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Binary Power Plant on Olkaria IV Brine

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ABSTRACT

Binary power plants are widely used all over the world because of their ability to generate electricity at low temperatures. There is a lot of potential in the utilization of brine from the Olkaria geothermal field but the main challenges are the cooling of the reservoir and silica scaling in the reinjection pipeline. There has been evolution on the way silica scaling is being managed to harness as much heat as possible from the geothermal fluid. Interest in silica scaling moved from actual concentration, to concentration ration, to incubation period and to polymerization. Silica scaling kinetics is affected by silica degree of supersaturation, aeration, salinity, purity of geothermal fluid, pH and temperature. This study took into consideration the cooling of the reservoir and silica scaling kinetics in the determination of the binary power plant brine discharge temperature.

Olkaria IV power plant was commissioned in September, 2014 and has two single flash units each with an installed capacity of 74,924 kW. Olkaria IV steam field has a two phase fluid with separation temperatures of about 187 ˚C – 189˚C and the brine is directly re-injected after separation. There exists an opportunity to utilize high temperatures of brine while avoiding and managing scaling impact.

Binary power plant design is based on: separators pressures and temperatures, steam chemistry and flow rates, dry cell cooling tower and the ambient temperatures of Olkaria IV. Four options of utilizing Olkaria IV field brine for power generation are analyzed based on individual separators and combined flow rates. Silica scaling in heat exchangers, piping and reinjection wells are considered in plant design for sustainable operations and maintenance.

The proposed binary power plant, unlike conventional plants, will be relatively cheap to implement because it uses an exciting steam gathering system, reinjection wells, and developed site. The binary power plant will increase overall steam utilization factor and can take a shorter period to commission.

1. INTRODUCTION

1.1 General Background

Geothermal energy is clean, renewable, inexpensive and reliable, however it has relatively long lead time from concept to production, high upfront cost and high upfront risks (Deloitte 2008). Among renewable energy power generation technologies, geothermal power plants have the higher plant capacity factor and therefore are attractive (Zeyghami 2015). It is therefore important to continuously increase steam utilization of the finite geothermal resource. Introduction of binary power plant will definitely increase geothermal utilization for Olkaria IV steam supply by extracting heat on geothermal fluid before final reinjection.

KenGen is the leading electric power generation company in Kenya contributing about 75% of power produced annually. The company generates electricity from hydro, geothermal, thermal and wind power plants which are located in various location within the country. Hydro constitute 50%, geothermal 33%, thermal 16% and wind 2% of the company's installed capacity. Geothermal energy is base load because of its reliability, stability and low cost and hence has been contributing approximately 50% of the company's generated electricity for the last three years. The company's geothermal resource development is in the rift valley region and has an installed capacity of 533 MW in the Olkaria area. All the power plant units are single flash type and consist of both conventional and well head units.

There are currently many energy conversion systems for utilization of geothermal resources and advanced technology has provided more choices for decision makers (Jalilinasrabady et al. 2012).

1.2 Area of Study

Olkaria IV power plant was commissioned in September, 2014 and has two single flash units each with a rated capacity of 74,924 kW. The station is located in the east Africa rift within Olkaria volcanic complex as shown in Figure 1 below. There are twenty-one production wells which continuously supply two phase geothermal fluid which is further separated into dry steam and brine by four different separators at a pressure of 10.8 bara. The separated brine is reinjected back to the production zone reservoir. The total brine flow from the four separators is eight hundred and sixty-four tones per hour.

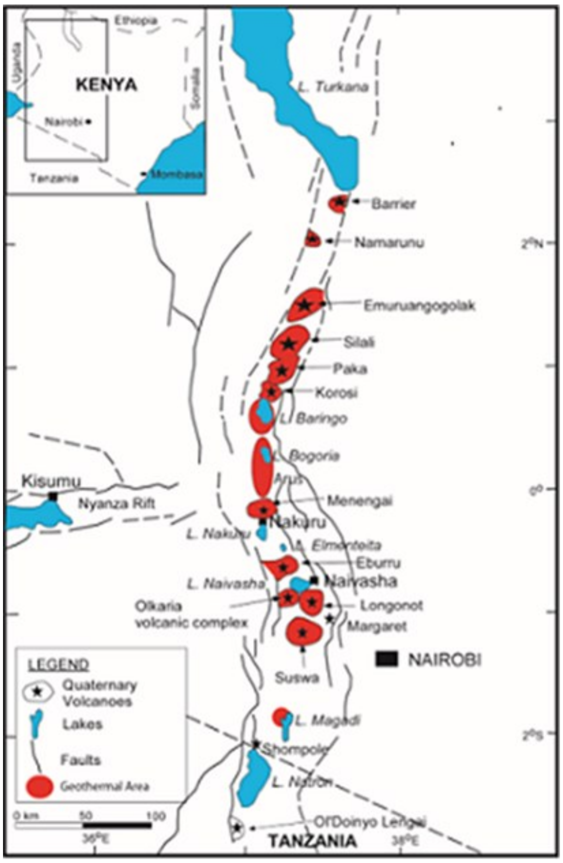

Figure 1: Kenya's geothermal fields

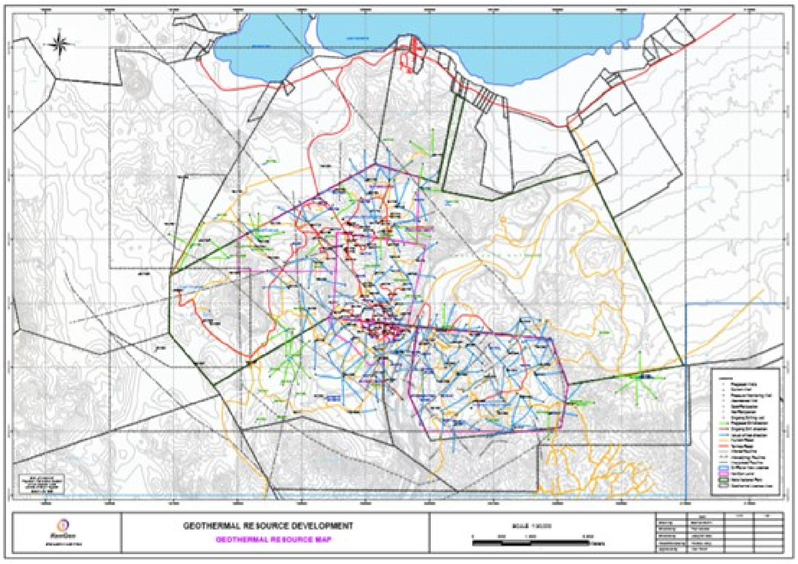

Figure 2: Location of Olkaria IV wells

2. CONCEPTUAL MODEL

2.1 Objective

This project study objective is to increase power generation from geothermal fluid through introduction of a binary plant in Olkaria IV brine line from separators. The binary plant will utilize the heat of the brine before it's finally re-injected to the reservoir and thus increasse thermal efficiency of the geothermal fluid. Geothermal fluid in Olkaria IV steam field is only generating electricity by use of a conventional single flash power plant.

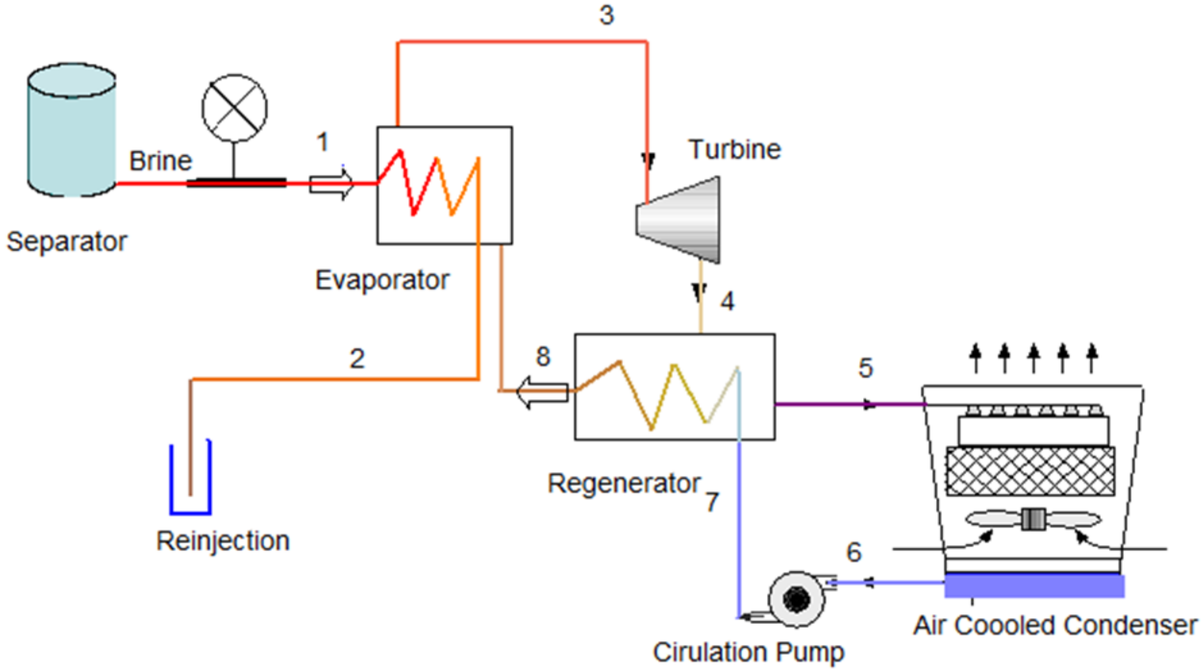

Figure 3: Conceptual Model for Olkaria IV Binary Plant

2.2 Design data

Olkaria IV power plant has four steam separators (S1, S2, S3 and S4) with brine flow rates of: 229.7, 421.8, 170.7 and 42.4 tones per hour respectively. The outlet temperatures of the four separators ranges between 187 ˚C – 189˚C and 187 ˚C has been used for design of the proposed binary plant. The separators get steam supply from 21 production wells with pH of between 9.16 and 10.3 and weighted average silica concentration is 864 ppm.

2.3 Design Options

The following four options were considered in the design: combination of all the four separators' brine, utilization of separator 1 only, use of separator 2 only and finally use of brine from only separator 3.

3. LITERATURE REVIEW

3.1 Introduction.

Binary plants are the most widely used type of geothermal power plant in the world with 203 units in operation as of December, 2014 generating 1245 MW of power in 15 countries. The binary plants constitute 35% of all geothermal units but generates only 10.4% (Di Pippo and DiPippo 2012) . Organic Rankine Cycle (ORC) is more efficient from the view of power output as compared to single flash and double flash energy conversion systems (Jalilinasrabady et al. 2012)

There are several challenges and risks associated with geothermal exploration, drilling and development. Deloitte summarized geothermal strengths and weaknesses in their report on risks mitigation strategies as shown in Figure 4 below. A binary power plant on a developed geothermal field has negligible weaknesses as highlighted in the Deloitte report.

Geothermal Energy	
Strength	**Weakness**
• Clean, Renewable Energy • Base-load Energy Source • Inexpensive • Reliable source	• Relatively long lead time from concept to production • Large Entry Barriers – High upfront cost – High upfront risk – Lack of pre-drilling feasibility assessment • Remote location and siting restrictions

Figure 4: Geothermal strength and weaknesses (Deloitte 2008).

Binary power plants can use geothermal fluid from the well or added to an existing power plant to recover heat from brine and therefore increase overall thermal efficiency. A simplified flow diagram of geothermal fluid and organic or working fluid is provided below. If the pressure is kept significantly high, non-condensable gases will not be separated from the liquid and hence a gas extraction system is not required.

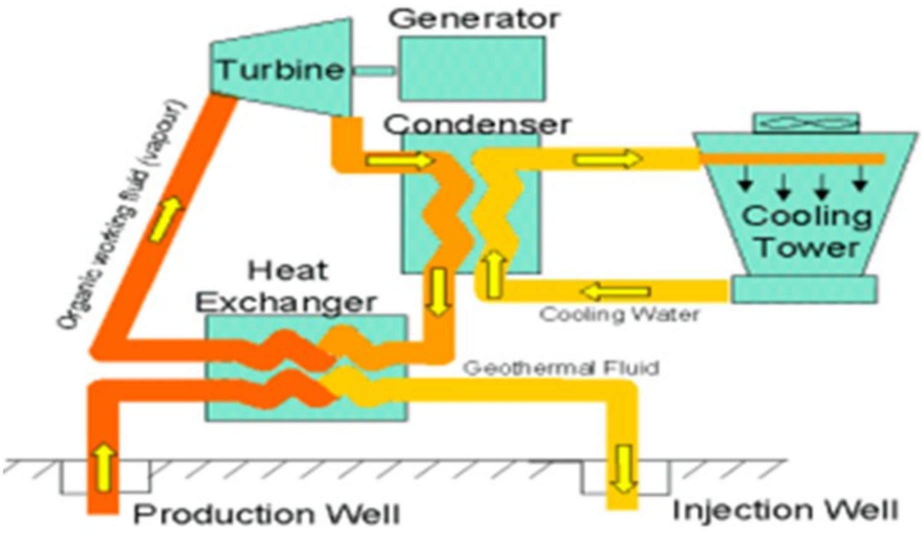

Figure 5: Binary power plant schematic diagram.

3.2 Binary Thermodynamic Processes

Working fluid is heated in the pre heater to its boiling point before entering a vaporizer where it will be heated to saturation or even superheat in some cases. Working fluid will enter the turbine and will cause it to rotate through expansion. A circulation pump raises the pressure of the working fluid before it enters pre heater. Heat transfer and analysis for various components is as shown below.

Analysis of each component must fulfill a mass and energy balance. Mass balance for a steady system which is not changing with time requires that the sum of all mass flows into a component must be equal to mass flow out. The energy flow into a component must be equal to energy flow out of it. The flow of energy can take the form of energy of working fluid, work performed or consumed, and heat flow (Parlsson 2006).

The air-cooled condensers do not require any amount of chemical additives or periodic cleaning like wet cooling towers do. Binary plants with dry cooling systems are sustainable choices, requiring no additional water and with near zero emissions of pollutants and greenhouse gases. The dry cooling towers consume more parasitic power due to the operation of fans thus requiring more capital cost but, on the other hand, they are a more environmentally friendly choice (Nazif, Valdimarsson, and Thòrhallsson 2015).

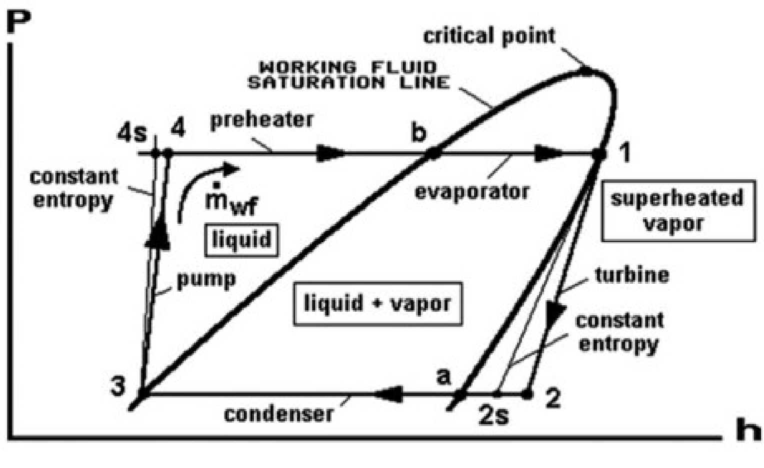

Figure 6: Pressure Enthalpy diagram for basic binary plant (Di Pippo and DiPippo 2012)**.**

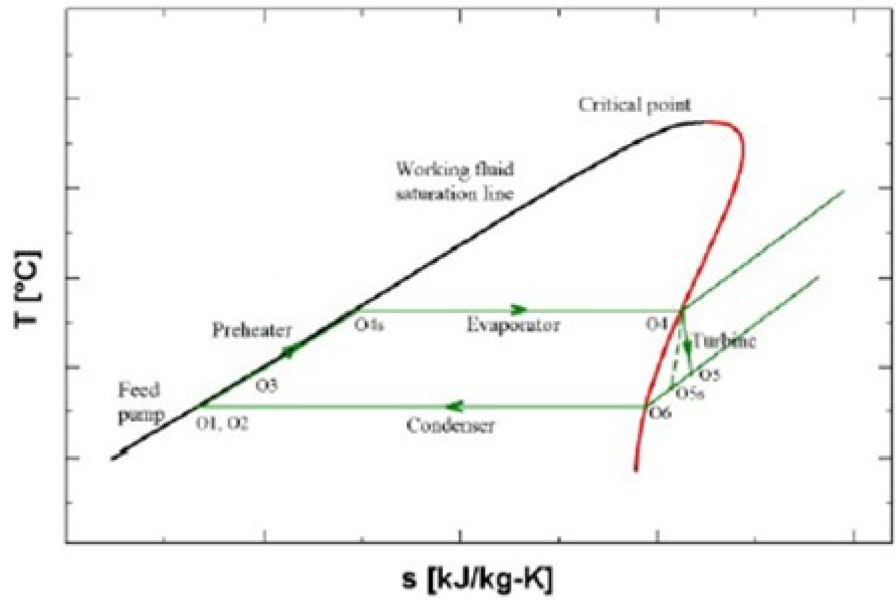

Figure 7: T-S diagram of binary cycle (Nazif, Valdimarsson, and Thòrhallsson 2015)**.**

3.2.1 Turbine

The analysis of the turbine is done with the assumption that potential and kinetic energy are negligible and flow is steady. Then the maximum work produced by working fluid is given as follows:

$$W_t = m_{wf}(h_1 - h_2) \qquad (1)$$

Where: W_t = Work done by turbine.

m_{wf} = Mass of working fluid.

h_1= Enthalpy of working fluid at turbine entry.

h_2= Enthalpy of working fluid at turbine exit.

However, work in equation (1) above is not possible because the expansion in the turbine is not fully isentropic and hence isentropic efficiency is introduced.

$$\eta_t = \frac{h_1 - h_2}{h_1 - h_{2s}} \qquad (2)$$

Where: η_t = Isentropic efficiency.

h_{2S}= Enthalpy of steam at saturated state.

h_1 & h_2 are same as above

Therefore, power generated by the working fluid will be given by:

$$\dot{W}_t = \eta_t \, m_{wf}(h_1 - h_2) \qquad (3)$$

Gross electrical power is obtained by multiplication of turbine work and generator efficiency.

$$W_g = \eta_g \, \dot{w}_t \qquad (4)$$

Where: Wg = Gross electrical power.

η_g = Generator efficiency.

3.2.2 Air cooled Condenser

An air-cooled condenser is a fin-fan type heat exchanger in which low-temperature vapor coming from the regenerator is condensed by heat transfer to ambient air, blown by the fans to the condenser. The exhaust working fluid from the organic turbine enters the condenser in a superheated state and is condensed to saturated liquid (Nazif, Valdimarsson, and Thòrhallsson 2015).

Heat transferred by working fluid to air is given by equation (5).

$$Q_c = M_{wf}(h_2 - h_3) \qquad (5)$$

Where: Qc =Heat transferred by working fluid.

h_3= Enthalpy of working fluid at the exit of condenser.

Therefore, air cooled condenser should be designed to dissipate heat for the specified mass flow.

3.2.3 Feed Pump Analysis

Power given to the working fluid by the circulation pump is given by:

$$W_p = M_{wf} (h_4 - h_3)\ \eta_p \quad (6)$$

Where: W_p = Power given to working fluid.

η_p = Isentropic pump efficiency.

3.2.4 Pre heater and Evaporator

This is the components where heat is transferred from brine to the working fluid. It is assumed that the heat exchangers are well insulated so that heat transfer is only between working fluid and brine. It is further assumed that the mass flows are steady, difference between entering and leaving potential and kinetic energies are negligible.

Temperature – heat (T-q) thermodynamic diagram shown below is used in designing heat exchangers. The amount of heat transferred from brine to working fluid is represented by the abscissa. Point 5 is the boiling point of the working fluid where evaporation occurs between this point and 1. Pinch point temperature (ΔTPP) is the minimum temperature difference between working fluid and the brine.

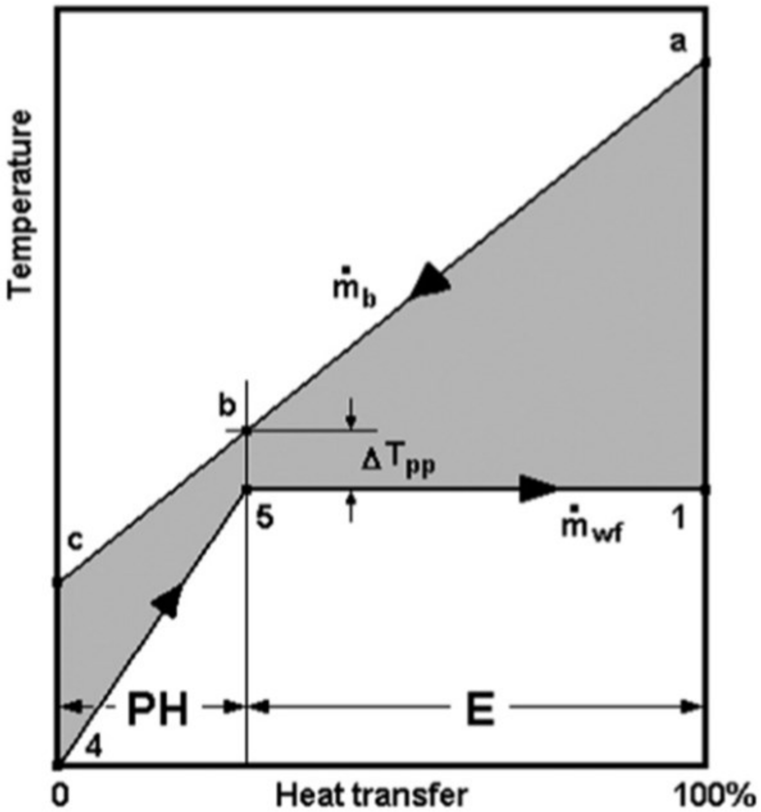

Figure 8: Temperature – Heat transfer diagram for preheater and evaporator.(Di Pippo and DiPippo 2012)

Heat exchange in preheater (PH) is given by:

$$\dot{M}_b \bar{C}_b (T_b - T_c) = \dot{M}_{wf} (h_5 - h_4) \quad (7)$$

Where: $\dot{M}_b$ = Mass flow rate of brine.

$\bar{C}_b$ =Specific heat of brine.

T_b = Brine inlet temperature to preheater.

T_b = T5 + ΔTPP

T_c = Brine exit temperature from preheater.

h_5 = Enthalpy of working fluid at exit of preheater.

h_4 = Enthalpy of working fluid at entry of preheater.

Heat exchange in Evaporator (E) is given by:

$$\dot{M}_b \bar{C}_b (T_a - T_b) = \dot{M}_{wf} (h_1 - h_5) \qquad (8)$$

Where $\dot{M}_b$ = Mass flow rate of brine.

$\bar{C}_b$ = Specific heat of brine.

T_a = Brine inlet temperature to evaporator.

T_b = Brine exit temperature from evaporator.

h_1 = Enthalpy of working fluid at exit of evaporator.

h_5 = Enthalpy of working fluid at entry of evaporator.

3.3 Scaling

As fluid moves towards and through the plant, pressure, temperature and chemistry conditions are altered which impacts the solubility of various fluid components resulting in deposition or scaling of several different species (Richardson, Addison, and Lawson 2015). In this proposed binary power plant, the areas that will be prone to silica scaling are evaporator, preheater, brine handling and reinjection system.

Figure 9: Olkaria IV turbine blades and scaling management in Olkaria IAU pressure letdown station.

There are several studies that have been done on silica scaling chemical formation processes and factors that speed or reduce its formation. The interest shifted from silica concentration to supersaturation concentration ratio to induction or incubation period to polymerization (Grassiani 1999) . Induction periods may vary from several minutes to several hours and in many cases are long enough to permit normal flow and heat transfer inside the critical heat exchanger of the binary plant unit. Furthermore, design and operational experience have evolved in recent years to a point where scaling is handled on a routine basis.

Silica kinetics has been found to be important in the scaling process. Supersaturation implies that a precipitate will form but it is insufficient to describe how fast that might happen or what form that precipitate might take. Such qualitative aspects of silica scaling can be much more difficult to characterize, as they are often affected by such parameters as:(1) Degree of supersaturation (2) Salinity (3) Aeration (4) Temperature (5) Fluid flow regime (6) Availability of nucleating species and (7) pH. (Zarrouk, Woodhurst, and Morris 2014)

It has been shown that kinetics of pure silica deposition and from experience on several geothermal power developments that a general rule is to limit silica concentration index (SSI) to a maximum of 1.15, 1.3 and 2 for single flash, double flash and binary plants respectively.

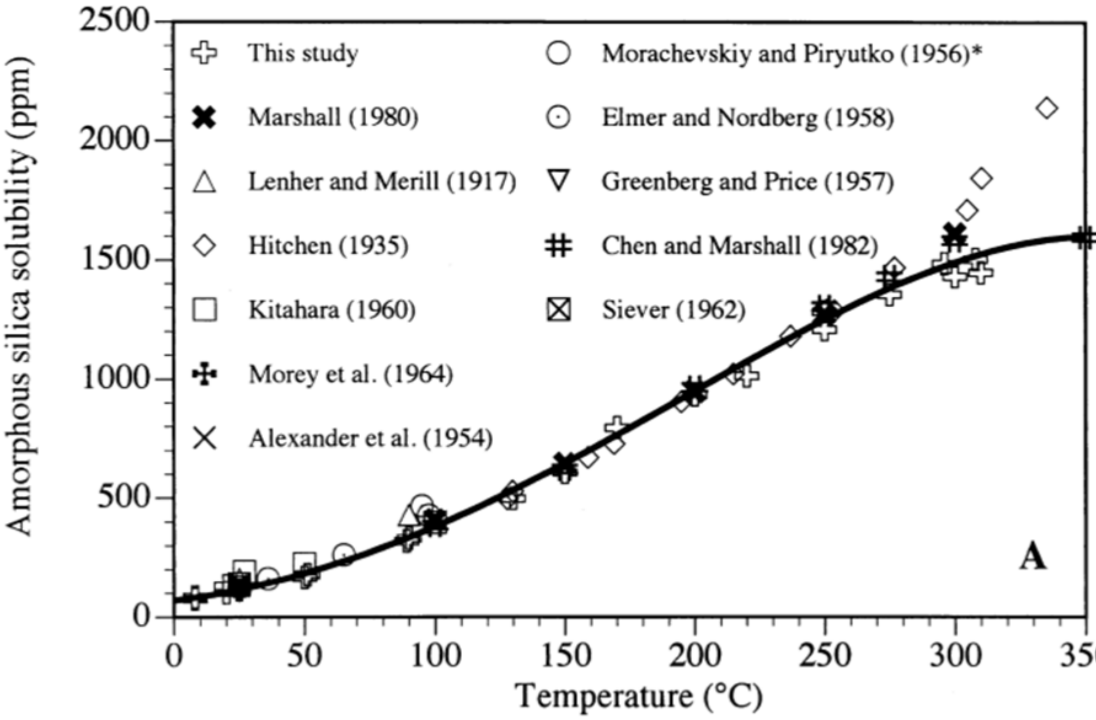

Figure 10: Amorphous silica solubility (Therapy 2000)**.**

In this proposed binary power plant silica saturation index was set at approximately 1.45 at the exit of the heat exchanger. The brine pH can be modified through addition of acid to allow use of geothermal brine with a SSI of more than 2.0 while minimizing scaling. The pH modification does not significantly change silica solubility but it does change kinetics of polymerization reaction and therefore avoid scaling in heat exchanger and re-injection pipeline (Richardson, Addison, and Lawson 2015).

3.4 Working Fluid

The binary working fluid must not only have the necessary thermos physical properties for the required application but also non-toxic, non- flammable, and possess adequate chemical stability in the desired temperature range (Zeyghami 2015). Working fluid with high density, low liquid specific heat, high latent heat and low viscosity are expected to produce high net - work output in ORC. Zeyghami, Rayegan and others have written on chlorine included working fluids that have been discarded because of the negative effect it has on the ozone layer. The table below provides list of environmentally friendly working fluid available for selection.

Table 1: ORC Working fluid options (Zeyghami 2015)

Name	T_{cr} [°C]	P_{cr} [MPa]	Fluid type	Name	T_{cr} [°C]	P_{cr} [MPa]	Fluid type
Acetone (C3H6O)	234.9	4.7	Wet	Propane (C3H8)	96.68	4.25	Wet
Benzene (C6H6)	288.87	4.91	Dry	Propene (R-1270) (C3H6)	92.42	4.66	Wet
Butane (C4H10)	151.98	3.8	Dry	Propyne (C3H4)	129.23	5.63	Wet
Butene (C4H8)	146.14	4.01	Dry	R-116 (C2F6)	19.88	3.05	Wet
Perfluorobutane (C4F10)	113.18	2.32	Dry	R-123 (C2HCl2F3)	183.68	3.66	Dry
Perfluoropentane (C5F12)	147.41	2.05	Dry	R-124 (C2HClF4)	122.28	3.62	Dry
Cis-butene (C4H8)	162.6	4.23	Dry	R-134a (C2H2F4)	101.06	4.06	Wet
Cyclohexane (C6H12)	280.45	4.08	Dry	R-152a (C2H4F2)	113.26	4.52	Wet
Cyclopropane (HC-270)	125.15	5.58	Wet	R-218 (C3F8)	71.9	2.64	Dry
Decane (C10H22)	344.55	2.1	Dry	R-227ea (C3HF7)	102.8	3	Dry
Difluoromethane (R32) (CH2F2)	78	5.78	Dry	R-23 (CHF3)	26.14	4.83	Wet
Dodecane (C12H26)	384.9	1.82	Dry	R-236ea (C3H2F6)	139.29	3.5	Dry
Ethane (C2H6)	32.18	4.87	Wet	R236fa (C3H2F6)	124.9	3.2	Dry
Heptane (C7H16)	266.98	2.74	Dry	R-245ca (C3H3F5)	174.42	3.93	Dry
Hexane (C6H12)	234.7	3.03	Dry	R-245fa (C3H3F5)	154.05	3.64	Dry
Isobutene (C4H8)	144.94	4.01	Dry	R-365mfc (C4H5F5)	186.85	3.27	Dry
Isobutane (C4H10)	134.66	3.63	Dry	R-41 (CH3F)	44.13	5.9	Wet
Isohexane (C6H14)	224.55	3.04	Dry	R-413A	96.6	4.02	Wet
Isopentane (C5H12)	187.25	3.37	Dry	R-423A	99.1	3.56	Wet
Neopentane (C5H12)	160.59	3.2	Dry	R-426A	99.8	4.09	Wet
Nonane (C9H20)	321.4	2.28	Dry	R-C138	115.23	2.78	Dry
Octane (C8H18)	296.17	2.5	Dry	Toluene (C7H8)	318.6	4.13	Dry
Pentane (C5H12)	196.55	3.37	Dry	Trans-butene (C4H8)	155.5	4.03	Dry

At temperatures close to critical point, working fluid conditions are unstable. Any small changes in temperature can cause a large variation in the fluid condition. For wet and isentropic fluid fluids, T Max is considered 10˚C lower than the critical temperature (Delgado-Torres and García-Rodríguez 2007).

4 RESULTS AND DISCUSSIONS

Designing the process for the binary plant was done as per the conceptual model described above and the Engineering Equations Solver (EES) was used in the calculations and analysis.

4.2 Optimization

Optimum operating pressures for eight working fluids selected were obtained based on the gross power. Critical temperatures and pressures were also put into consideration in the process of optimization. Optimum condenser pressure was the same for all the working fluid at 0.86 bar which is atmospheric for area of study. Sample results of optimization are as shown in the figures below.

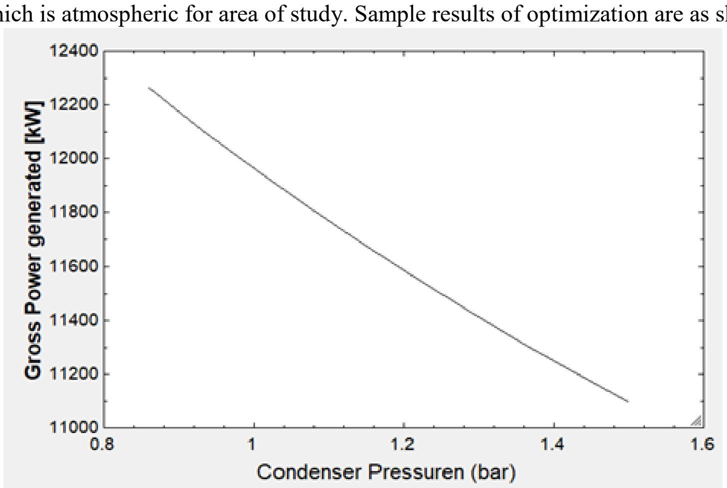

Figure 11: Condenser pressure Vs Gross power generation.

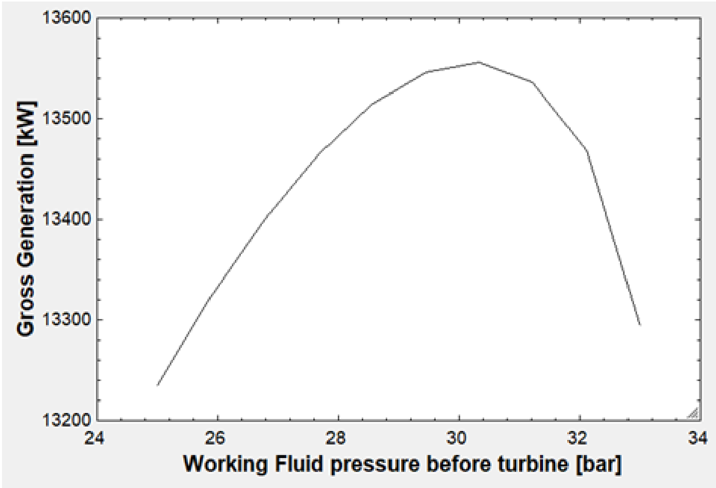

Figure 12: Working fluid pressure Vs Gross power output.

Optimum operating working pressures for the working fluid were obtained as shown in the table below:

Table 2: Optimum working fluid pressures at turbine inlet

Working Fluid	Isopentane	Benzene	R123	Butene	Neopentane	R245fa	Cis- Butene	Isobutane
Optimum Pressure (Bar)	30	11	31	33.3	29.2	31.8	34	30

4.3 Working Fluid selection

Working fluids with critical temperatures closer to the available brine temperature were analyzed based on the net power. Isopentane was selected as preferred working fluid because it had the highest generated power and is easily available in the market. The outcome of the analysis is as shown in figure 13 below.

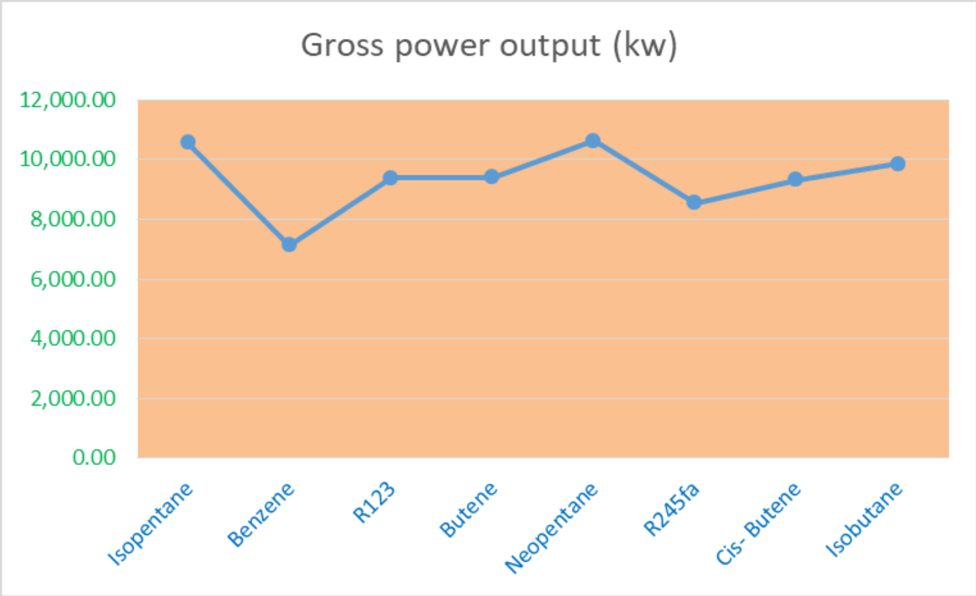

Figure 13: Working fluid Vs gross power

4.4 Design Options Results

Isopentane working fluid was then used to calculate the outcome of the various options with optimum pressures and temperatures. The outcome of the four options is as summarized in the table below:

Table 3: Design options Results

Options	Brine Flow Rate (Kg/s)	Gross Power (kw)	Auxiliary Power (kw)	Net Power (kw)
1	240	13,555.0	2989.2	10,565.8
2	64	3,615.0	797.13	2,817.9
3	117	6,608.0	1456.6	5,151.4
4	47	2,655.0	585.52	2,069.5

4.5 Discussion of Results

Assuming that the binary power plants will have an average monthly availability of 90% then the power generated from each option is as shown in table 4 below.

Options	Approximate Annual Generation (GWh)
1	82.17
2	21.91
3	40.06
4	16.09

5 CONCLUSIONS

Electricity generation from Olkaria IV brine line will raise geothermal fluid utilization and increase electricity generation by 10 MW. The power generation from binary is mainly limited by silica scaling which can be managed through design and maintenance.

There is a huge opportunity in Olkaria steam field to generate extra electricity from brine which is being reinjected to the reservoir at high temperatures. Olkaria IV and Olkaria V steam gathering systems are in the same field and therefore brine from all separators serving both plants can be channeled to a single binary plant. The single binary plant will generate over 25 MW and as shown in Figure 14 below.

The binary plant does not have non- condensable, circulating water and chemical dosing systems and hence will be easier to operate and maintain as compared to the single flash systems installed in Olkaria IV & V. The proposed binary plant can be operated from either Olkaria IV or Olkaria V control room.

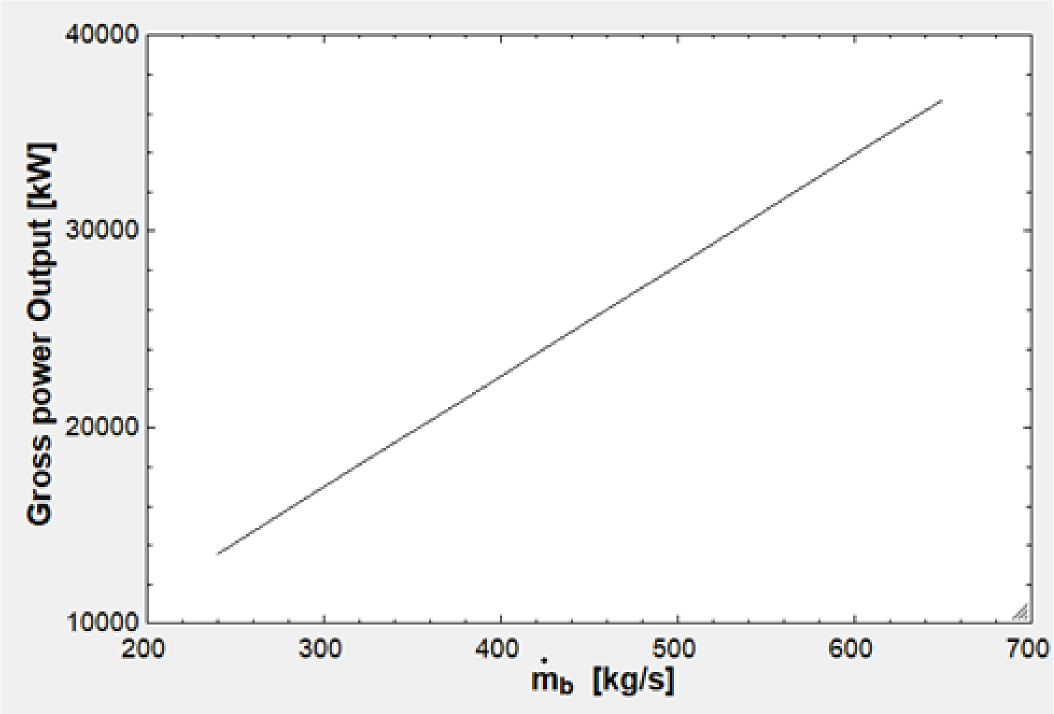

Figure 14: Gross power output Vs Brine flow rate

REFERENCES

Delgado-Torres, Agustín Manuel, and Lourdes García-Rodríguez. 2007. "Comparison of Solar Technologies for Driving a Desalination System by Means of an Organic Rankine Cycle." *Desalination* 216(1–3): 276–91.

Deloitte. 2008. "Department of Energy – Office of Energy Efficiency and Renewable Energy Geothermal Program." *Department of Energy - Office of Energy Efficiency and Renewable Energy Geothermal Program*: 44. http://www1.eere.energy.gov/geothermal/pdfs/geothermal_risk_mitigation.pdf.

Grassiani, Moshe. 1999. "Siliceous Scaling Aspects of Geothermal Power Generation Using Binary Cycle Heat Recovery." *Bulletin d'Hydrogiologie No I7*: 3167–71.

Jalilinasrabady, Saeid et al. 2012. "Flash Cycle Optimization of Sabalan Geothermal Power Plant Employing Exergy Concept." *Geothermics* 43: 75–82. http://dx.doi.org/10.1016/j.geothermics.2012.02.003.

Nazif, Havidh, Pàll Valdimarsson, and Sverrir Thòrhallsson. 2015. "Developing Choices for Optimal Binary Power Plants in the Existing Geothermal Production Areas in Indonesia." *World Geothermal Congress 2015* (April): 12.

Parlsson, Halldor. 2006. *Utilization of Geothermal Energy For Power Production*.

Di Pippo, Ronald, and Ronald DiPippo. 2012. Geothermal Power Plants *Geothermal Power Plants*. http://books.google.com/books?hl=fr&lr=&id=Ea2osquPZwUC&pgis=1%0Ahttp://linkinghub.elsevier.com/retrieve/pii/B9780080982069000245.

Richardson, Ian, Simon Addison, and Rebecca Lawson. 2015. "Chemistry Challenges in Geothermal Power Generation." *Power Plant Chem* (1): 1–17.

Therapy, In. 2000. "AMD : A Revolution In Therapy Begins." 64(13): 2295–2307.

Zarrouk, Sadiq J., Blair C. Woodhurst, and Chris Morris. 2014. "Silica Scaling in Geothermal Heat Exchangers and Its Impact on Pressure Drop and Performance: Wairakei Binary Plant, New Zealand." *Geothermics* 51: 445–59. http://dx.doi.org/10.1016/j.geothermics.2014.03.005.

Zeyghami, Mehdi. 2015. "Performance Analysis and Binary Working Fluid Selection of Combined Flash-Binary Geothermal Cycle." *Energy* 88: 765–74. http://dx.doi.org/10.1016/j.energy.2015.05.092.