plant with wet type cooling tower having more than 6.1% of net power output than air cooled condenser has more negative external effects for the environments. They deviate a large amount of water which disrupts and damages the local aquatic ecosystems through excessive withdrawals and thermal pollution been rejected. Djibouti being among of the country are classified as hydric stress water where strict water regulations prevail, ACC was preferred than the latter.

In the wake of ACC binary plant and Hybrid solar –binary was compared technically and economically. With a geothermal fluid mass flow of 443 kg/s and temperature of 145.7°C. The air-cooled condenser binary model produces 10924 kWe of gross power output with an auxiliary power of 22.6% of the total gross output power that the fan power represents 51.8% of the latter. The cycle efficiency is 10.44%. With the same condition, the hybrid solar-geothermal power plant power output is 13865 kWe where 20.6% go for the use of the auxiliary components. With 10.18 as cycle efficiency, the hybrid specific power output is 12.13 kW/(kg/s).

The air-cooled condenser binary model has a NPV of US $2,770,609, an IRR of 11.0%, and 24 year discounted payback period.

The hybrid solar-geothermal plant is the most economical use for the project, as it generates the highest NPV of the two proposed options ($9.9 million). It also has the highest IRR and quickest payback period on investment, of 13.0% and 18 years, respectively.

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