DEMOCRATIC AND POPULAR REPUBLIC OF ALGERIA

Ministry of Higher Education and Scientific Research

University of Tlemcen

PAN AFRICAN UNIVERSITY

Institute for Water and Energy Sciences (Incl. Climate Change)

Potential for Organic Rankine Cycle Plants in Kenya

Student name

Kay Nyaboe Nyakundi

Date: 28th August, 2016

Master in ***Energy Engineering track***

Members of Jury:

President: Prof. Cherif Weld Houcine

Supervisor: Dr. Pall Valdimarsson

Co-Supervisor: Dr. Sofiane Amara

Examiner: Prof. Chakih Seladji

Academic Year: 2015-2016

DECLARATION.

This thesis is my original work and has not been presented for a degree in another university.

Signature………………… Date…………………….

Kay Nyaboe Nyakundi

This thesis has been submitted with our approval as the university supervisors.

Signature………………… Date…………………….

Prof. Safiane Amara

Pan African University Institute of Water and Energy Sciences (including Climate Change (PAUWES) Tlemcen, Algeria.

DEDICATION.

I look up in the skies where does my help come from, my help comes from the Lord. With utmost humility, I dedicate this work to my young yet coming up family. A special thanks to my life partner James Coleman Randiki, who encouraged and cheered me all through my two years, thanks Coleman for always having the ability to tickle my mind until I get a light bulb moment that went along way to the success completion of this report. My mother, for always praying for me and constant daily words of advice. This words are and still linger in my mind and will go a long way to shaping my future. Then to my lovely sister Gillian Kwamboka Nyakundi, thank you for listening to engineering theorems. Lastly, to my friends who were always there for me to assist and offer me the much needed break from my research work.

ACKNOWLEDGEMENTS.

First and foremost, I give my thanks and praise to the Almighty God for providing me with strength and good health all throughout my master thesis. I do not take it for granted that I have been able to proceed and finish this thesis successfully if it is not through His Grace. Then, my heartfelt and sincere gratitude goes to a whole team that made sure my success in my master thesis completion. I would like to acknowledge and thank in no particular order:

PAUWES team led by the program director Prof Adellatif Zerga, for offering me an opportunity to persue my masters by awarding me a two year scholarship sponsored by the Africa Union and in cooperation with the German government. In addition, to all the support accorded to me by the PAUWES administration.

UNU-GTP members of staff led by the program director Lúdvík S. Georgsson, who were so supportive and helpful as they hosted me and offered me an opportunity of a life time at their state of the act Research Centre to do my master thesis in geothermal while in Iceland.

Prof. Páll Valdimarsson, of PVald Company in Iceland for his selfless commitment in guiding me as my supervisor.

KenGen management and staff led by Mr. Peketsa Mangi, who awarded me an internship that was tailored made for my master thesis topic which went a long way to helping me understand better my thesis with a practical approach and availed the data that my research work needed.

Finally, to all my friends and family for their emotional, moral support, encouragement, tender love, care and belief in me that I can make it and with God all things are possible.

Thank you all for your unconditional support and help it all went and helped a greater way to the successful completion of this thesis.

ABSTRACT.

Binary power plants utilizing Organic Rankine Cycle is a the most preferred way of utilizing geothermal resource that is water dominated or has low to medium enthalpy and a new way that is gaining momentum is the use of separated brine. In Kenya, binary power plants are rarely used and they are currently only used by two IPPs. Most of the geothermal power plants in Kenya are single flash plants. The major challenge that the single flash plants being operated in Kenya face is the inefficiencies due to the energy loss from the geothermal separated brine. Geothermal separated brine is a by-product of geothermal electricity generation which contains substantial amount of energy. In Olkaria, Kenya the geothermal fluid is basically a two phase mixture that consists of significantly of 50-90% brine by mass and 4% by volume while the steam is 10-50% by volume. The separated brine has extractable energy of about 1500t/h which is currently reinjected back into the ground. In addition, wells that are drilled and are more water dominated and have low enthalpy are just disregarded though this are quite a small number. In this study, we shall look the general overview of the potential Organic Rankine cycle plants in Olkaria, Kenya. In order to assess the prefeasibility of binary power plants we access and rank the available geothermal resources of Olkaria. The technical analysis is done by modelling an air cooled binary power plant by use of the EES software for the best ranked geothermal resource while the economic analysis is done by a costing comparison of the main components of the modelled binary power plants. The choice of the cooling medium is air as it is free and air cooled binary power plants are easy to maintain with a better aesthetic value. The working fluid is selected based on their harmful effects and analysis of their thermodynamic properties. The regenerative air cooled model is found to be the most technical and economic option as compared to the basic air cooled model for binary power plants for Kenya.

Key words: Binary Power Plant, Olkaria and prefeasibility.

TABLE OF CONTEXT

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATION.

AU – Additional Unit.

EGS - enhanced/engineered geothermal system.

EES - Engineering Equation Solver.

GDC – Geothermal Development Company

GWP – Global Warming Potential.

GW – Giga Watt.

h – Enthalpy.

H_2S – Hydrogen Sulphate.

HE – Heat exchanger.

IPP - Independent Power Producer.

KenGen – Kenya Electricity Generating Company.

km – kilometer.

kW – Kilo Watt.

MW – Mega Watt.

ODP – Ozone layer Deflection Potential.

ORC- Organic Rankine Cycle.

SST- Silica saturation temperature.

T - Temperature.

wf – working fluid.

WHP – Well Head Pressure.

CHAPTER ONE:

1. INTRODUCTION.

The global energy demand is expected to increase by over one-third in the period between 2012 to 2035 due to growth in economies and population [1]. According to the Kenya National Bureau of Statistics economic survey report 2015, the domestic demand for electricity in Kenya recorded an increase of 12.1 per cent to 7,768.6 million KWh in 2014 from 6,928.1 million KWh in 2013 while the electricity consumption of the country increased by over 5900 GWh in the years 2008 to 2011. The total electricity generation expanded by 8.2 per cent from 8,447.9 GWh in 2013 to 9,138.7 GWh in 2014. Generation from geothermal plants went up to 2,917.4 GWh in 2014 from 1,780.9 GWh recorded in 2013 [2]. This was mainly attributed to increased generation due to enhanced capacity during the year.

Energy consumption is an indispensable component for the continued development of the human population and economically. Therefore, this leads to the big question does Kenya have enough energy resources to satisfy its increasing energy demand in a sustainable way without compromising its future. Energy as a whole plays an essential role in an economy on both demand and supply. On the demand side, energy is one of the products a consumer decides to buy to maximize his or her utility. On the supply side, energy is a key factor of production in addition to capital, labor and materials and is seen to play a vital role in the economic and social development of countries, being a key factor in increasing economic growth and living standard. The rate of energy consumption can be used may be considered as an indication of the national economic growth. According to a report from the World Bank [3] developing countries' economic growth will accelerate from 4.8% in 2013 to 5.3% in 2014 and the energy consumption will also increase.

Kenya's current power generation over the years has been hydro which has been the leading source of electricity with an installed capacity of about 820MW, geothermal energy comes closely at second place with steady growth and its current installed capacity of about

789MW which accounts now for more than 50% of the electricity consumed in the country. Other sources include wind and thermal [4].

However, this is changing fast due to the effects of climate change the level of water in the hydro plants dropping at a fast an alarming rate due to unreliable weather pattern changes. This makes hydro power very unreliable considering it was the main power supply for the base load for Kenya. Geothermal energy estimated availability measured with respect to hours in a set time period is mostly over 95% [5]. This makes them strong candidate for base load plants. Due to Kenya's huge geothermal potential we have seen heavy investment on more and more geothermal drilling is being done to be used as base load plants to counter the unreliable hydro power. As seen currently already plans are underway for the construction of Olkaria V which follows the recently commissioned 280MW Olkaria IAU and IV [6].

1.1 Problem Statement.

Geothermal is an indigenous and abundantly occurring resource in Kenya. The resource in Kenya have been under development since 1950's and the current installed capacity stands at 573 MWe against total potential of about 10,000 MWe as at 2014 [4]. Most development and exploration of geothermal potential in Kenya is around the Rift Valley and due to its abundance of the geothermal resource at its high temperature of around 160-200°C. The exploration of low-medium temperature geothermal reservoirs, water dominated geothermal reservoirs and brine reinjection resources in Kenya has not yet been analyzed, ranked and proposed for mature commercial technology solutions.

Olkaria geothermal field uses conventional method that includes single flash model for all its four power plants. In all the four plants there is minimal and efficient utilization of the hot brine that is ejected by the single flash plants. Generally, the Olkaria geothermal power plants generate about 200kg/s of hot brine at 6bars [8]. 70% of this is from its Northeast field which supplies power to Olkaria II. The rest comes from Olkaria I power plant. However, more than 90% of this brine from the Olkaria East field is currently directed to the infiltration lagoon. However, this is not sufficient use of the hot brine as still before the infiltration lagoon there is still the possibility of utilizing the hot brine. Apart from the lagoon the rest of the brine is reinjected back. This is the case for the brine from the Northeast field, all the brine is reinjected and therefore it can be easily utilized before reinjection so as to improve the plants efficiency. In addition, an exergy analysis done by for Olkaria I geothermal power plant shows that the plant does not operate at full capacity, but produces 11 MW thermal energy loss in the steam transmission system and 6 MW of thermal energy is wasted in the separated brine. The brine produced by the interconnected production wells is currently discharged to the open drains while still at high temperatures (greater than 160°C), high pressure (6 to 9 bar) and at 197 tons/hr in which is a significant amount of available energy that is lost [1]. This is one of the potential and untapped resources for geothermal electricity production. However, no study has been done to analyze this resources from the existing power plants and rank this resources and their potential as a resource for ORC plants in Kenya.

1.2 Rationale.

Generally, geothermal energy production is very expensive both to the developed and developing countries. Right from the initial stages of exploration to drilling of new geothermal wells and putting up an operational and running power plant it is usually capital intensive. Therefore, Kenya as a country needs to look for alternative ways of reducing this costs while still exploring the vast resource of geothermal energy it has so as to supply it high and increasing demand for energy. Some of the ways is the birth of wellhead power plants technology. Wellhead is an innovative new technology developed and pioneered by KenGen in Kenya so as to enable early generation of electricity from single wells before construction of large power plants. This in turn has benefits in terms of revenue collection from early generation and which will enable company meet its cost of drilling and cost of power plant development. In this technology steam is tapped in mobile power plants while awaiting installation of large plants.

Increasing the power capacity of an existing geothermal power plant is another untapped area for Kenya to look at as it is looking on ways to reduce this huge investment related to geothermal energy. This can be obtained in a cost effective manner by utilizing otherwise untapped geothermal energy, from the existing geothermal power plants hot brine, without necessary drilling new production wells. Moreover, this re-powering also provides additional environmental benefits.

Looking at the geothermal plants configuration (See table 1.1 below) in Kenya most of the plants have convectional single flash plant which have hot brine rejected at or above 160 ºC and on average 6 bars [9]. The hot brine is usually reinjected at very high temperature by using this brine in the existing plants we can produce and increase the power plants capacity by incorporating ORC plants. This utilizes untapped geothermal resource without any new drilling this in turn improves the overall efficiency of the power plants and profitability of the plant. In addition, using the reinjected brine is also environmental friendly. For instance, the available energy of the separated brine in Olkaria I geothermal power plant presents a potential for improvement. 6 MW of geothermal energy that is currently wasted in the separated brine, this brine can be utilized by employing a binary cycle power plant to generate more electricity [1].

Binary plant technology is a very cost-effective and reliable means of converting into electricity the energy available from geothermal fields (below 170 °C) [8]. Binary plants are usually constructed in small modular units of a few hundred kWp to a few MWe capacities. These units can either be linked up to the existing power plants to efficiently use this waste energy and improve their efficiency and capacity; or independent power plants (low-medium temperatures and water dominated geothermal fields which have a high environmental benefit as compared to conventional plants due to the fact of almost 100% reinjection of geothermal fluids.

The Olkaria geothermal reservoir in Kenya has performed well and it should be developed further to realize its full potential since it is still under-utilized. Energy utilization of the Olkaria resource will remain low unless some use is found for the energy contained in the water portion [10]. Not all the geothermal well drilled in Kenya are or have high enthalpy so that they can qualify for the conventional flash plants some wells are water-dominated with low and medium geothermal fields. This make strong candidates for geothermal ORC binary plants rather than the wells being disregarded. Their production can be maximized by use of ORC plants. ORC plants have been found to have a multiple effect when it comes to its advantages.

Kenya as a one of the first African countries to utilize geothermal it needs to always adapt to the changing environment and invest on new technology. ORC power plants are quickly gaining momentum from its above mentioned advantages we can clearly see Kenya's keen interest from the expression of interest advertised for a feasibility Study on Binary Power Generation from Brine Produced at Olkaria I & II Power plants [11].

Table 1.1- Configuration and capacities of power plants in Kenya [7].

LOCALITY	POWER PLANT NAME	YEAR COMMISSIONED	NO. OF UNITS	TYPE OF UNIT	TOTAL INSTALLED CAPACITY (MW)
OLKARIA	Olkaria I	1981 (15MW), 1982 (15MW), 1985 (15MW)	3	Flash Plant	45
OLKARIA	Olkaria II	2003	3	Flash Plant	70
OLKARIA	Olkaria II Unit 3	2010	3	Flash Plant	35
EBURRU	Eburru	2010	1	Flash Plant	2.5
OSERIAN	Oserian	2003, 2006	2	Binary	4

OLKARIA	Olkaria Wellhead OW37	2013	1	Flash Plant	5
OLKARIA	Olkaria Wellhead OW43	2014	4	Flash Plant	12.8
OLKARIA	Or Power 4 - Unit I	2000	-	Binary	52.8
OLKARIA	Or Power 4 - Unit II	2008		Binary	39.6
OLKARIA	Or Power 4 - Unit III	2014	1	Binary	17.6
OLKARIA	Olkaria IV Unit 1	2014	1	Flash Plant	70
OLKARIA	Olkaria IV Unit 2	2014	1	Flash Plant	70
OLKARIA	Olkaria I Unit 4	2014	1	Flash Plant	70
OLKARIA	Olkaria Wellhead	2014	1	Flash Plant	32.8
OLKARIA	Olkaria Wellhead	2014	1	Flash Plant	30
OLKARIA	Olkaria I Additional Unit	2014	1	Flash Plant	70
TOTAL					**573**

1.3 Objective.

The main objective of this research is to conduct a pre-feasibility study of the best geothermal resources for use in Organic Rankine cycle power plants in Kenya. To achieve this, we shall have the following specific objectives need to be achieved:

i. To identify possible sources of streams for ORC plant i.e.
   a. To identify geothermal resources in Kenya which do not have sufficiently high enthalpy for conventional plants.
   b. To identify brine reinjection streams in existing geothermal plants which have potential for being heat source for ORC plants.

ii. To rank these possible sources and model ORC configurations for the best source.

iii. To analyse the modelled ORC configurations to assess their feasibility.

1.4 Research Questions.

The questions the research seeks to answer are:

i. Does Kenya have the potential for ORC power plants in terms of -What are the temperature ranges of the available geothermal resources that are not sufficiently high enthalpy in Kenya?

ii. How does these geothermal resources (not sufficiently high enthalpy and water dominated geothermal fields and brine reinjection streams rank in terms of their potential to be used for ORC plants in Kenya (both in terms of technically and economically)?

1.5 Olkaria Geothermal Area Overview – Case Study Area.

Olkaria is located 130km North West of Nairobi and 30km from Naivasha town along Moi South Road. It covers an area of 204 Km^2. It is the first ever geothermal field to be conducted geothermal exploration and it is generally a high geothermal field with Temperature of up to 200°C. This study is based on the Olkaria geothermal area. The local ambient temperature of Olkaria region is on average 23°C while altitude above sea level is about 1505m a.s.l. It is located near the Lake Naivasha region in the Great Rift Valley area and it is in the Nakuru municipal county. The figure below is a map of the physical location of Olkaria within the Rift Valley region.

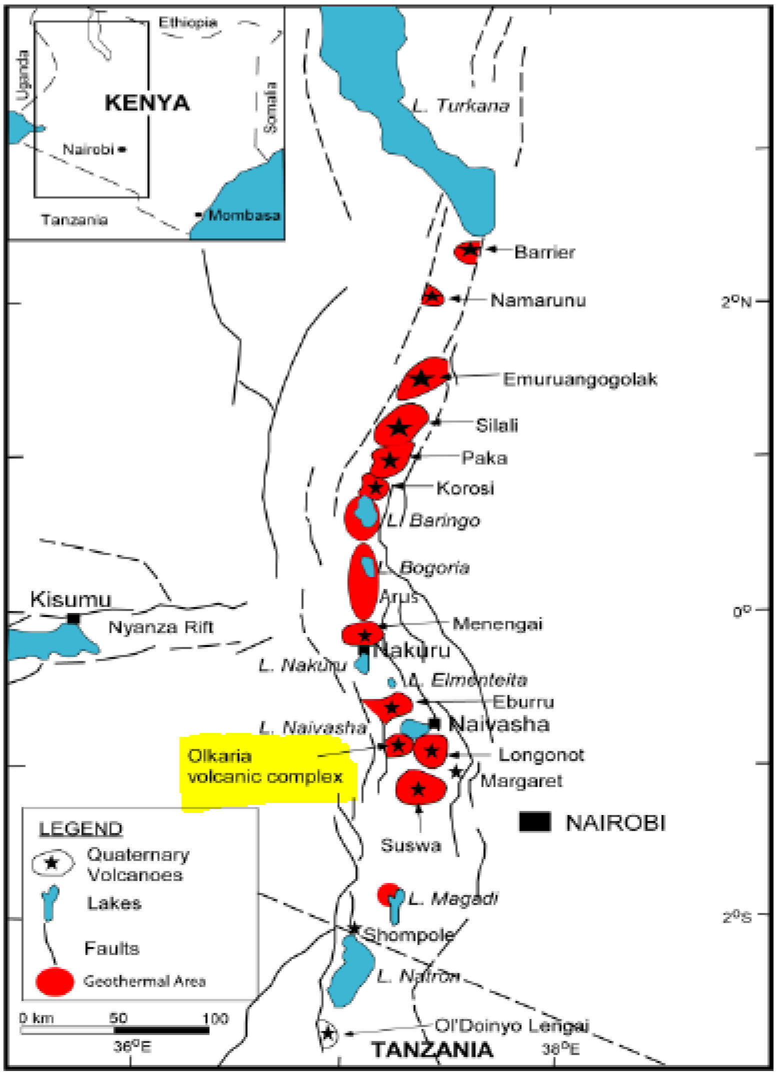


Figure 1.1- Location of Olkaria Field and geothermal prospects within Kenya [7].

Olkaria geothermal field is divided into various sub sections fields they include Olkaria East, Olkaria South East, Olkaria North West, Olkaria North East and Olkaria Domes. This sub section have steam fields with wells that serve and operate four power Plants. They are Olkaria I, II, III and IV.

CHAPTER TWO:

2. LITERATURE REVIEW.

2.1 Background.

Geothermal energy is a renewable source of energy. It originates from two Greek words, “geo” meaning earth and “thermos” meaning heat. Therefore, geothermal is heat coming from the earth. They are two major sources of the earth’s heat or geothermal energy which are a natural occurrence either:

a. Left over heat from the formation of our planet or
b. Radiogenic heat which is as a result of radioactive decay within the earth

Geothermal energy tends to be relatively diffuse, which makes it difficult to tap. On average, the temperature of the earth increases by about 3ºC for every 100 m in depth. This means that at a depth of 2 km, the temperature is about 70ºC, increasing to 100ºC at a depth of 3 km, and so on. However, in some places, tectonic activity allows hot or molten rock to approach the earth’s surface, thus creating pockets of higher temperature resources at easily accessible depths [12].

Geothermal energy can either be used directly or indirectly that is to generate electricity. Some of the applications that can be used directly include:

i. Domestic use such cooking and heating.
ii. Recreation activities such as spas, steam and sauna baths.
iii. Commercial services - Agricultural such as drying crops, green houses.

The heat can also be used for electricity generation (indirect use) by drilling wells into the earth’s crust and trapping this heat so that it can be used to drive turbines that will in turn generator electricity by turning generators there are various configurations of geothermal power plants.

Geothermal resources are majorly classified based on temperatures that is either high, medium or low temperatures [13].However more detailed analysis has been done so as to understand better the resource. Detailed classification based on more aspects such as temperature, enthalpy and nature of geological setting are available as shown on the table below. [14]

Table 2.1- Summary of categories of geothermal systems [14]

TEMPERATURE	**ENTHALPY**	**PHYSICAL STATE**
LOW TEMPERATURE (LT) SYSTEMS I. RESERVOIR TEMPERATURES AT 1KM DEPTH 150ºC II. CHARACTERIZED BY HOT SPRINGS OR BOILING SPRINGS	Low enthalpy systems i. Reservoir fluid enthalpies less than 800kJ/kg. ii. Temperatures less than about 190ºC	Liquid dominated reservoirs i. Geothermal reservoirs with water temperature at or below the boiling point at the prevailing pressure and the water phase controls the pressure in the reservoir ii. Some steam may be present
MEDIUM TEMPERATURE (MT) SYSTEMS I. RESERVOIR TEMPERATURES AT 1KM DEPTH BETWEEN 150-200 ºC		
HIGH TEMPERATURE (HT) SYSTEMS	High enthalpy	Two phase geothermal reservoirs

<table>
<tr><td rowspan="2">I. RESERVOIR TEMPERATURES AT 1KM DEPTH ABOVE 200ºC.
II. CHARACTERIZED BY FUMAROLES, STEAM VENTS, MUD, POOLS AND HIGHLY ALTERED GROUND</td><td rowspan="2">i. Reservoir fluid enthalpies greater than 800kJ/kg</td><td>i. Steam and water co-exist
ii. Temperature and pressure follow the boiling point curve.</td></tr>
<tr><td>Vapour dominated reservoirs
i. Temperature is at or above boiling at the prevailing pressure.
ii. Steam phase controls the pressure in the reservoir
iii. Some liquid water may be present.</td></tr>
</table>

Another category of geothermal systems includes geological setting and nature. Here geothermal resources are further classified into volcanic, convective fractured controlled, sedimentary geo-pressured, hot dry rock also known as enhanced/engineered geothermal system (EGS) and shallow resources [14].

The Lindal's diagram below shows the various temperatures available for geothermal and their application.

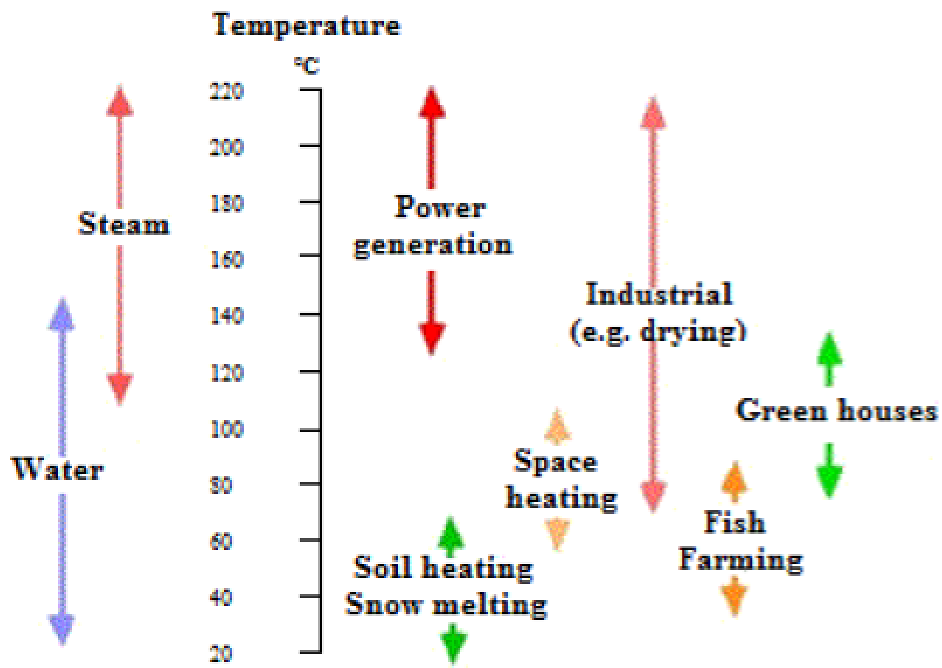


Figure 2.1- Lindal's geothermal utilization diagram

Some advantages of geothermal include:

1) It is a renewable source of energy which is non-polluting and thus being environment friendly.
2) Geothermal energy can be used directly. In ancient times, people used this source of energy for heating homes, cooking, etc.
3) Maintenance cost of geothermal power plants is very less.
4) Unlike other renewables for example solar, wind and hydro energy, it is not dependent on the weather conditions thus making it very reliable.

However, it also has some drawbacks that is:

1) Geothermal energy is site dependent and only few sites have the potential of Geothermal Energy in the world.

2) Most of the sites, where geothermal energy is produced, are far from markets or cities, where it needs to be consumed thus the need to have long transmission line which are expensive.
3) There is always a danger of eruption of volcano.
4) As it is with most renewables the initial cost of Installation cost of steam power plant is very high.

2.2 Geothermal Around the World and Kenya.

As at January 2015 the global geothermal installed operating power plants had a capacity of 12.8 GW power generation spread across 24 countries. According to the analysis done by Geothermal Energy Association, as at 2014 a total of 21 new power plants came online in adding about ~610 MW of new capacity to electricity grids globally. Based on this statistic this is the most capacity to come online in one year since 1997. Geothermal global growth has had a steady growth rate of 5% since the last three years. Geothermal is expected to grow between 14.5 GW and 17.6 GW by 2020 globally. However, if all countries would follow their set targets on renewables this would result to geothermal market reaching 27-30 GW by the early 2030s. According to the World Bank a large proportion of electricity demand for up to 40 countries globally could meet by geothermal energy. Looking at the current technology and geological knowledge only 6.5% of the global potential is tapped [15]. The figure below shows the global view of the potential of geothermal resource.

Kenya is the first African country to start exploiting the geothermal energy in Africa and has been exploiting the resource for the last 32 years. Exploration was commenced in 1956 in the areas mainly located on the floor of the East African Great Rift Valley region at a distance of about 120 km northwest of the capital city, Nairobi. The estimated geothermal resource potential was about 7,000 to 10,000 MW in 2013. Out of these, Olkaria geothermal field operated by Kenya Electricity Generating Company (KenGen) is the largest exploited field with an installed capacity of 573MWe from four power plants. Out of these 110MWe is operated by Or Power and 463Mwe by KenGen while 22.4MWt is used for direct use by

Oserian flower farm to heat green houses and fumigation of soils at the farm. In addition, the flower farm has 4MWe installed for its own use to generate electricity for the farm.

Geothermal resources development in Kenya has gained momentum with the recently formed company Geothermal Development Company (GDC) that as incorporated in 2008 and whose purpose was to fast track the development of geothermal resource in Kenya. As of end of October 2015, GDC had 409 MW of steam at the Olkaria geothermal field, out of which about 320 MW has been converted into electricity and fed into the national grid. Further, GDC has mined 135MW of steam at the Menengai [16]. More and more drilling is still being done in Menengai by GDC as well as detailed exploration has been undertaken in Suswa, Longonot, Baringo, Korosi, Paka and Silali geothermal prospects and exploration drilling is expected to commence in year 2015 in Baringo – Silali geothermal area. Lastly KenGen is still also developing geothermal with the recently commissioned 280MWe in September and October 2014 Olkaria 1 Additional Unit (AU) and Olkaria IV plans are also underway for Olkaria V [7].

Figure 2.2- Kenya’s geothermal prospects [17].

Currently the installed capacity globally of geothermal and the developing geothermal power markets installed capacity in MW as reported by the 2015 annual US and global geothermal power production report is shown on the table below.

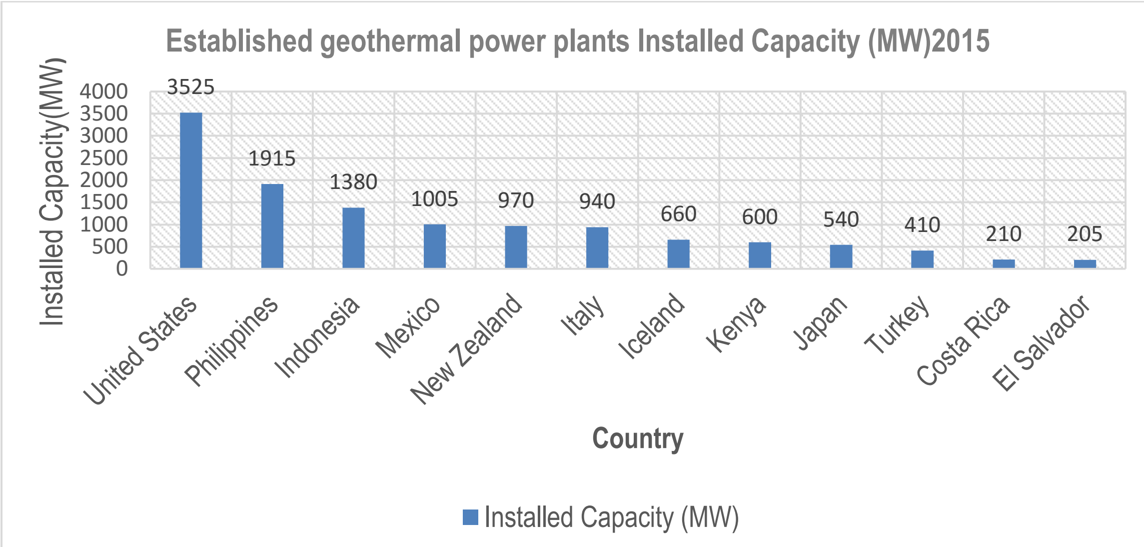


Figure 2.3 -Established geothermal power plants Installed Capacity (MW) [15].

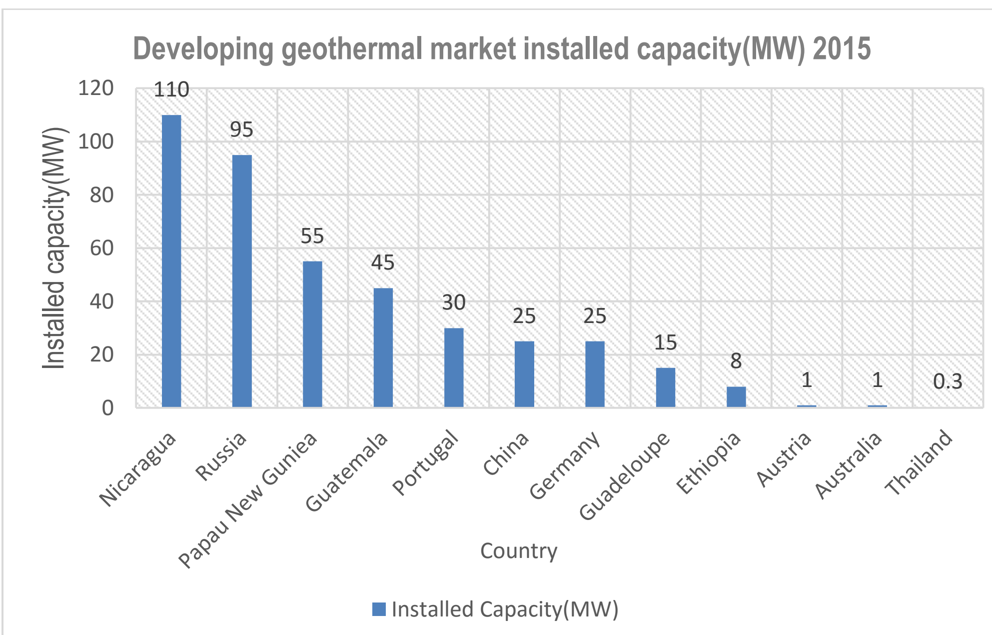


Figure 2.4- Developing geothermal market installed capacity [15]

2.2.1 Geothermal utilization in Kenya.

Geothermal utilization is the extraction of mass and heat from a geothermal source. In Kenya, geothermal has been majorly utilized for electricity generation. However, only 4%

of Kenya's potential in geothermal energy has been exploited. This is so despite the country's huge potential of the geothermal resource. With regard to direct use of geothermal energy in Kenya little has been done and more attention is needed to be focused on direct use to help utilize this abundant resource of energy [13]. Kenya's geothermal resource is mainly concentrated along The Great Rift Valley. One of the biggest geothermal fields is the Olkaria geothermal field which is operated by Kenya's leading power producer Kenya Electricity Generating company. Other geothermal field is the Menengai geothermal field operated by the Geothermal Development Company of Kenya. Currently, the Olkaria geothermal field has and operates four conventional geothermal power plants at Olkaria (figure 2.5) namely: Olkaria I, Olkaria II, Olkaria IAU (Additional Units) and Olkaria IV located about 120km northwest of the country's capital Nairobi. KenGen also operates well head generators (WHG) at both Olkaria and Eburru geothermal fields and is in the process of starting the development of an additional plant, Olkaria V.

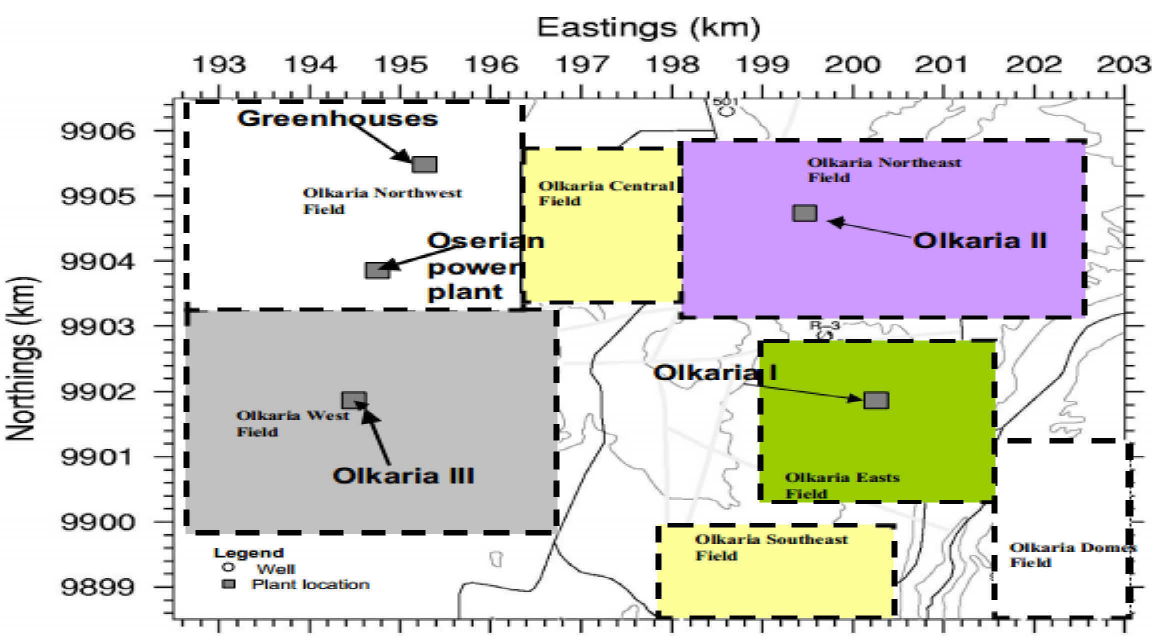


Figure 2.5 - Olkaria Geothermal fields power plants [18].

From the figure 2.5 above, we can see Olkaria III which is run by Or Power 4, Inc., an independent power producer (IPP) is currently generating 48 MWe, 12 MWe from an

Ormat binary plant commissioned in the year 2000 and 36 MWe is from a single flash plant commissioned in 2009. Oserian Development Company, (Oserian), constructed a 1.8 MWe binary plant Ormat OEC in 2004 and 2MWe from a back pressure turbine commissioned in 2007. Both of these plant use wells leased from KenGen [13].

Figure 2.6- Olkaria II power station, commissioned in 2003

The Olkaria geothermal field is a two-phase mixture of steam and hot water in general proportions of 85% steam and 15% hot water which is a suitable resource for electrical power generation [18]. The Olkaria I power plant is a single flash steam geothermal power plant that is constituted of three units commissioned in 1981 to 1984 and each unit generates 15MW of electrical power. The two phase mixture of steam and hot water from the ground enters the steam separator where steam is separated from hot water by density difference and cyclone action. The steam is supplied to the turbine whereas the hot water (brine) is discharged to open drains. The brine produced by the interconnected production wells is disposed at a temperature of greater than 160^{o}C, pressure of 6 to 9 bars and mass flow rate of 197 tons/hr which contain about 3.5% of the total power generated and is untapped energy [19].

Moreover, Olkaria I was observed to have a declining steam production at a rate of 4% during the first 10 years of operation [24]. Consequently, the capacity of the power plant was reduced from 45 to 30 MW. In order to restore the design capacity, make up wells were drilled and the declined wells were retired. Recently some of the retired wells in the Olkaria field are being used as reinjection wells [4]. However, drilling additional wells is not a sustainable approach to utilization of geothermal resources and may increase the possibility of local earthquakes [24].

As for direct use as earlier mentioned little has been done and a lot of research is being done to utilize this form of use of geothermal energy. Some of the commercial applications of geothermal energy in Kenya include:

- The Oserian which leased a well OW-101 from KenGen since 2003 for green house heating as shown below.

Figure 2.7 - Direct use in Oserian flower farm [13]

- Eburru geothermal resource where the local community use geothermal energy for drying pyrethrum products.
- Other minor geothermal direct uses are at Lake Bogoria hotel, where a naturally occurring geothermal hot spring is being used to warm a swimming pool. With most recently the installed geothermal swimming pool at Olkaria.
- The geothermal features such as hot springs have been also as tourist attraction for Kenya.

2.2.2 Electricity from geothermal energy in Kenya.

Energy in Kenya more so the commercial energy is dominated by petroleum while household electricity is dominated by wood fuel which provides energy needs for the traditional sector including rural communities and the urban poor. The total primary energy consumption on a national level is about 68% of wood fuel and other biomass, closely followed by petroleum at 22%, electricity at 9% (121 KWh per capita) while others including coal accounts for less than 1%. Solar energy is also extensively used for drying and, to some extent, for heating and lighting. Current installed electric capacity in Kenya is dominated by hydro sources which has installed capacity of 820 MWe while fossil fuel fired plants had 776 MW (Table 2.2). During the same period, 573 MWe of geothermal plants were installed and 69.5 MW from wind [7].

Table 2.2- Present and planned production of electricity in Kenya, 2014 [7].

	Geothermal		**Fossil Fuels**		**Hydro**		**Other Renewables (Wind)**	
	Capacity MWe	**Gross Prod. GWh/yr**	**Capacity MWe**	**Gross Prod. GWh/yr**	**Capacity MWe**	**Gross Prod. GWh/yr**	**Capacity MWe**	**Gross Prod. GWh/yr**
In operation	573	5,063	776	4,080	820.2	4,311	69.5	182
Under construction	105	901	0	0	400	2,102	0	0
Funds committed, but not yet under construction	1,115	9,279	0	0	90	473	610	1870
Estimated total projected use by 2020	2,765	21,800	3753	26,718	1310.2	6,886	679.5	2121

2.3 Geothermal Power Plants Configurations (Technologies).

Geothermal power plants configurations are categorized in three main ways depending on the fluid temperature, pressures and chemistry [13]. They include:

- Condensing power plants (dry steam, single or double flash systems) also known as conventional power plants.
- Back-pressure turbines (release to the atmosphere).
- Binary plants (for lower temperature or separated brine).

Globally, up to two thirds of the geothermal technology market (58%) consists of flash technologies, which includes both the including double and triple flash whereas dry steam plants consist of about a quarter (26%). Binary plants consist of the remaining 15%. The remaining 1% consists of back pressure and other developing and experimental types of geothermal technologies [20].

Depending on the enthalpy, geothermal fluid can be utilized either for electricity generation or direct applications. Electricity generation is the most important form of utilization of high-temperature geothermal resources while low to medium resources are better suited for non-electric (direct) application. The table below shows the technology used within which temperatures.

Table 2.3- Technology commonly used in geothermal [13]

Reservoir Temperature	**Reservoir Fluid**	**Technology commonly used**
High temperature >220	Water or Steam	i. Power generation • Flash Steam. • Combined (Flash and binary) cycle. ii. Direct Use • Direct fluid use. • Heat exchangers. • Heat pumps.
Medium/intermediate temperature 100-200	Water	i. Power generation • Binary cycle ii. Direct Use • Direct fluid use. • Heat exchangers. • Heat pumps.
Low temperatures 30-150	Water	i. Direct use • Direct fluid use. • Heat exchangers. • Heat pumps.

Geothermal energy power generation began in the early 1904 in Tuscany village of Larderello when Prince Piero Ginori Conti powered ¾ horsepower reciprocating engine to drive a small generator. He used this power to light a few bulbs in his boric acid factory that was situated in the boron rich geothermal steam field. In 1905, he upgraded the power system to 20kW. However, commercial power generation of geothermal energy through the use of dry steam plants began in 1914 when a 250kW unit was constructed on Lardello to provide electricity in the nearby cities of Volterra and Pomarance. However, in 1944 the power station which and a total power capacity of 136,800kW and annual generation of 900GWh with an annual capacity factor of 75% was destroyed during the World War II. It was later rebuilt and currently has over 740MW installed at the Larderello and nearby geothermal fields of Tuscany region in Italy [20].

In 1958, the first flash plant was constructed in Wairakei, New Zealand to operate commercially the liquid dominated hot water type of geothermal reservoir. This was closely followed in 1960 by the United States when Pacific Gas and Electric Company commissioned an 11MW Geyser Unit. Consequently, this has led to the USA being leader in terms of its installed capacity. [20]

Geothermal power plants technologies are divided into two main cycle power plants groups namely:

i. Steam cycle power plants
ii. Binary cycle power plants

Steam power plants typically known as the conventional power plants. They normally are used in high enthalpies geothermal fields while the binary cycle plants are used for medium, low temperature and water dominated geothermal fields. Steam cycles convert thermal energy from geothermal fluid to electricity by separating the water and steam. The steam is flashed out at high temperatures and it drives steam turbines which in turn generator to generate electricity. The brine is usually either reinjected at either high or low temperatures or flashed again at lower pressures. They are further sub divided into:

i. Dry steam plants.
ii. Flashed steam Plants. Which are further sub divided into
    a. Single flash cycle.
    b. Double flash cycle.

Binary cycle plants on the other hand are plants that use a secondary fluid for example organic fluid or mixture of two fluids that are heated by the geothermal fluid (primary fluid) to generate electricity. The choice of which appropriate geothermal conversation technologies to be used in generation basically depends on the characteristics of the geothermal fluid. Most literature suggest that the major characteristic of geothermal fluid to be considered is fluid temperature with the Lindal diagram as the basis to ensure the most economical technology is selected.

One major advantage of geothermal energy worth mentioning is that geothermal power plants can be fully automated. This means that plant can be operated unmanned and can undergo self-starting in case of tripping off due to faults unrelated to the power plants. This plants can also be monitored and operated remotely. This has a positive impact on the amount spent on operation and maintenance lowering its cost [5]. Some examples of automated plants include Reykjanes and Svartsengi plants in Iceland.

Globally, the flash and dry steam plants are and continue to be more and more prevalent technology and the most developed. Flash technology make up to two thirds of the global market (58%), dry steam is about a quarter, binary comes in at a close third with 15% while the remaining 1% includes back pressure plants and other developing types of geothermal technologies. The graph below shows the technology evolution by turbine technology within the years.

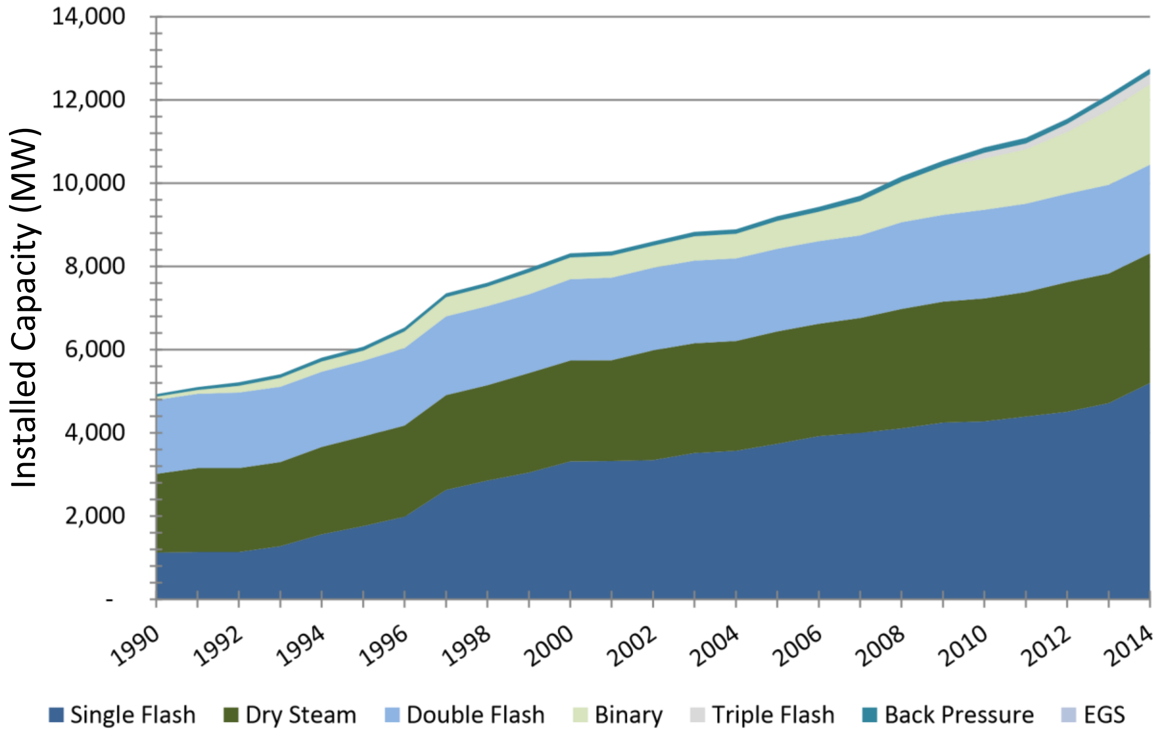


Figure 2.8 - Operating Capacity by Technology Type [15].

The geothermal turbine technology is a mature technology with by several companies who are well knowledgeable. Some of these companies include Toshiba, Mitsubishi and Fuji who are mainly specialized in high temperature projects. The lower and moderate temperatures are dominated by the Organic Rankine Cycle mostly dominated by Ormat Technologies which has provided almost 85 % of the ORC market. However, this is changing since other manufacture have currently started to venture into ORC technology. One of the latest innovation on geothermal technology is the exergy section that has emerged from ORC market. Apart from the geothermal turbine technology and exergy the geothermal market for co-produced fluids geothermal facilities has its place in the geothermal market with ElectraTherm continuing being one of the leaders in its design.

2.3.1 Dry Steam plants.

They are used in dry steam or vapor dominated reservoirs which are generally a rare type of geothermal reservoir to be found globally with the only known reservoirs being

Larderello in Italy and The Geysers in USA. The dry steam consists the noncondensable gases of various composition and concentration. These steam from the wells is cleaned to remove solids, dusts, rock bits and drain pots/traps by use of in-line centrifugal cyclone separators situated near and between each wellhead of the geothermal field. [20] It is passed through pipes which are directly coupled to steam turbines which are coupled to generators in the powerhouse. This is a conventional and well developed technology commercially with available typical sizes in the range of 35-120MW_e capacity. Most recent technology development include the trend of installing modular standard generating units of 20 $MW_{e.}$ For instance, in Italy which has smaller units in 15-20 $MW_{e.}$ [21]. An example of a dry steam generation operation is at the Geysers in northern California.

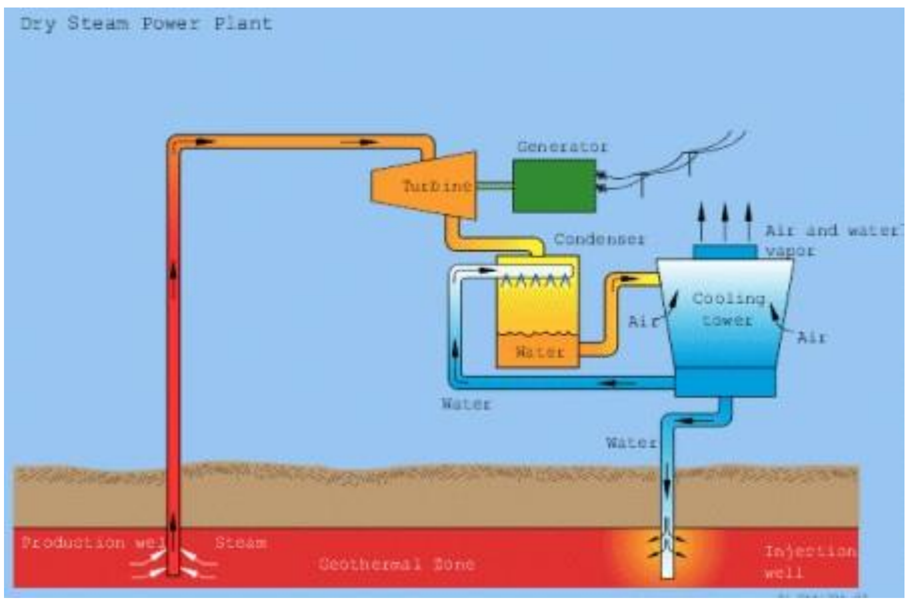


Figure 2.9 - Dry steam power plants [13]

Gas extraction is critical plant component of dry steam plant technology bearing in mind the country's and global environmental standards due to the noncondensable gases found in geothermal steam (2-10% of water of steam but in some cases it can be higher). This is usually done using 2-stage steam ejectors with inter and after condensers however, in some special cases vacuum pimps and tubrocompressors are required [20].

Cooling of this type of plants can either be water cooled or surface type. The latter is used when the noncondensable gases require treatment before being released to the atmosphere due them exceeding the set limits. For instance, a chemical treatment plant for H_2S to remove excess H_2S this is the case of the Geysers plant in Northern California. As for the water cooled condenser the cooled steam is used to make up for the cooling tower water and the excess condensate being reinjected back through the low temperature reinjection wells. This helps in replenishing the reservoir. The air cooled can allow up to 100 reinjection of the steam however it is so far very uneconomical. The mechanical induced cooling towers use either counter flow or cross flow for the water cooling condenser [20].

2.3.2 Flash Steam Plants.

Flash steam plants is one of the oldest (conventional) and first forms of geothermal power plants. When the geothermal source is liquid dominated we use flash dominated plants. It is more complex than the dry steam plants and the most commonly used type of geothermal power plants. The liquid used is usually sufficiently hot (above 160°C). Typically, the flash steam plants of are usually 10-55 MWe. Depending on the steam characteristics, gas content, pressures, and power plant design, between 6000 kg and 9000 kg of steam each hour is required to produce each MW of electrical power. Small power plants (less than 10 MW) are often called well head units as they only require the steam of one well and are located adjacent to the well on the drilling pad in order to reduce pipeline costs. More often than not they won't require and do not have condensers and are called back pressure units. They are very simple to install and cheap however very inefficient with typical use of 10-20 tons per hour of steam and have higher environmental impacts [13]. The flash plants are further sub divided into two sections namely:

2.3.2.1 Single flash systems.

In a single flash system shown on figure 2.10 below the hot geothermal fluid is flashed only once. From the geothermal production well it passes through 1 where it is directed to the separator. The steam and the water separates here and due to pressure differences the steam is flashed out through 2 at high pressures through reducing the pressure of the entering liquid. The steam is then directed into the steam turbines to turn generators and produce electricity. While the separated hot brine is usually reinjected into the well via line 6 and 7. However, depending on the geothermal resource most of this brine is usually at high temperatures and can be a strong candidate for direct use of geothermal. For instance, in Kenya the Olkaria geothermal brine is reinjected at 160 and at 6 bars [9] this is a very good resource for Binary plant as a bottoming plant. After expansion in the turbine condensation occurs at 3. The non-condensable gases if any are treated and expelled at lower and within environmental limits into the atmosphere. The condensate from the turbine is cooled in the condenser. The condenser can either be air called or water cooled. However, the one in the figure below is air cooled, with the cooling air entering the condenser at station c1 and leaving at station c2 with the aid of a pump. The condensed steam is reinjected at lower temperatures via line 4 and 5.

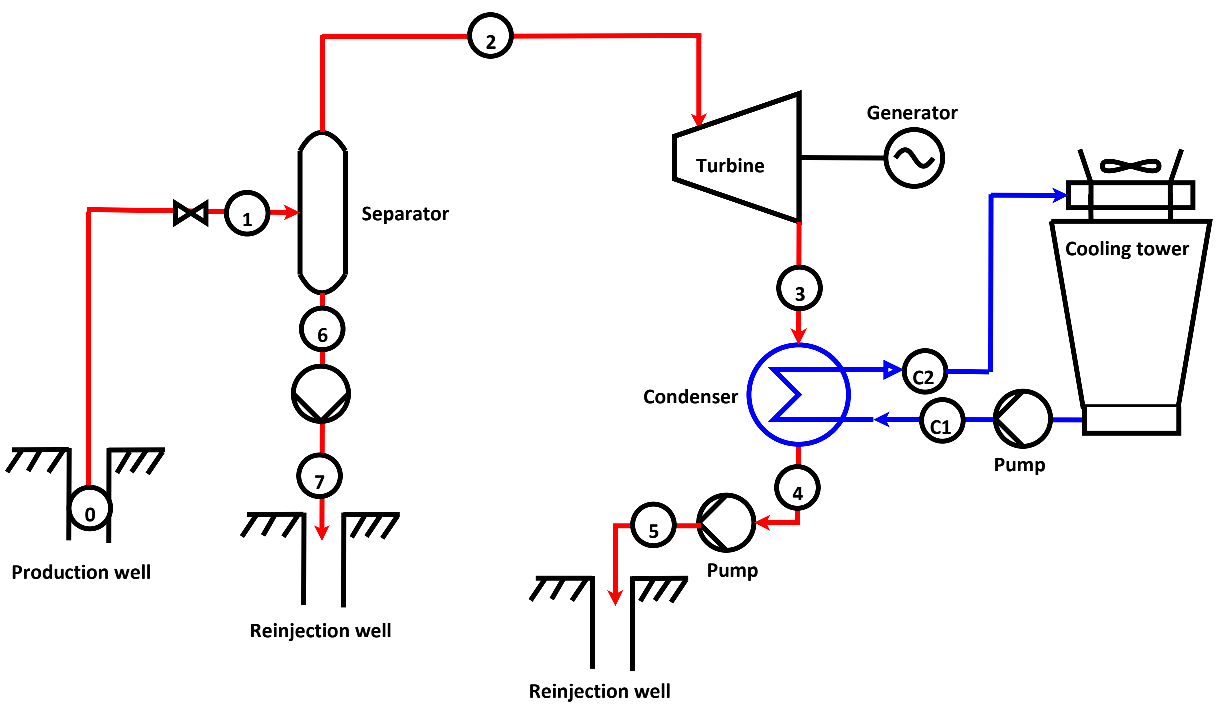


Figure 2.10- Schematic flow diagram of Single flash cycle [5]

2.3.2.1.1 Thermodynamic analysis of Single flash plant.

Thermodynamic analysis of single flash plants is done while considering its flow diagram shown in the figure 2.10 above. The analysis is done with the T-s diagram below in consideration.

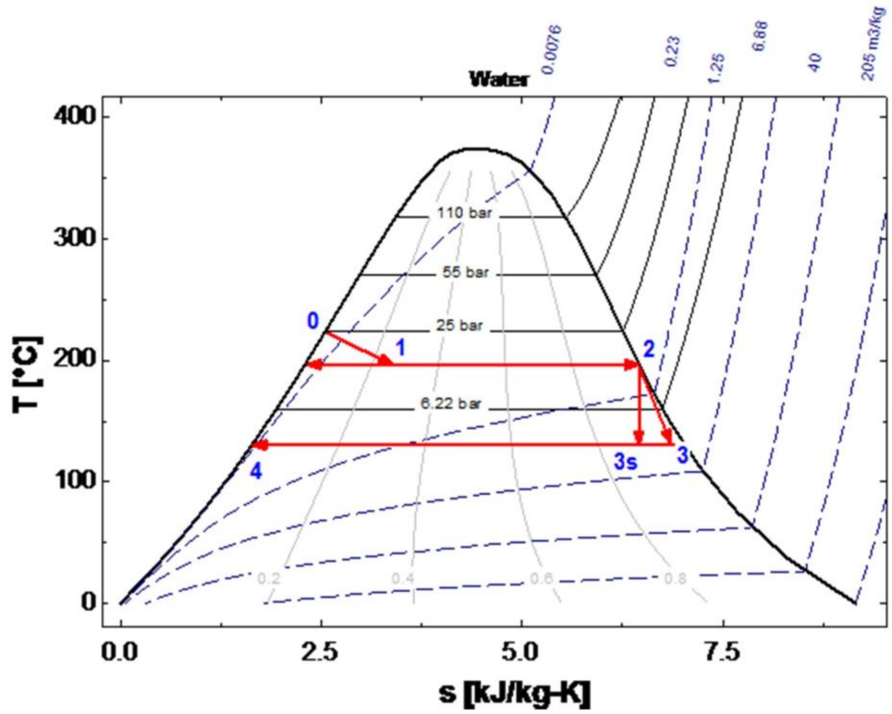


Figure 2.11 -T -s curve of single flash plants

It is assumed that at the production well the geothermal fluid is assumed to be in one state that is liquid phase at a saturated pressure. Another assumption made is that there is no heat long along the pipe network or they are quite small thus being negligible. Thus we assume process 0 to 1 is adiabatic and no mass loss giving us

$$h_0=h_1 \quad (1)$$

$$\dot{m}_0=\dot{m}_1 \quad (2)$$

The fluid is throttled into the separator which reduces the pressure of the geothermal fluid at 1. The reduction in pressure results to the boiling of the fluid. Thus the steam separates from the fluid with it rising up and the fluid staying down this causes the steam to flash out at high pressures and drive the turbines. The level of the separator pressure and enthalpy determines how much steam is produced. Therefore, the lower the separator pressure the more the steam is produced hence the less the liquid by product and vice versa. For a single flash plant, the main aim is to have get optimum steam flow and enthalpy. A key parameter while designing for single flash geothermal plants is an optimal pressure separator by looking at the separator pressure and turbine output relationship. This pressure is coupled along with the wellhead pressure so as to ascertain if boiling starts at the well or not. Considering if boiling starts at the well there is risk of scaling to occur along the fluid path thus blocking the pipes which will result to short life span of the well. This monitored keenly and adjusted made accordingly by adjusting the well head pressure to avoid scaling in the well formation.

Therefore, the steam fraction entering the separator is defined as:

$$x_1 = \frac{h_1 - h_6}{h_2 - h_6} \quad (3)$$

Where x_1 the steam fraction at separator is entrance through line 1 and $h$is the fluid enthalpy.

Thus,

$$\dot{m}1 = \dot{m}2 + \dot{m}6 \quad (4)$$

Where $\dot{m}_1$ is the total mass flow rate entering the separator, $\dot{m}_2$ is the total mass flow rate of steam leaving the separator to the turbine and $\dot{m}_6$ is the total mass flow rate of water leaving the separator

Hence,

$$\dot{m}2 = x1 * \dot{m}1 \quad (5)$$

$$\dot{m}6 = (1 - x1)\, \dot{m}1 \quad (6)$$

The steam from line 2 is expanded more through the turbine converting mechanical power into electrical power. The steam at the turbine entry is at the same state as it leaves the turbine however the pressure drops as a result the enthalpy also drops. Theoretically and ideally the process is assumed to be isentropic (the enthalpy at the entrance of the turbine is the same as the enthalpy of steam leaving the turbine).

Practically this is not the case therefore the isentropic turbine efficiency is given by*:*

$$\eta_{turbine} = \frac{h_2 - h_3}{h_2 - h_{3s}} \qquad (7)$$

Where $\eta_{turbine}$ is isentropic turbine efficiency and h_{3s} is isentropic enthalpy at point 3.

The total work done by the turbine ($\dot{W}_t$)will become:

$$\dot{W}_t = \eta_{turbine} * \dot{m}_2(h_2 - h_{3s}) \qquad (8)$$

Once the steam leaves the turbine it is expelled to the atmosphere through the atmosphere exhaust for a back pressure system. The steam is led to condense from steam or vapor state to liquid state at 3 to 4 via the condenser. The condenser is one of the key important facilities in the flash plants cycle because it assists the turbine in obtaining maximum efficiency in its energy conversion. Pressure at this point is kept as low as possible in order to extract more energy from the turbine process. The condenser is coupled to a cooling system which commonly either uses water or air the water can be either freshwater access or a circulation process with a cooling tower. The lower the temperature of the condenser, the more efficient the turbine process becomes. A cooling tower cools the water from the condenser using air. This means that the condenser temperature can be partly dependent on the local average temperature of the area. There are basically two types of condensing systems either the direct contact condensers or surface condensers.

Direct contact condensers are designed in such a way that the production steam directly contact the cooling water which in turns cools the steam down to form a liquid. While the surface condenser allows two separate fluids to exchange heat without directly coming into contact with each other. Surface condensers require more fresh water for the system to operate effectively and are mostly used in binary power plants however they can also be used in flash plants depending upon the characteristics of the fluid in use. Direct contact condensers are mostly used in flash plants with the ability of the condensate being recycled.

Another component of the flash geothermal plant is the cooling tower system that can either be air or water cooled. For the water cooled system they use water that can either be sprayed in direct contact condensers or passed through the shell and tube condenser that is the surface condensers. As for the air cooled cooling tower air is passed through the use of fans that are electrically driven in most case the electricity used is generated from the power plant itself. Economically it has been found out that it is more economic to use water cooled tower for flash technology and air cooling for binary or even where the water accessibility is limited [5].

Therefore, the heat rejected from the working fluid to the cooling medium in the condensers is given by:

$$\dot{Q}_c = \dot{m}_{wf}(h_3 - h_4) \qquad (9)$$

Where $\dot{Q}_c$the heat is rejected from the working fluid, $\dot{m}_{wf}$ is the mass flow rate of the working fluid and h is the enthalpy.

Hence the heat rejected by the working fluid is equal to heat accepted by the cooling water:

$$\dot{Q}_c = \dot{Q}_{cw}$$

(10)

Where $\dot{Q}_{cw}$the heat is accepted by the cooling water and is given by:

$$\dot{Q}_{cw} = \dot{m}_{cw}(h_{c2} - h_{c1}) \qquad (11)$$

Or

$$\dot{Q}_{cw} = \dot{m}_{cw} * C_{pcw}(T_{c2} - T_{c1}) \qquad (12)$$

Where h is cooling water enthalpy , C_{pcw} is the specific heat capacity for cooling water and T is the cooling water temperature.

The hot water from the condenser is sprayed in the cooling tower where it comes into contact with ambient air. The process converts some amount of water into vapor which is released into the environment and, hence, there is an exchange of both heat and mass between the water and the air. The heat that is collected from the condenser via cooling water is rejected into the atmosphere by evaporation through the cooling tower. When the cooling water reaches the cooling tower, it is allowed to come into direct contact with the ambient air, thereby rejecting the heat to the air. The cooling towers can be designed either with forced air counter flow or induced air cross flow [5].

2.3.2.2 Multiple Flash

It much similar to the single flash both in terms of thermodynamics and flow diagram as shown on the figure 2.12 below. The geothermal fluid is sprayed into a separator tank held at a much lower pressure than the fluid, causing some of the fluid to rapidly vaporize, or "flash." The vapor then drives a turbine, which drives a generator. However, if any liquid remains in the tank, it can be flashed again and again in a second, third or as many tanks that the system is desired to have so as to extract even more energy. An example of a multiple flash plant is a double flash plant. The diagram below shows the schematic flow diagram of double flash steam plants.

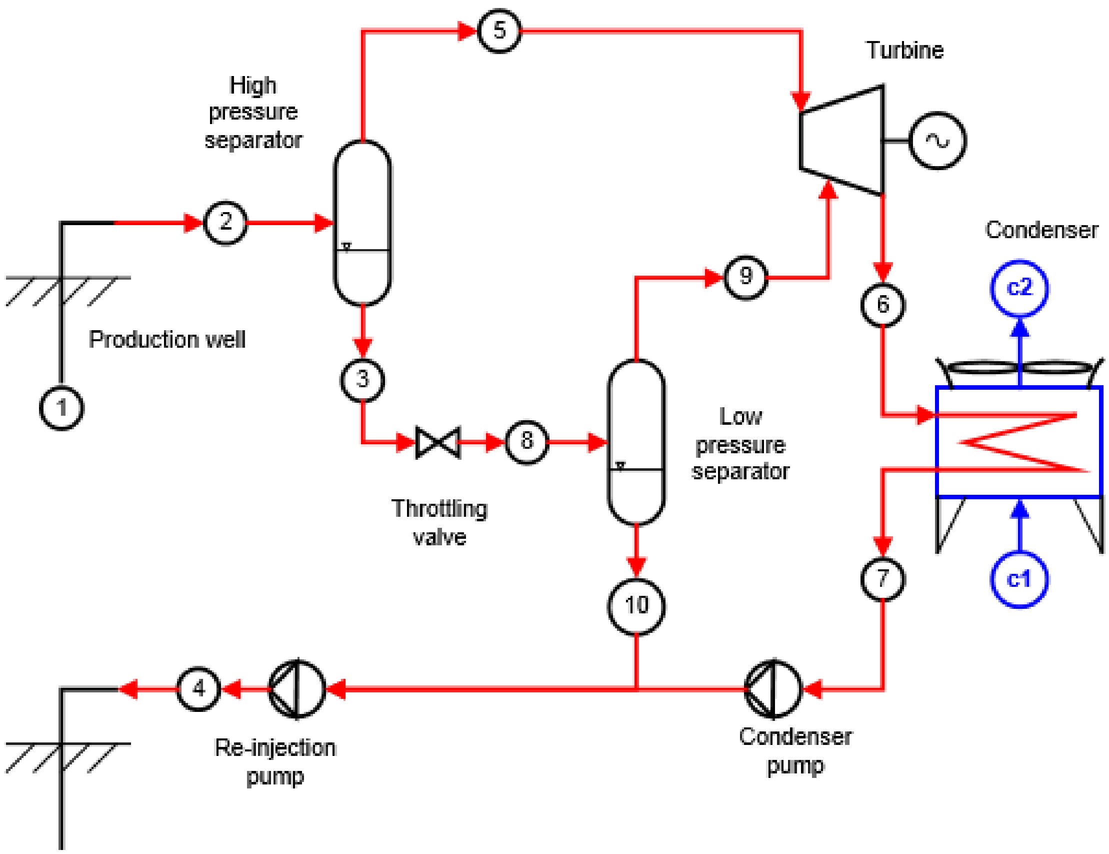


Figure 2.12- Schematic diagram of Double flash power plants [22]

From the flow chart above figure 2.13, the production well releases the geothermal fluid from point 1. As the fluid is entering the high pressure separator it begins to boil due to pressure drop at point 2. At the separator the brine separates and goes down through 3 at a lower pressure as compared to the hot steam that flashes out to go drive the steam turbine through 5. The brine which is partially boiled is passed through the lower pressure separator at 8 through the throttle valve. The low pressure separator separates the steam that passes through 9 to the steam turbine. The steam turbine is designed in such a way, that the pressure difference over the first stages is the same as the pressure difference between the high and low pressure separators. For the low pressure separators, the mass flow is higher than the high pressure separator which is in actual sense the reverse of a traditional fuel fired power plant with a bleed for the feed water heaters from the turbine. At 10 the re-injection of the brine separated from the lower pressure separator take place while that of the hot well is through 7. Both re-injection occurs through the re-injection pump at 4. However, cooling of the condenser is air cooled with air entering at c1 and leaving at c2. The condensate from the turbine occurs 6; where by condensation of the steam from 5 and that of low pressure steam enters at 9 which enters at a later stage [22]. Below are the T-s and T-h graphs for the above double flash plant.

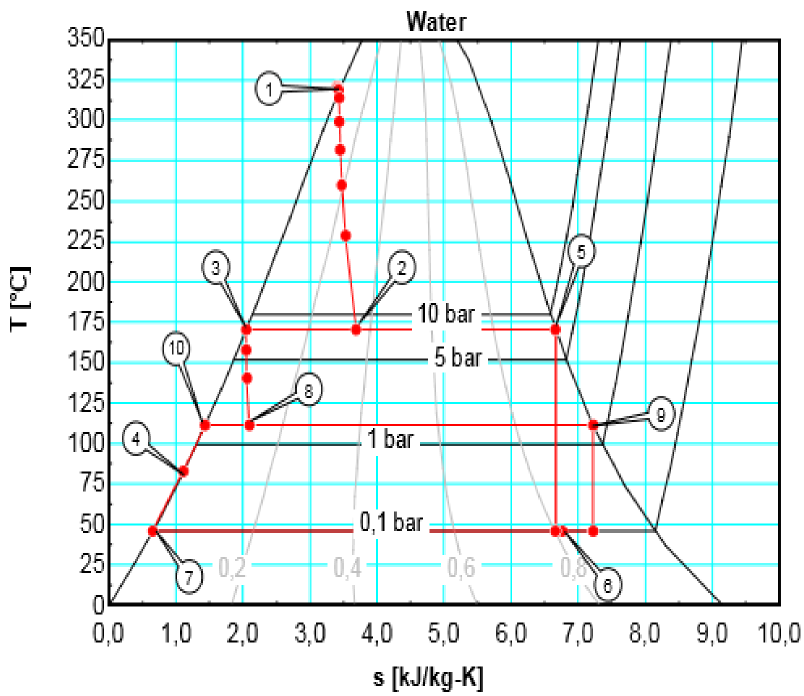


Figure 2.13- T-s curve for double flash cycle [22]

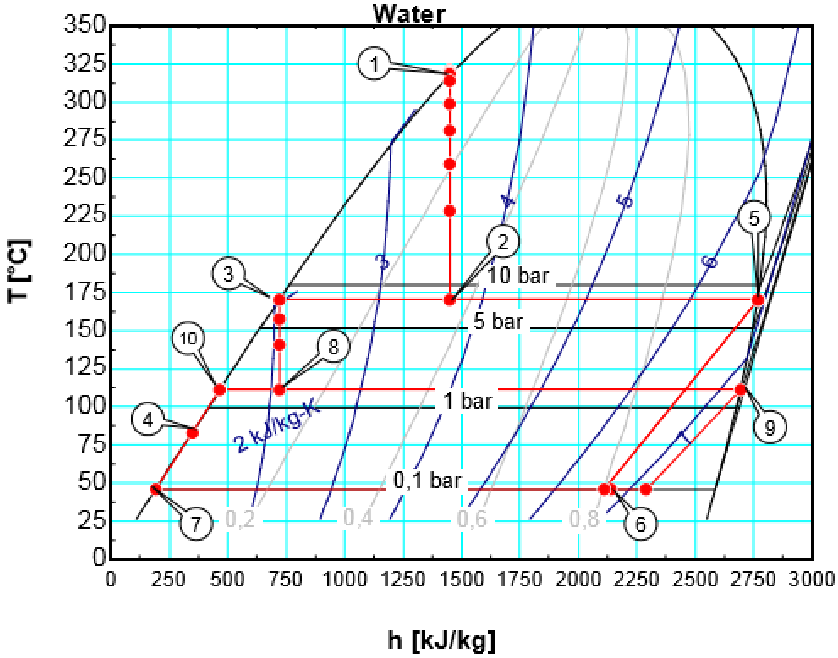


Figure 2.14- T-h curve of a double flash cycle [22].

Generally, the convectional power plants of geothermal that is dry steam plants and flash steam plants are low cost plants due to their simplicity in construction. However, their major drawback is that the geothermal resource is partially utilized. This is so due to the fact that all the only hot steam is used to drive the turbine/generator while the warm brine is rejected and reinjected in the hot and cold reinjection wells respectively. This energy from the rejected brine is usually at mass flow rate of hundreds of tons/hours and temperatures higher than 100°C [19] which is a great potential source for Binary plants. As a result, flash plants have a low efficiency due to the rejected hot brine and most times than not cause thermal pollution to the environment [23].

A comparison between single flash plants and multiple flash plants at the same source and sink temperature shows that double flash plants has a greater efficiency by 3% as compared to single flash. Also the costs of double flash plants are 5% higher than a single flash [19].

2.3.3 Binary Plants.

This is a type of geothermal power plant configuration that is mainly used where geothermal source of heat is moderate to low temperatures and water dominated. The binary configuration normal operates under the normal steam cycle principle with various plant configurations of binary power plants exist. Binary power plants are further subdivided into:

i. Organic Rankine Cycle (ORC)
ii. Kalina Cycle.

Binary plants consist of a heat exchanger which enables exchange of heat from the primary fluid which is the warm geothermal fluid to a secondary ("binary") fluid which has a lower boiling point than water. The steam turbines are driven by vapor from the vaporization of the secondary fluid which has been heated up by the warm geothermal fluid in the heat exchanger. The secondary fluid runs through a closed loop system and it is recycled. The two types of binary plant configurations are distinguished by their characteristic of their secondary fluid. Thus no emissions to the atmosphere occurs. The cooling system of the binary plants can either be air cooled or water cooled.

The operating temperature range for binary plants varies from (85 -170) °C [24] , (120-190) °C [25] and (100-220) °C [26]. This study will analyze the geothermal resources with optimal temperature ranges of 85-220°C. Applications of binary plants on high temperature fields has had issues related to thermal stability with the organic fluid as for the ORC plants [24] while when applied to low temperature fields become impractical and uneconomical. Furthermore, at these low temperatures the heat exchangers size for a given capacity becomes impractical and are the parasitic loads requires a large percentage of power generated [27].

Generally, most recent research show that the binary plants are gaining momentum configuration plants for geothermal plants. Moderate-temperature brine is by far the more common geothermal resource, and most geothermal power plants in the future will be binary-cycle plants.

Binary plants are mostly considered to be a viable energy conversion system technically and environmentally when compared to other geothermal conversion technologies as all the fluid are re-injected and no flashing occurs thus no release of non-condensable gases into the environment. With the increase of demand of cleaner energy Binary plants are the best solution to geothermal technologies advancement and a means to use the Brine from conventional plants so as to improve the geothermal plants overall efficiency.

2.3.3.1 Organic Rankine Cycle (ORC) plants

Organic Rankine cycle is one of the types of binary power plants whereby it uses an organic liquid as its secondary fluid. In the heat exchanger heat from the warm geothermal fluid vaporize the organic fluid which has a lower boiling point than water and the organic fluid expands and releases steam which drives the steam turbine in turn. The organic fluid is then condensed on condenser which is pumped back to the heat exchanger in a closed cycle loop. Here the warm geothermal fluid is not in contact with the steam turbine. ORC plants can also be used for high temperature geothermal sources whereby high temperature thermal oil is used as a heat carrier and a regenerator is added to further improve the cycle performance. The diagram below illustrates the schematic system of an ORC that incorporates a regenerator figure 2.15 with its respective T-s and T-h curves figure 2.16 and 2.17 respectively for a basic binary power plant.

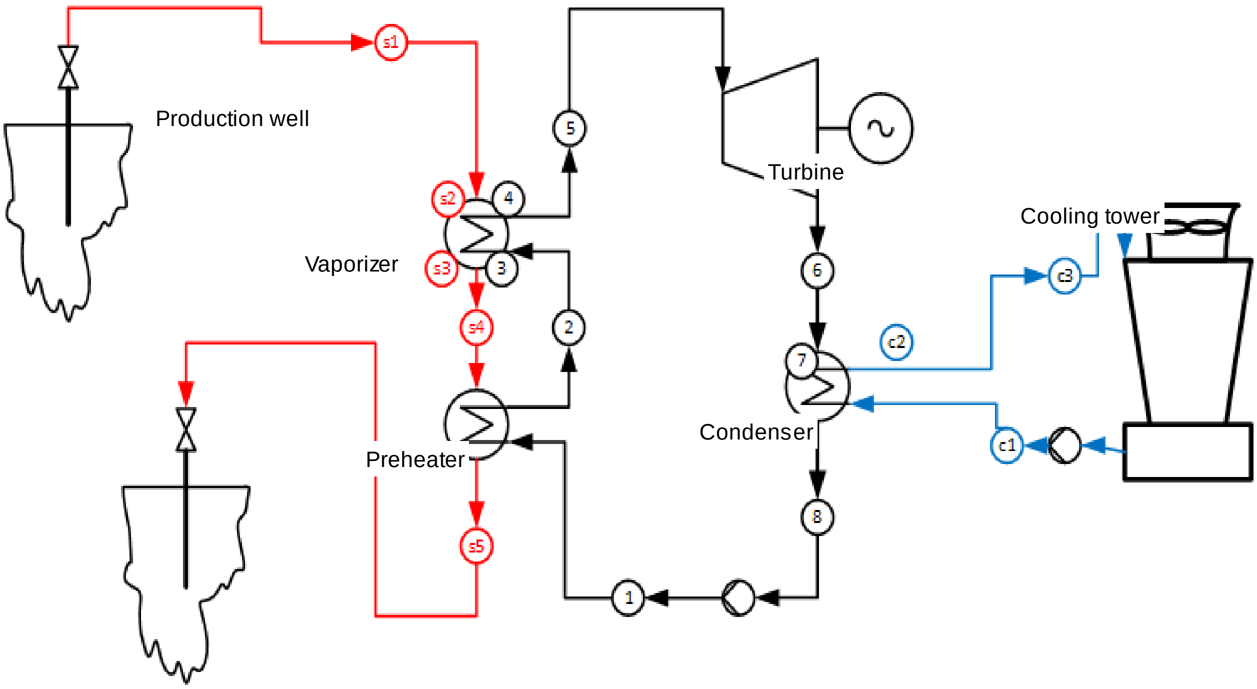


Figure 2.15 - Schematic flow diagram of ORC plant [5].

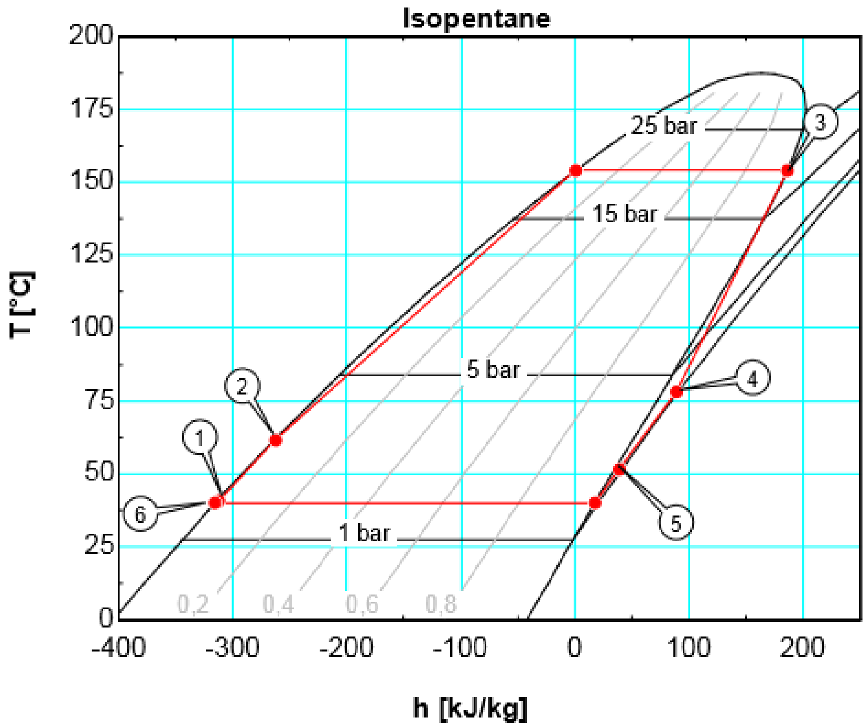


Figure 2.16- T-h curve for ORC using Isopentane [22]

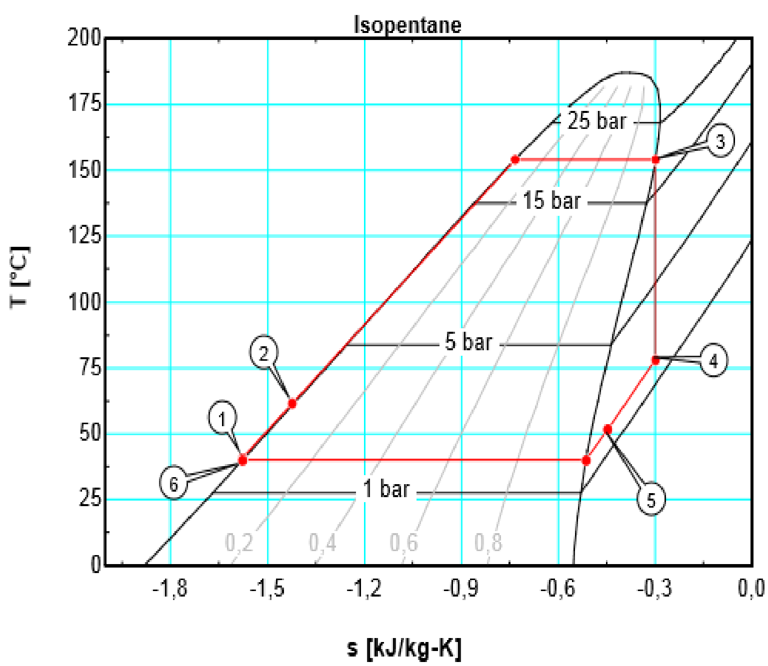


Figure 2.17- T-s curve for ORC using Isopentane [22]

One of the key process of the ORC is the selection of the organic fluid. Due to the low temperature while selecting the ORC organic fluid heat transfer inefficiencies are of concern. Thus refrigerants and hydrocarbons make the best candidate for organic fluid to be used in ORC plants. One of the most commonly used organic fluid is Isopentane. Most of the world's binary ORC plants use Isopentane simply due to its longer experience and proven technology in ORC. However, that is not a must to use Isopentane as the organic fluids others can be used. Importantly to note is that ORC technology can be used in various energy conversion techniques such as solar powered plants, geothermal, biomass combined heat and power and waste heat recovery plants. Some of the organic fluids that can be used apart from Isopentane include Pentane, Benzene, propylene and Toluene just to mention a few [28].

Some of these advantages make it a very good subject of interest to Kenya to study its potential this include:

- High turbine thermodynamic cycle efficiency.
- Low turbine mechanical stress and absence of moisture during vapor expansion responsible for erosion of blades of turbine which in turn lead to simple or minimal maintenance procedures this is particular with Olkaria power plant this will in turn reduce the amount of money spent in maintenance.
- The ORC plants are automatic and do not supervision for continuous operation (in some cases no new operator will be required we shall just use the same operators for the power plants- in the case of in cooperating ORC plant in existing plants). This in turn cuts down on the number of employees hired thus increasing the profitability of the plant since less is paid as salaries.
- ORC plants have long life spans over 20 years.
- No need to demineralize the water. For conventional plants the water has to be treated first before it is recycled so as to demineralize it in ORC plants that is not the case which in turns makes a great financial saving to the amount that would

be spent on building a water treatment plant. The figure 2.15 shows the general layout of a binary plant.

An example of an existing ORC power plants in Kenya is the Or Power and Oserian in Naivasha, Kenya that uses Pentane as its organic fluid and Soda Lake in Nevada USA. Most recently in 2000 one of the ORC producing companies UTC engineered a new system based on ORC technology. It suggested an air conditioner that uses electricity to generate cooling. Whereby the process is reversed and uses heat to produce electricity. The simple evaporation process is entirely closed just like binary plants thus no emissions and all the water is returned to the earth. This system can operate at 75°C geothermal fluid and the refrigerant cab use hydrothermal resources of up to 150°C. Two plants exist of 225kW and are operational in Alaska's Chena Hot Springs resort [29]

2.3.3.1.1 Thermodynamic analysis of Organic Rankine Cycle.

The ORC basically has two working fluids as earlier mentioned. The primary fluid which is the geothermal heat source fluid and the heat source for the cycle and the secondary fluid which is the working fluid. The secondary fluid runs in a closed loop and has low boiling point and high vapor pressure as compared to water at a common given temperature. The secondary fluid will get its heat from the primary geothermal fluid through heat exchangers. The cycle is cooled by a cooling system that is coupled to the cycle's condenser.

For thermodynamics analysis of the ORC cycle as shown on figure 2.16 and 2.17 above the primary cycle is designated with a subscript (s), the secondary cycle with subscript (wf) and the cooling cycle with subscript (c) respectively. The primary fluid heats up the working fluid as shown below.

The geothermal fluid from the well enters vaporizer through s1 this is the primary cycle. It vaporizes and super heats the working fluid at s2. It will leave the vaporizer at s3 and enter the pre-heater to heat up the working fluid so as to exist the pre-heater at point s4. While the working fluid which is the secondary cycle enters the pre-heater at point wf1 to be heated up by the geothermal fluid from primary cycle. Then it enters the vaporizer through point wf2 to be vaporized and superheated by the geothermal fluid and exist the vaporizer at sf3. The working fluid leaves vaporizer as superheated vapor through wf_4 and it is directed to the turbine to turn it and in turn generate power.

Thermodynamically, the heat rejected by the geothermal fluid is receive by the working fluid through the heat exchangers mechanism and is given by:

$$\dot{Q}_s = \dot{Q}_{wf} \quad \text{(kJ/s)} \tag{13}$$

Where $\dot{Q}_c$the total heat is rejected by the geothermal fluid and $\dot{Q}_{wf}$ is the total heat received by the working fluid.

Therefore,

$$\dot{Q}_s = \dot{m}_s * (h_{s1} - h_{s4}) \quad \text{(kJ/s)} \tag{14}$$

Where h_s is source of enthalpy (kJ/kg) and $\dot{m}_s$ is the geothermal fluid mass flow (kg/s)

The total heat rejected by the geothermal fluid can also be given by

$$\dot{Q}_s = \dot{m}_s * \ C_{p\_s}(T_{s1} - T_{s4}) \quad \text{(kJ/s)} \tag{15}$$

Where C_{p_s} the specific is heat capacity of the geothermal fluid (kJ/kg^{-}°C) and T_s is the source temperature (°C).

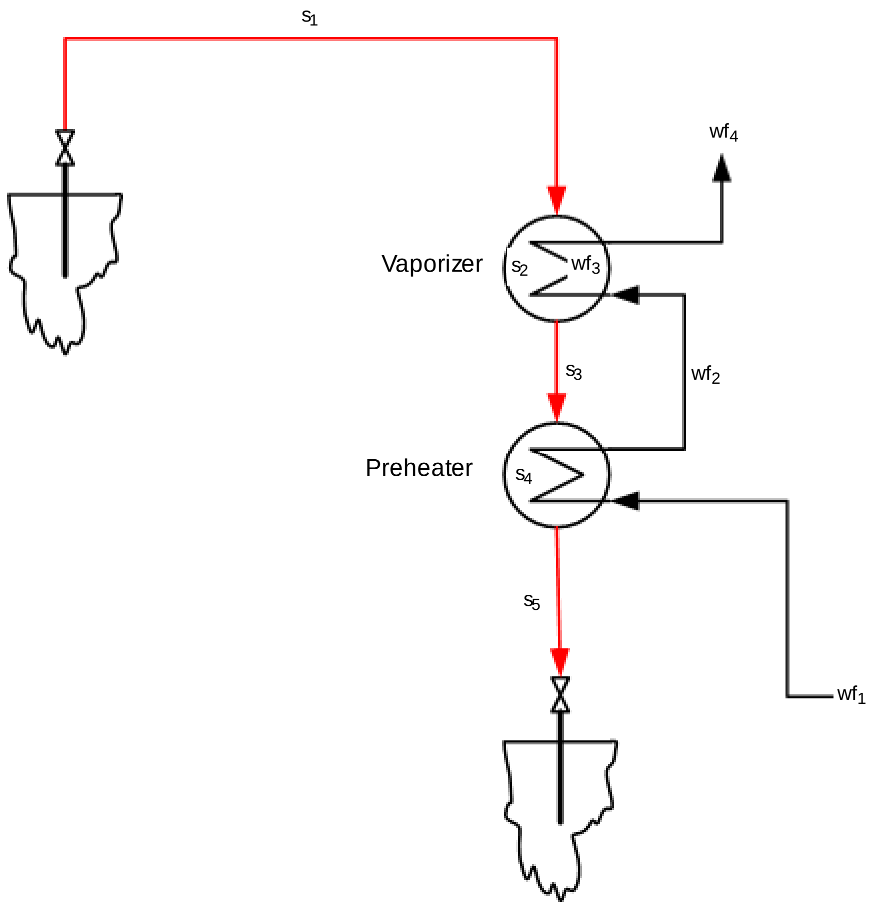


Figure 2.18 - Preheater and vaporizer section of a binary cycle

Therefore;

$$\dot{m}_s * C_{p\_s}(T_{s1} - T_{s4}) = \dot{m}_{wf} * (h_{wf4} - h_{wf1}) \quad (16)$$

For the mass balance cross each component we shall have,

Pre-heater:

$$\dot{m}_s * C_{p\_s}(T_{s3} - T_{s4}) = \dot{m}_{wf} * (h_{wf2} - h_{wf1}) \quad (17)$$

Vaporizer:

$$\dot{m}_s * C_{p\_s}(T_{s1} - T_{s3}) = \dot{m}_{wf} * (h_{wf4} - h_{wf2}) \quad (18)$$

The temperatures at wf2 and s3 have the pinch effect. The pinch effect is the pinch temperature that is the smallest difference that can be reached between the primary fluid temperature and the secondary fluid temperature. This is usually provided by the heat exchanger manufacturers.

This is given by; $$T_{s3} = T_{wf2} + T_{pinch\_HE} \qquad (19)$$

Where T_{pinch_HE} is the heat exchanger pinch temperature difference (°C)

The pinch temperature difference is usually used to determine the heat exchanger sizes in the larger the pinch temperature difference the larger the heat exchanger size and vice versa.

The working fluid leaves the vaporizer at point wf5 to enter the steam turbine as vapor and usually has some pressure drop (ΔP) at the entry point of the turbine. This pressure drop is so small and thus negligible and doesn't affect the work output. The pressure drop is due to vapor transportation in the pipeline connecting the vaporizer to the turbine.

At the turbine the vapor is expanded from wf5 to wf6 where it exists the turbine. The mechanical work produced is used to turn the turbine and as a result turns the rotor of the generator to generate electricity. This work causes a drop in temperature of the vapor thus a drop in enthalpy. Ideally, this process is assumed to be isentropic i.e. entropy at the entry point of the turbine is the same as entropy at the exit of the turbine. However, this is not the case actually an irreversible expansion occurs and there is an increase on the fluid entropy.

At point wf_6 we have both the real enthalpy given as h_{s_wf6} and the isentropic enthalpy given as h_{wf6} .

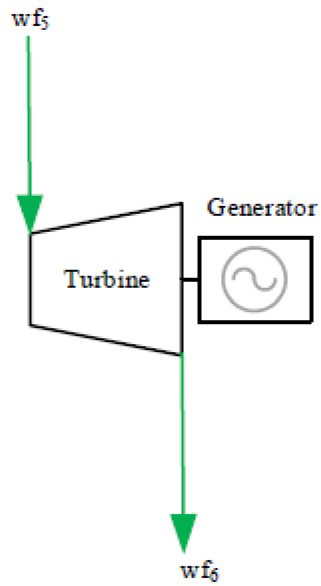


Figure 2.19 - Turbine section of the binary cycle

Therefore, we have a relationship between the enthalpy and the isentropic turbine efficiency given by;

$$\eta_{turbine} = \frac{h_{wf5} - h_{wf6}}{h_{wf5} - h_{s\_wf6}} \qquad (20)$$

The turbine efficiency is generally provided by the turbine manufactures and its common practice to assume it as 85%.

Thus the mechanical work power output done by the turbine is given as

$$\dot{W}_t = \eta_{turbine} * \dot{m}_{wf} * (h_{wf5} - h_{s_{wf6}}) \qquad (21)$$

For a binary cycle without recuperation the vapor will be led to the condenser from the turbine from wf6. The condenser is cooled either through use of water or air and the pressure are kept at minimum with the aim having all the energy extracted at the turbine stage. For one with recuperation the vapor will be directed to the reciprocator to extract any left energy

At the condenser, as shown below the condensing temperature is determined by the inlet temperature, dew point and temperature range of the cooling medium. There is usually a small temperature difference between the dew point temperature of the cooling medium and its exit temperature. The condensing temperature is given as;

$$T_{condenser} = T_{c2} + T_{pinch\_condenser} \text{ (°C)} \tag{22}$$

Where $T_{condenser}$ is the condenser temperature, T_{c2} is the cooling medium dew point temperature and $T_{pinch\_condenser}$ is the condenser pinch temperature difference.

Hence the heat rejected by the working fluid on the condenser assuming all the heat rejected by the working fluid is accepted by the cooling medium is given by;

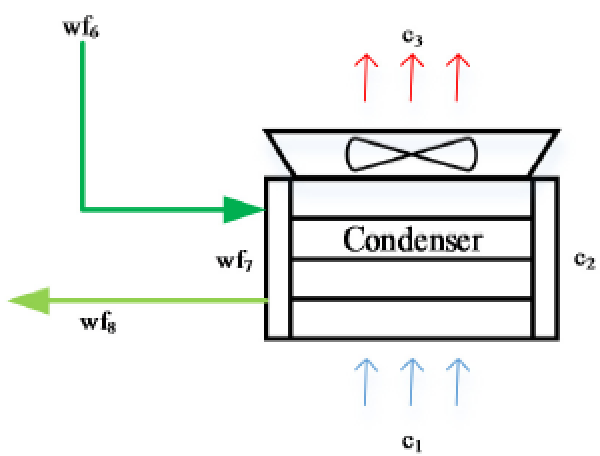


Figure 2.20 - Condenser section of the binary cycle

$$\dot{Q}_{wf\_c} = \dot{Q}_{c\_c} \text{ (kJ/s)} \tag{23}$$

Where $\dot{Q}_{c\_c}$ is the heat to cool the medium in the condenser and $\dot{Q}_{wf\_c}$ is the heat from the working fluid in the condenser.

The heat rejected by the working fluid is calculated as;

$$\dot{Q}_{wf\_c} = \dot{m}_{wf} * (h_{wf6} - h_{wf8}) \text{ (kJ/s)} \tag{24}$$

While that of the cooling medium is found as;

$$\dot{Q}_{c\_c} = \dot{m}_c * (h_{c3} - h_{c1}) \quad \text{(kJ/s)} \qquad (25)$$

Or when we use temperature instead of enthalpy we get;

$$\dot{Q}_{c\_c} = \dot{m}_c * C_{pc}(T_{c3} - T_{c1}) \quad \text{(kJ/s)} \qquad (26)$$

The working fluid is directed to a circulation pump for recirculation after is has been condensed.

2.3.3.1.2 Selection of working Fluid for binary plants.

The working fluid of binary plants has to be carefully selected considering a number of factors. Some of the key factors considered while selecting the working fluid include safety, environmental and the performance of working fluid.

The table below shows the properties of some the binary plants working fluids [30].

Fluid	Formula	Critical Temp (°C)	Critical Pressure (bar)	Toxicity	Flammability	ODP	GWP
R-12	CCl_2F_2	-	-	Non-toxic	Non-flammable	1	4500
R-114	$C_2Cl_2F_4$	-	-	Non-toxic	Non-flammable	0.7	5850
Propane	C_3H_8	96.95	42.36	Low	Very high	0	3
i-Butane	i- C_4H_{10}	135.92	36.85	Low	Very high	0	3
n-Butane	C_4H_{10}	150.8	37.18	Low	Very high	0	3
i-Pentane	i- C_5H_{12}	187.8	34.09	Low	Very high	0	3
n-Pentane	C_5H_{12}	193.9	32.4	Low	Very high	0	3
Ammonia	NH_3	133.65	116.27	Low	Lower	0	0

Water	**H_2O**	374.14	220.89	Non-toxic	Non-flammable	0	-

The environmental safety and health properties of the working fluid should be considered such properties include their toxicity, flammability and its global warming potential. The main aim is to select and use the fluid with the least effect and one that will give less impact. The table above shows that most of the working fluid have lower critical temperatures and pressure than water. Which is helps in reduction of thermodynamic losses in the heat exchanges hence making the fluids suitable for use in ORC plants. The fluids also have a low toxicity levels as well as low ODP and global warming potential.

All things being equal, an ideal binary power plant is considered to have no emissions to the atmosphere hence being environmentally friendly. However, the secondary fluid used in binary plants is mostly flammable and hazardous to the environment such that if not handled properly in terms of leakages, emissions into the atmosphere [20].

2.3.3.2 Kalina Plants.

The most recent improvements in the binary plants is the Kalina cycle plants. The Kalina cycle is different from the ORC cycle in fact that the binary fluid is a mixture of two fluids most commonly used fluids is an ammonia/water mixture instead of one organic fluid. The ammonia/water mixture boils at variable temperature unlike a pure substance (organic fluid) which has a constant boiling temperature. This in turn improves thermodynamic efficiency and flexibility of various operating conditions such as the working fluid matching better with the temperature gradient of the heat source fluid as it cools in the heat exchanger thus increasing heat transfer efficiency. The binary fluid lowers the operating temperatures which in turn increases the relative gain of Kalina cycle as compared to Rankine cycle. A Kalina plant can have large internal heat recovery, and will then have high re-injection temperature when compared to an ORC plant.

For Kalina cycle, condensation can occur slightly above atmospheric pressure due to different mixture composition of the working fluid thus no need of vacuum conditions and costly gas extraction equipment. In addition, the molecular weight for ammonium is similar to that of water which decrease friction and increases the thermodynamic efficiency of the overall process of Kalina cycle. Thus the standard steam turbines can be used in Kalina plants with no need of especially designed process. Lastly, despite Kalina cycle has higher thermal efficiency than ORC and ORC plants coming in standardized modules with longer experiences, Kalina technology is still young and not fully accepted however it is progressing quickly. Countries like Iceland and USA which are focusing more on more on low temperatures reservoirs are focusing on Kalina plants as a more efficient effective and economic solution. The figure 2.21 below shows the Kalina Plant in Husavik, Iceland. This plant is not operating today.

Figure 2.21 - Binary Kalina plant in Husavik, Iceland [29]

A simplified flow diagram of a Kalina cycle is represented by the figure 2.22 below.

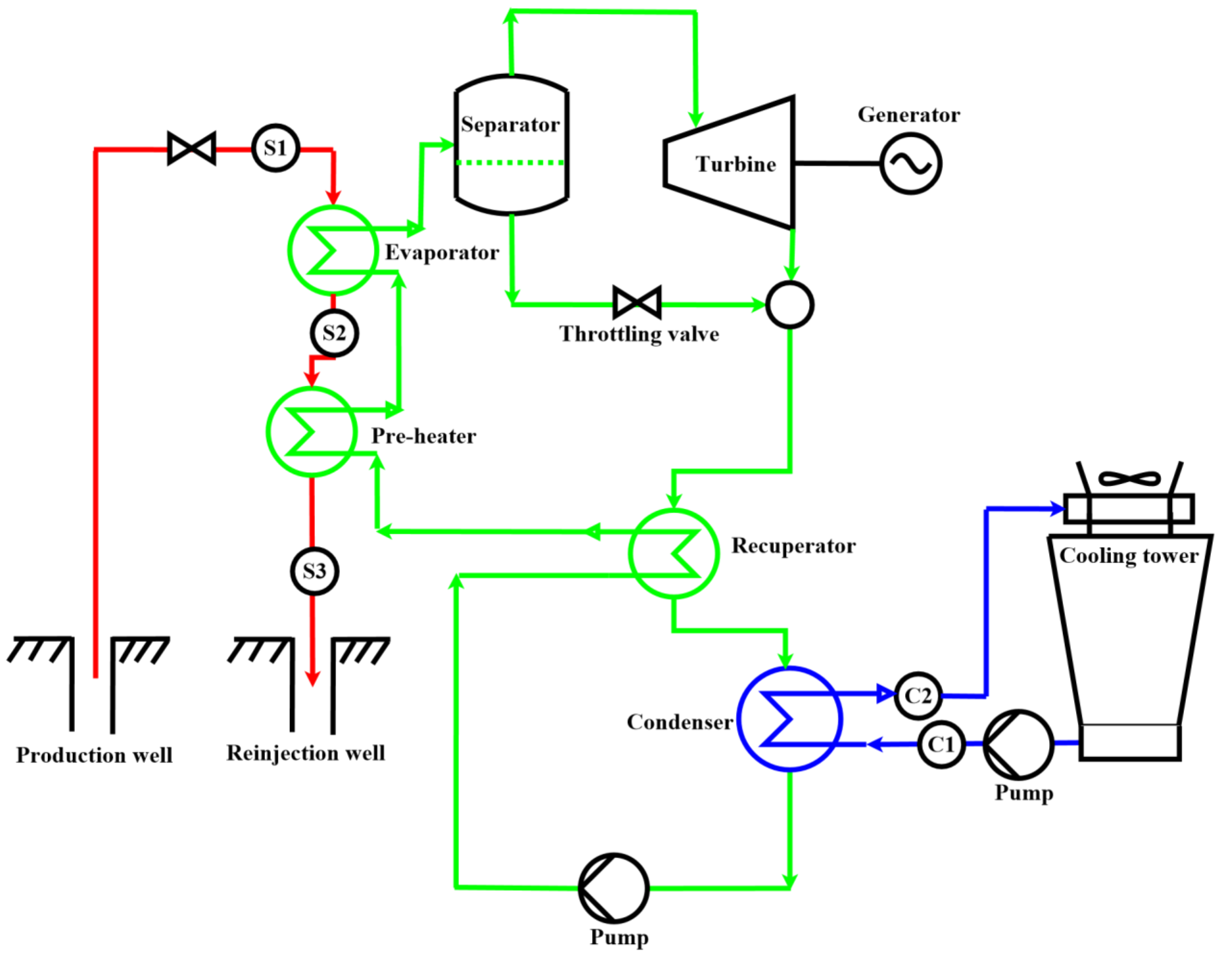


Figure 2.22 - Schematic flow diagram of Kalina power plant [5]

Most recent advancements being made in Kalina cycle is the concept of incorporating an organic fluid in the working fluid in order to maximize the operation. Some of the organic compound being used include mixture of R22 and R114 and mixture of Hexamethyldisiloxane and Decamethyltetrasiloxane. This is mostly use in geothermal operations and waste heat recovery plants mostly due to their different varying thermo-physical properties in the concentration of the working fluid [30]. Some of the added advantages of the Kalina cycles include:

- They have lower upfront capital costs due to smaller heat exchanges and no heat transfer oil loop (compared to ORC systems)
- Are unmanned or minimally supervised and have lower plant auxiliary loads.

- Superior heat transfer means lower demand for cooling water and cooling infrastructure.
- Minimal downtime for maintenance.

2.3.4 Combined Cycle plants.

This type of plants is also known as hybrid cycle plants. As the name states is a combination of two or more geothermal conversion cycle technologies. Mostly combined is conventional plant and binary plants. Flash plants be it single or double is combined with a binary plant. Examples of power plants using combined cycle are the Bottoming power plants whereby the Binary cycle primary source of heat is the back pressure of a flash plant or the brine from a separator. Some of the advantages of bottoming plants is it free from scaling problems [31]. Generally, combined cycle plants improve the efficiency of geothermal plants by using the resource efficiently and avoiding wastage. The diagram below shows a sample of a combined cycle plant the mode of operation is as discussed earlier that is depending on what is combined they will operate based on their individual cycles. The figure 2.23 below shows a combination of a single flash power plant and binary power plant. An example of a combined cycle power plant is the Svartsengi plant in Iceland.

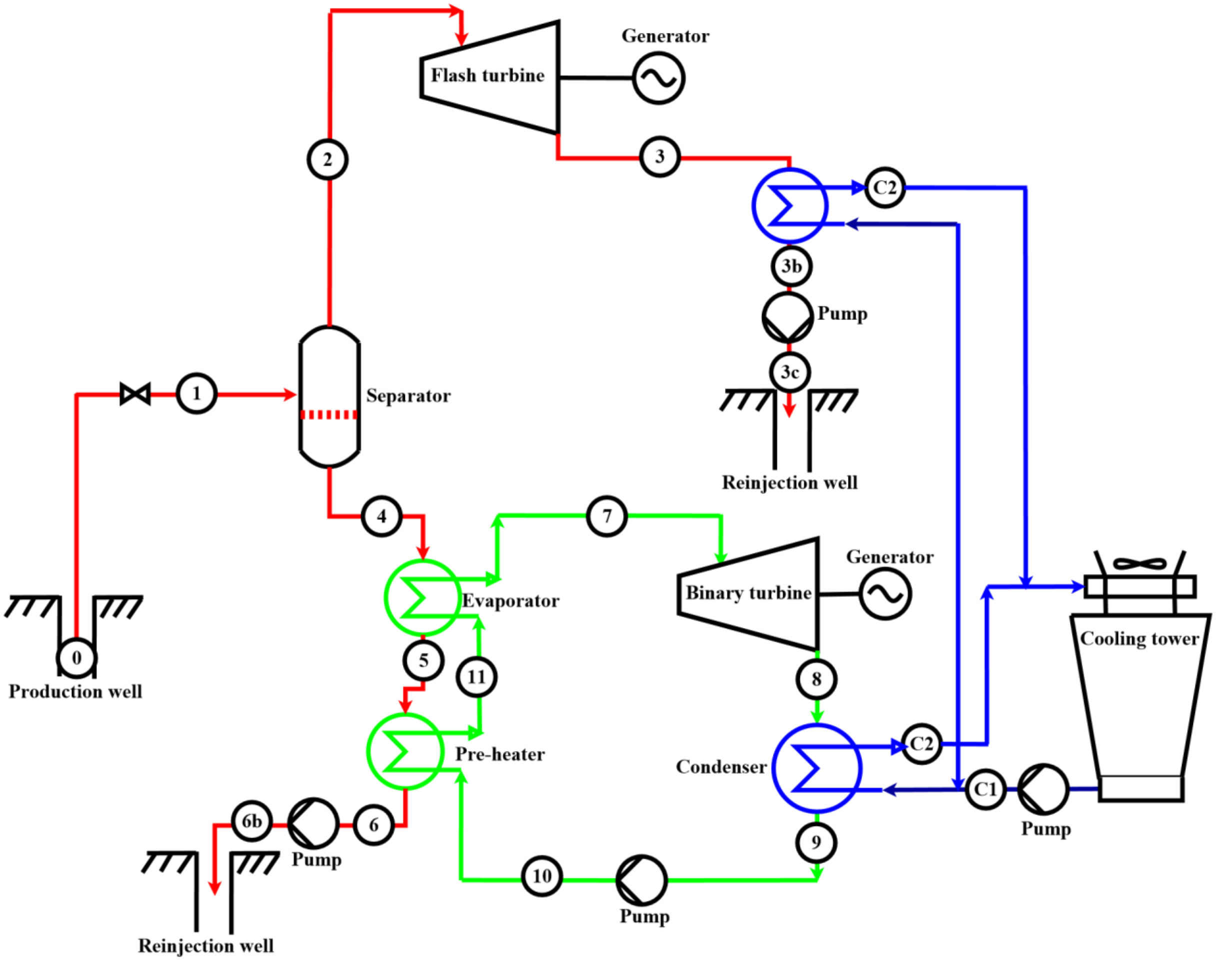


Figure 2.23 - Schematic flow diagram of combined cycle power plant [5]

2.4 Possible Sources of Streams for ORC Plants in Kenya.

Generally, the geothermal systems are associated with the Kenya Rift Valley which is related to volcanism. Kenya's geothermal resource are controlled by two major tectonics regimes

i. Quaternary volcanoes
ii. Fissures related to active fault systems along the flanks of the Rift

The quaternary volcanism are mostly high enthalpy systems and the later which is the fissures related to active faults are low enthalpy systems. The low enthalpy systems are therefore more prevalent along the flanks of the Rift Valley. Sources of streams for Organic Rankine cycle geothermal power plants in Kenya can either be from low enthalpy wells or brine from existing present power plants.

2.4.1 Present power plants.

Most of the present geothermal power plants in Kenya currently are around the area of Olkaria which is mainly a high enthalpy geothermal field. The Olkaria geothermal field has basically conventional single flash type of power plants as earlier seen. A significant and common component of all this power plants is the hot separated reinjected brine in the Olkaria field. Generally, the Olkaria field is a high enthalpy with for over 30 years no reinjection and the surface discharges being higher steam fraction. Currently, the discharge is almost dry steam (> 90 %) while the hot separated brine flow is a significant part of the discharge from the wells (50 – 30 %) [32]. At the domes field (Olkaria IV) the deeper wells drilled there tap mainly in the liquid reservoir with flashing happening as the fluid rises to the surface. At the surface a 50% brine discharge is common. The deeper wells commonly achieve significantly higher discharge pressure and hence higher separation pressure schemes have been employed more recently. At the westerly field (Olkaria III), Ormat under the company Or Power installed binary machines utilizing both steam and brine resources since 1998.

Traditionally, Olkaria has just been using conventional plants and the hot brine being reinjected however studies have shown this is very inefficient and uneconomical Therefore it is important to come to a compromise on this considering the huge costs related to geothermal exploration and utilization. This is still a green area and untapped resource that Kenya needs to explore having being the pioneers on geothermal energy in Africa at large. It is also a market for ORC plants with the use of the hot rejected brine or even better binary power plants like Olkaria III that are environmental friendly and with so low operation and maintenance cost.

In Kenya, the Olkaria geothermal plant has separated brine at typically between 150 – 175 °C and therefore a delta T= (10 – 25) °C is possible mainly at enthalpies in the range of 160 – 220 KWh/t. This ensures a safe limit of about 5°C of the recommended reinjection temperature for avoidance of silica scaling risk [32].

The initial developments at Olkaria involved either dedicated separators at each well or shared separators by two or three wells close to each other. In the 280 MWe developments, the separation process is shared among a number of wells so that for each of the 140MWe with approximately 20 wells, the fluids will be separated at only 3 separation stations. The design itself presents a great opportunity for utilization of the consolidated hot brines available at the separator stations at same conditions. The separators are however designed to allow full reinjection after separation processes.

The saturated conditions of the steam and brine from the separator is as shown below

Table 2.4 Saturated conditions of separated brine from Olkaria Power plants [32]

PROPERTY		**METRIC**		**STANDARD**	
Temperature (*T*)		155.00	∘C	311.00	∘F
Pressure (P)		5.4350	Bar	78.828	psi
Density	Saturated Liquid (ρ_f)	912.28	kg/m^3	56.952	lb/ft^3
	Saturated Vapor (ρ_g)	2.8863		0.18019	
Specific Volume	Saturated Liquid (v_f)	0.0010962	m^3/kg	0.017559	ft^3/lb
	Saturated Vapor (v_g)	0.34646		5.5498	
Enthalpy	Saturated Liquid (h_f)	653.79		281.08	

	KWh/t	181.61			
	Evaporated (h_{fg})	2098.0	kJ/kg	902.0	Btu/lb
	Saturated Vapor (h_g)	2751.8		1183.1	
Entropy	Saturated Liquid (s_f)	1.8924	kJ/kg-K(mayer)	0.45199	Btu/lb-°R
	Evaporated (s_{fg})	0		0	
	Saturated Vapor (s_g)	6.7926		1.6224	

From the table 2.4 above it is very clear that brine is at high enthalpy. Separated hot brine still contains extractable energy (160 – 220 KWh/t). However, before utilizing this separated brine we need to consider scaling conditions.

Brine resources available at Olkaria after the development of the current 280MW project stand at about 1500 t/hr considering the scaling limit of 140 °C [32]. Commonly achieved conversion efficiency of ORC machines gives new and free 20MWe for the four different fields. It is to be noted here that installation of ORC machines is generally expensive and time consuming. The table below gives an analysis showing the available brine resources per field of the Olkaria geothermal field and presents possible generation by ORC technology at 6% conversion efficiency.

Table 2.5- Volarization of brines at Olkaria per field using ORC technology [32].

Field Sector	Brine Flow (t/hr)	Brine Enthalpy KJ/Kg	Separation Temp (°C)	deltaT (140°C)	MWt	MWe (6% eff)
OLK1	13	640	152	12	2.31	0.14
OLK2	164	640	152	12	29.16	1.75
OLK1AU	529	790	186	46	116.09	6.97
OLK4	814	799	188	48	180.66	10.84
Total	**1520**				**328.22**	**19.69**

2.4.2 Low enthalpy wells.

Kenya also has a number of low enthalpy wells that are not within the Olkaria field. This is so due to its position on The Great Rift Valley. These low enthalpy wells require more analysis and study to be conducted on them. A number of these low enthalpy wells are located off the Great Rift Valley which is good for the expansion of the country's grid. These wells occur on the flanks of the Rift Valley and have surface temperatures from (52-95) °C. They include

i. Homa Mountain springs – These springs are located on Homa bay in Nyanza province in Kenya and are located near Lake Victoria The Quartz geothermometry analysis done gave their reservoir temperatures to be of the range (142-179)°C and surface discharge of (64-90)°C [33].
ii. Majimoto springs – They pass through the Mozambiquian metamorphic and Tertiary volcanic rocks and are located near Narok town in Kenya. The Quartz geothermometry analysis done gave their reservoir temperatures to be of about (92) °C and surface discharge of the range (52-57) °C [33].
iii. Kapendo springs – They flow through a volcanic ridge, pass through the Pleistocene sediments and occur along Kapendo region in Kenya. The Quartz geothermometry analysis done gave their reservoir temperatures to be of 126°C and surface discharge of 52 °C [33].
iv. Magadi Springs – These springs are located on the banks of Lake Magadi in the southern part of the Kenya Rift Valley. The entire Magadi basin is covered by several faults that are part of the main Rift Valley. It has 200 geothermal springs which have maximum surface discharge of 95°C and the Quartz geothermometry analysis done gave their reservoir temperatures to be of 150°C [33].
v. Kureswa springs – Along the Kerio Valley which is part of the Kenya Rift Valley these springs are located. The springs flow through Miocene phonolites with and surface discharge temperature of 63°C. Quartz geothermometry analysis done gave their reservoir temperatures to be of 122°C [33].

Looking at these low temperature geothermal resources we see Kenya has a huge untapped resource that can be used for binary power plants especially the ORC plants. For instance, the Homa springs can be used for electricity generation that can be used for cold storage for the fish industry considering it strategic location near the Lake Victoria which is one of the largest producer of fresh water fish.

2.5 Consideration of Scaling Potential.

Generally, geothermal water when in the reservoir, mixes with the host rock thus in the process it dissolves some constituents from the rocks until they reach a chemical equilibrium at reservoir conditions. This depends on a number of factors such as the geology of the resource, temperature, pressure as well as the source of the water. Different geothermal fields will therefore have geothermal fluid with different chemical compositions due to the above factors named. The physical and chemical conditions of the geothermal water changes as the geothermal fluid is being utilized for various uses. As this changes occur some of the dissolved components do not remain soluble in the geothermal fluid thus forming deposits or depositions along the way. However, some of this minerals have a high solubility in the geothermal fluid while the fluid is in higher temperature than in lower temperature. Thus precipitating at lower temperature thus the need to consider and set a reinjection temperature of the geothermal fluid [30].

For instance, in flash system some of the minerals will precipitate when the fluid is being flashed and a portion of the fluid into steam. This precipitate mostly occurs on the surface of the power plant equipment or in the wells. The major scaling chemicals in geothermal power plants are Silica and Calcite scaling. Generally scaling occurs on the power plant equipment and wells (production and reinjection) equipment. Cleaning the scaling once it occurs on the equipment is an additional expense above the generally high production costs of geothermal power plants. Therefore, it is important to design and model geothermal power plants while operating above the limits of scaling [34]. Some of the common and related issues or problems associated with scaling include

- Brine leaks and spills.
- Well and line plugging.
- Reduced brine flow

- Power production losses
- Equipment failure and damage.

Silica scaling mostly is seen in the form of quartz, tridymite, cristobalite, amorphous silica and many others. The most common form that is associated with geothermal is the amorphous silica and quartz [34]. Thus scaling in geothermal is considered while using concentrated fluid with these two chemicals. This is done by checking the geothermal fluid while in the reservoir using quartz and once the fluid has been used and temperatures cooled down the silica solubility is controlled using amorphous silica [30]. In terms of solubility Amorphous silica is more soluble than quartz and this provides a window of opportunity to utilize the geothermal fluid between the quartz solubility curve and the amorphous silica solubility curve without experiencing silica scaling [34] as the fluid tends to precipitate the silica through flashing and lowering temperature. Beyond the amorphous silica solubility curve, scaling is inevitable.

Calcite scaling occurs near the flash point in the production wells due to a decrease in calcite solubility as some fluid turns to vapor. Calcium solubility varies with the pressure of carbon dioxide (CO2) and temperature of the fluid. Prevention of calcite scaling in wells is mostly by using various chemical inhibitors such as sodium polyacrylate. A capillary tube is inserted into a production well to the depth of flashing point where the chemical inhibitor is directly injected for scaling prevention [35]. A common way of preventing Calcite scaling is flashing the production well by keeping the well head pressures sufficiently high thus maintaining the liquid phase.

The Olkaria Field in Kenya is well exploited and studies show that to prevent scaling is to work with a reasonable reinjection temperature way above the 80°C. However, this is not so much of an issue in Kenya considering that most of our power plants are flash. However, for this project it is a fundamental component since we are design for a binary power plant that is using both low enthalpy wells and ejected hot brine from the single flash plants.

To utilize and achieve maximum power from a geothermal fluid the fluid needs to be cooled to the lowest temperature while considering the set limits that scaling starts to occur. As the geothermal fluid is utilized and it cools precipitation starts this encompasses minerals and silica and the fluid becomes supersaturated. The temperature at which this begins is called Silica saturation temperature[1]. It is the temperature of the geothermal fluid at the exit of the heat exchanger before the fluid reaches saturation with respect to the amorphous Silica [34]

Analysis of amorphous Silica is done with respect to temperature and is given by; which gives the SST for a given resource temperature of range 0° to 250°C [36]

$$\log C = \left(-\frac{731}{T} + 4.52\right) \quad (27)$$

Where *C* is the amorphous silica concentration (mg/L) and *T* is the absolute temperature (°K)

For the quartz solubility is given by with also respect to temperature as

$$Q(t) = 41.598 + 0.23932t - 0.011172t^2 + 1.1713 * 10^{-4}t^3 - 1.9708 * 10^{-7}t^4 \quad (28)$$

Where *Q* is the silica concentration (mg/kg) and *T* is the reservoir temperature (°C). The figure 2.24 below shows the Silica solubility curve as performed by Fournier and Rowe

[1] SST- Silica saturation température.

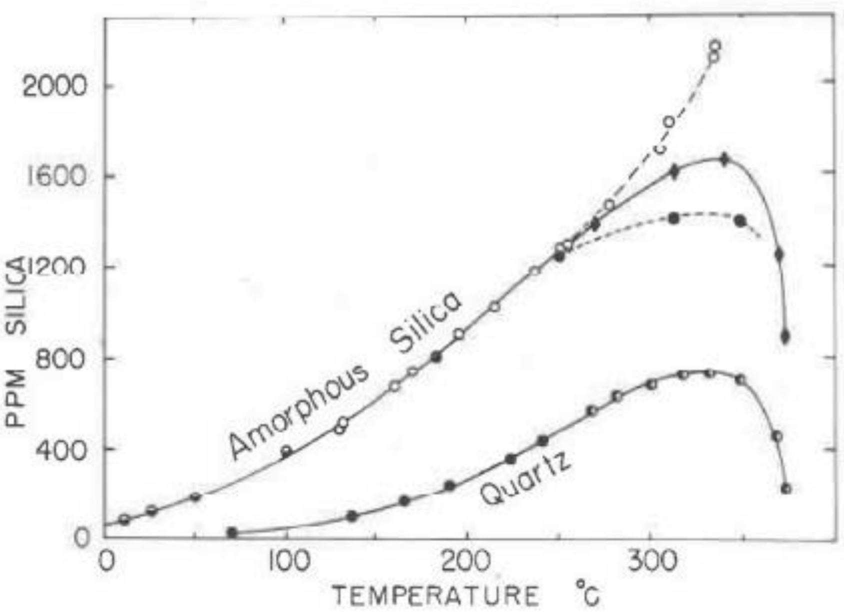


Figure 2.24 - Silica solubility curve [37]

2.6 Source of Data.

The data used in this study were obtained from the following sources:

- Published literature for the separated brine.
- Well data was from internal (KenGen) well testing data.
- The assumption and estimation done where there was minimal or no data was from published literature

CHAPTER THREE:

3. MODELLING OF THE BINARY POWER PLANT.

3.1 General Approach.

The case study chosen for the model is the Olkaria Geothermal power plant in Kenya. While the software used for modelling the binary power plant is Engineering Equation Solver (EES). EES program provides solutions of set algebraic equations, differential equations and do various optimizations and analyses while generating plots to the analyses. EES program has a library of mathematical and thermophysical properties of vast number of fluids that are associated with geothermal plant cycles. These built-in functions of steam tables facilitate thermodynamic modelling of geothermal power plants. Modelling of the power plant assumes that the cycle reaches a steady state and that pressure drops in pipes and heat exchangers as well as heat losses to the environment in the turbine and all the heat [27].

Below is the scope, assumptions and estimations used in this study. Considering the study is based on Olkaria geothermal plant this can be seen as a limitation however the model tries as much as possible to cover a range of reservoir temperature the model can operate at so that it gives a bigger picture for the potential of binary power plants in Kenya. Therefore, when the area has a different temperature the same steps can be used with now the exact data for the specific area.

3.2 Identification of Best Resources

The case study for this research was chosen to be the Olkaria Geothermal power plant. Olkaria as earlier introduced in the literature is one of the largest geothermal power plants in Kenya and in Africa. It is a high enthalpy field which uses the conventional system of single flash technology. This has resulted to having a lot of brine that van be used for binary power plants thus ensuring a better use of the geothermal fluid before it is reinjected. The brine is generally of high enthalpy with it having temperatures of up to 158-180(°C). Generally, Olkaria has a total of 261 well drilled a summation of production and reinjection wells and a total of 34 unattached wells as shown in the table below.

Table 3.1 - General outlook of wells in the Olkaria geothermal field.

Production Wells					**Reinjection Wells**				**Overall Summary**		
No	**Plant**	**No of Wells**	**MW**		**No**	**Plant**	**No of Wells**		**No**	**Plant**	**No of Wells**
1	Olkaria I	20	56.8		1	Olkaria I	2		1	Olkaria I	22
2	Olkaria II	22	104.9		2	Olkaria II	7		2	Olkaria II	29
3	Olkaria IAU	20	176.8		3	Olkaria IAU	9		3	Olkaria IAU	29
4	Olkaria IV	21	165		4	Olkaria IV	9		4	Olkaria IV	30
5	Olkaria I Unit 6	12	85.2		5	Olkaria I Unit 6	1		5	Olkaria I Unit 6	13
6	Olkaria V	26	168.1		6	Olkaria V	7		6	Olkaria V	33
7	Olkaria VI	40	118.7		7	Olkaria VI	1		7	Olkaria VI	41
8	Olkaria VII	17	29.6		8	Olkaria VII	0		8	Olkaria VII	17
9	Wellheads	13	107.7		9	Wellheads	0		9	Wellheads	13
10	Oserian	2	2.7		10	Oserian	1		10	Oserian	3
									11	Unattached Wells	34
	Total	**191**	**1012.8**			**Total**	**36**			**Total**	**261**

The table above shows a summary of the wells in Olkaria. Olkaria as at the end of 2015 has 261 drilled wells which are a summation of production wells, reinjection wells and unattached wells. Currently, there is up to Olkaria IV power plants. Plans and construction are underway for Olkaria V and VI and wells have already been allocated to them as seen above. The unattached wells are wells drilled however, they are not connected to any of the existing steam gathering systems. The unattached drilled wells and the brine from the Olkaria geothermal field make the best source for binary plant in the Olkaria region. The unattached wells are spread out along the field and within the various zones. The table below shows a summary of the current unattached wells for the Olkaria geothermal field.

Table 3.2 - Summary of Olkaria unattached wells

Wells	**Region**	**Wells**	**Region**
OW- 805C	SEP	OW-903A	Domes
OW-39A	EPF	OW-905A	Domes
OW-46	EPF	OW-907B	Domes
OW-49	EPF	OW-912B	Domes
OW-50A	EPF		
OW-50B	EPF		

The enthalpy of the above unattached wells from table 3.1 range from as low as 794 kJ/kg from OW- 905A in the domes region to as high as above 2000 kJ/kg from wells in the region of east field well OW 50B. Some of the wells discharge and well monitoring curve are in the appendix. The identification of the best resource for use in the binary plant was done by ranking of the available geothermal resources. Ranking of the resources was based on the potential of the enthalpy and availability of the resources.

Table 3.3- Summary of the ranking of the geothermal resource.

Resource	**Ranking**
Separated brine from existing wells	Best
Separated brine with a combination of wells not connected	Average
Wells currently not connected alone	Poor

From the table below our model was based on the best geothermal resource which is the separated brine from the existing brine. However, the separated brine and a combination of the drilled geothermal well that are not connected make a good candidate however some due to the below factors they make them an average resource.

i. The wells not connected are from the various four regions of the Olkaria region there more and detailed mapping needs to be done on then to see how best they can be connected to the separated brine
ii. Some of the wells might be connected in the future or even be used as reinjection wells.

The wells not connected alone make a very weak candidate alone for use in binary power plants for Kenya. However, for this study we shall use the thermodynamic properties of the existing brine from the existing power plants and a number of the unattached well based on how near the unattached well is so that the fluid gathering system can be economically.

3.3 Modelling of ORC Plant.

Once the best resource for the binary plant model had been identified the next step was modelling of our binary power plant. In order to model for the ORC plant, we set some boundary conditions. Which provided input parameters to the model based on data at hand and standard assumptions for parameters that data was lacking. However, where data is not available, some reasonable assumptions based on literature review are made as reasonable as possible. Some of the boundary conditions for this research include geothermal fluid mass flow, working fluid for the cycle, equipment efficiency, pressures and temperatures which are discussed below.

3.3.1 Fluid gathering system.

Olkaria geothermal field is generally a high temperature field as seen on the literature review however, a keen analysis on the unattached wells show that they are generally low enthalpy wells. Fluid gathering system of the model requires field characteristics such as borehole pressure and well discharge from production unattached wells. Since the model considers scaling calcite prevention in a way of maintaining the geothermal fluid in liquid phase, the geo-fluid pressure is kept at slightly above the saturation pressure of the reservoir temperature. The saturation reservoir pressure at 180°C temperature is 10.03 bars. Considering that the fluid may lose some pressure along its path through the system to the reinjection well, consideration is made to keep the fluid from boiling even as it loses pressure in the system. As such 1 bar is added to the saturation pressure of the geo-fluid, hence the considered pressure for geo-fluid in this work is 11.03 bars [27].However for this study we shall use the saturation reservoir pressure at 168°C to 180 °C temperature for the case of separated brine from the existing plants and a minimum of saturation reservoir pressure at 180 °C for the wells not connected to the existing steam gathering network.

This study proposes to design a binary power plant from either separated brine from the existing power plants and or geothermal wells that are drilled and are not connected to the existing steam gathering plant. Depending on the model characteristics, required mass flow from the geothermal fluid that delivers the about or above 10MW is calculated for each model.

3.3.2 Scaling conditions

Scaling conditions are set so as to set a limit on the reinjection temperature of the brine. In flashing power plant, the silica concentration in the fluid increases with the increase of steam fraction as the fluid is being flashed. However, in a binary system, since the fluid is maintained in liquid phase, silica concentration remains constant as the fluid is being cooled in the process of extracting heat from the fluid [38]. As the geothermal fluid cools down the amorphous in the fluid begins to precipitate from the equations on the silica solubility curves on the literature above with a reservoir temperature of 180°C we shall have curves (a, b, and c) as shown below assuming that the fluid concertation remains constant through.

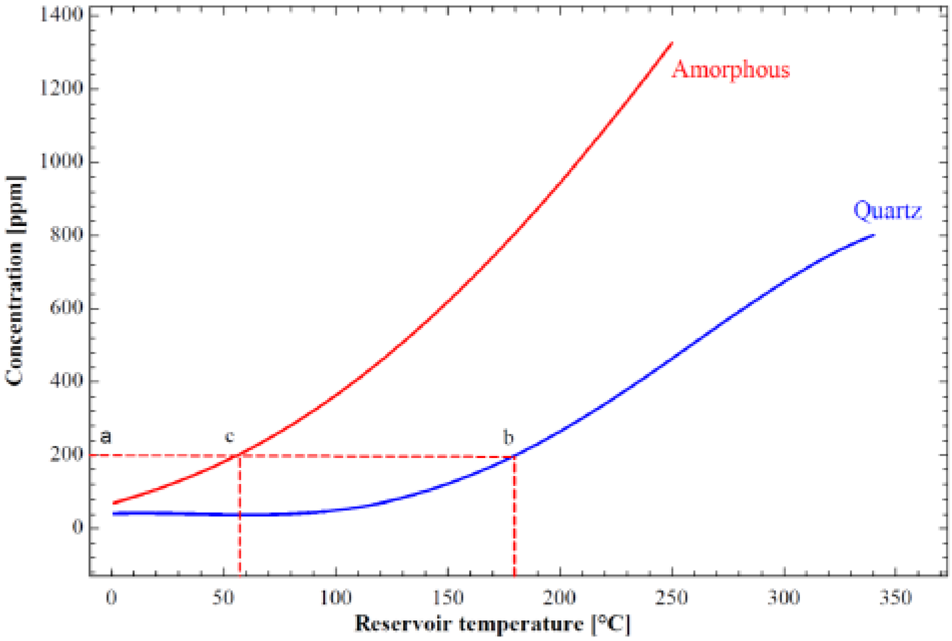


Figure 3.1 -Silica concentration in geothermal fluid *[27]*

From figure 3.2, at a reservoir temperature of 180°C the concertation of amorphous in the fluid is at point c and the temperature will be 60°C which is below the silica precipitation temperature (80°C) thus prone to scaling. Thus the need to maintain the geothermal fluid temperature above this solubility level. Therefore, as a rule of thumb it is important that geothermal fluid should cooled up to 100°C [31] below its initial reservoir temperature. Therefore, for this modelling we shall set our reinjection temperature to 80°C which is in line with the recommended scaling temperature and in line with the set rule of thumb.

3.3.3 Choice of working fluid.

Working fluids of binary power plants are divided into three types according to their saturation vapor curves that is wet fluids, isentropic fluids and dry fluids. Their difference is clearly portrayed on a T-s diagram (figure 3.3) with the wet fluids having a negative slope while the dry fluids having a positive slope as their saturation curve. The isentropic fluid will have a nearly infinite large slope that is almost vertical [39].Some examples of this types of working fluids are

- Wet Fluids – water and ammonia.
- Isentropic fluids – Flourinal 85 and R-11.

- Dry fluids also known as retrograde – normal butane, Isobutene, normal pentane, and Isopentane

Isentropic fluids remain in vapor saturated state as the working fluid expands through the turbine since it is a constant temperature process which results to no fluid condensing on the turbine outlet thereby having no liquid droplets from the working fluid. Contrary to the wet working fluids, which leave some saturated liquid at the turbine outlet due to negative saturation vapor curve which needs to be looked upon with care as they may damage the turbine blades. To prevent this and still use the wet working fluids in a sustainable way in the binary power plants the working fluid is usually super-heated at the turbine inlet and the dryness fraction of the fluid is maintained at 85% [39]. Below the 85% dryness fraction damage on the turbine blades will be very severe. However this is not the case while you use either dry or isentropic working fluids as they are already saturated vapor as they enter and exit the turbine. This is the major reason why most binary power plants prefer Isentropic and dry fluids as their working fluids. T-s curves of the three types of the working fluids are shown on Figure 3.2 below:

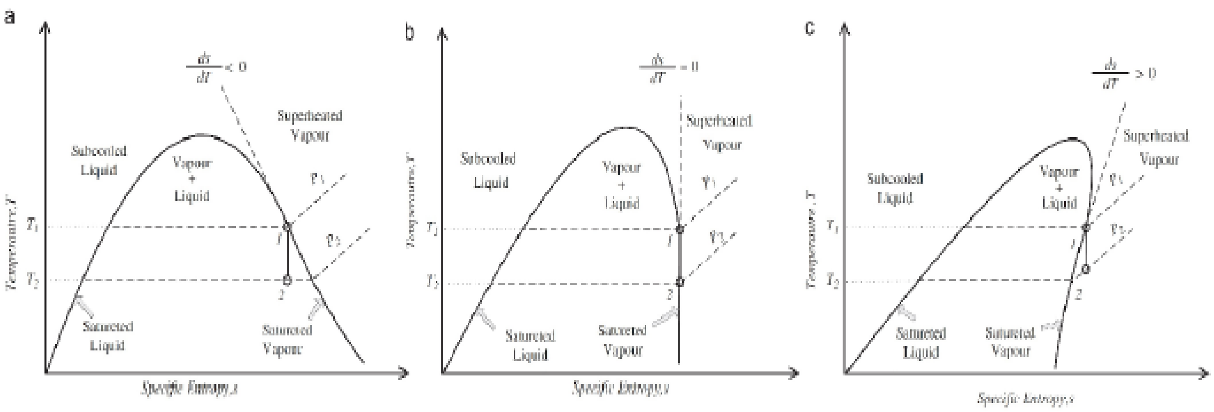


Figure 3.2 - T-s Diagram for a) Wet fluid, b) Isentropic fluid and c) Dry fluid *[39]*

According to DiPippo the working fluids that are environmentally friendly are then subjected to a thermal efficiency test in a simple binary cycle to see their performance under external source of heat. This is to show how different fluids utilize the geothermal heat under a given set of cycle parameters. In the simple cycle, heat is added to the working fluid from the geothermal fluid through a heat exchanger and removed from the fluid through the condenser after the fluid has driven a turbine. The cycle considers some parasitic load required to drive a circulation pump and related equipment depending on the fluid's pressure requirements [27].

Therefore, the thermal efficiency is given by [40]

$$\eta_{th} = 1 - \left(\frac{\Delta h_{wf\_c}}{\Delta h_{s\_HE}}\right) \quad (29)$$

Where η_{th} is the cycle's thermal efficiency, while Δh_{wf_c} is the enthalpy difference in the condenser and Δh_{s_HE} is the enthalpy difference across the preheater and vaporizer

For purposes of this study, four dry working fluids are considered i.e. n-butane, n-pentane, isobutene and Isopentane. The fluid that presents better results is recommended for use in the study.

Thermodynamically, show that Isopentane and n-pentane have better thermodynamic properties as seen in the curve below. The two can operate in temperatures between (150-200) °C while the rest have a maximum operating temperatures of approximately 150°C. The four working fluids are further subjected to vaporizer pressure (turbine inlet pressure in a working reservoir temperature of 168°C and geothermal fluid of 100kg/s. The table3.4 below shows the thermodynamic properties of the four working fluids.

Table 3.4 - Critical Temperature and pressure for various working fluids. [41]

Working Fluid	Critical Temperature (°C)	Critical Pressure (bar abs)
Isopentane	187.2	33.70
Isobutane	134.7	36.40
n – pentane	196.5	33.64
n – butane	152	37.96

The four working fluids chosen for the model are subjected to a varying vaporizer pressure from 5-20bars on EES and we obtain the figure 3.3 below.

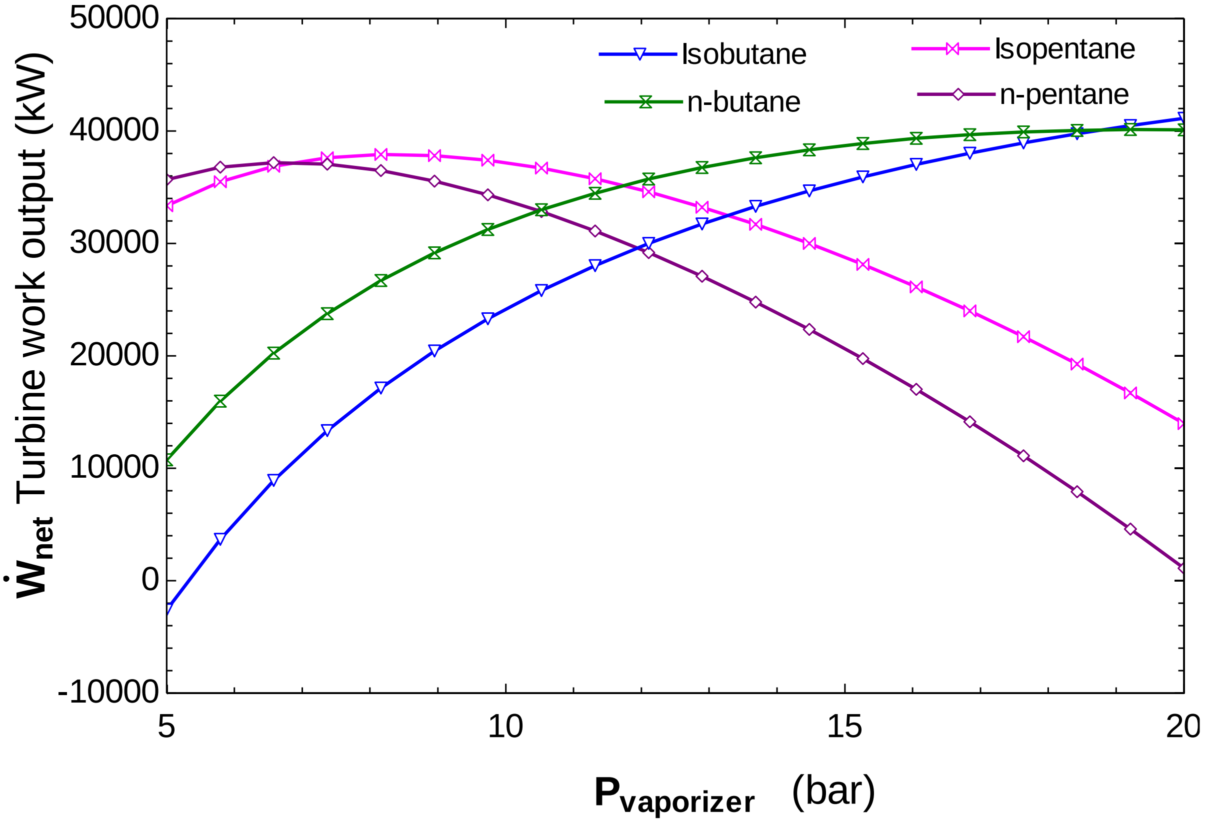


Figure 3.3- Turbine work output and Vaporizer pressure of the various working fluids.

From the figure 3.3 above it shows that the highest Turbine work output is produced by is Isobutane closely has followed by n-butane at also the highest vaporizer pressure as compared to Isopentane and n-pentane. This highest turbine work output for both cases of Isobutane and n-butane is achieved as you increase the vaporizer pressure. However, for Isopentane and n-pentane as the vaporizer pressure increase there is an increase in the turbine work output up to the maximum turbine work output achieved then we see any increase in the vaporizer pressure leads to a decrease in the turbine work output. The pressure at which we achieve the maximum turbine work output is called the optimal pressure. On comparison between Isopentane and n-pentane, Isopentane produces the highest turbine work output as compared to n-pentane which is at a higher vaporizer pressure too as compared to n-pentane.

We then subject the working fluid(s) to the reinjection temperature limit (80°C) to test which one will work best within the scaling limits. So that to get the best working fluid that will give the best turbine work output while still considering the scaling limit so as to obtain the maximum work from our reservoir fluid in the most efficient way. The geothermal/reservoir fluid is at 168-180°C.

The geothermal fluid is assumed at 168°C and a mass flow of 300 kg/s. The reinjection temperature is varied from condenser temperature until the geothermal fluid source temperature. With a key assumption that the working fluid cannot cool the geothermal fluid below the condenser temperature. This generates the curves below on figure 3.4.

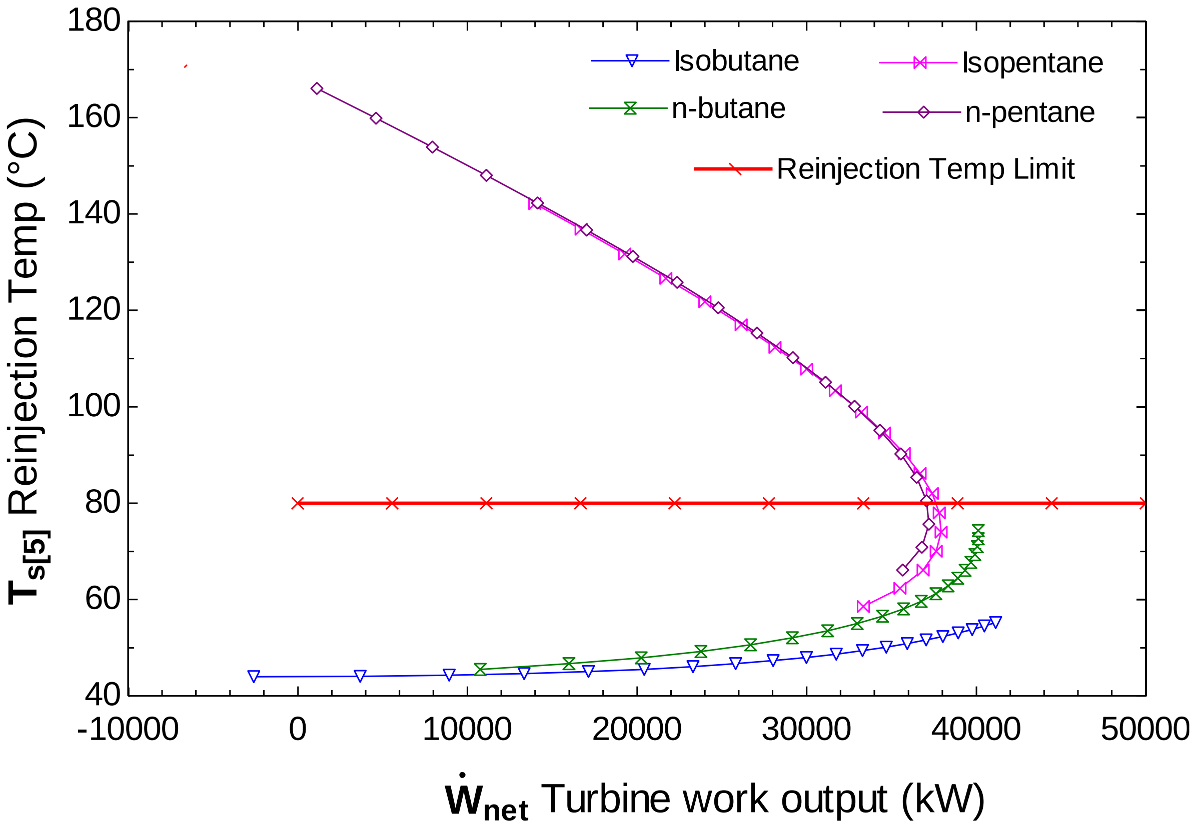


Figure 3.4- Reinjection temperature versus the turbine output curve.

The figure 3.4 above shows the model at the set limit of reinjection temperature 80°C, that all the four working fluids produce some considerable amount of turbine work output. Both Isobutene and n-butane achieve the all their maximum turbine power output below the set reinjection temperature. While Isopentane and n-pentane having almost the same curve but with Isopentane achieving the highest turbine output with respect to the reinjection temperature as compared to n-pentane.

Having a look at the two curves the reinjection temperature and vaporizer pressure curves with respect to Turbine work output the best performing working fluid is

Isopentane. Isopentane makes the strongest candidate both in terms of reinjection temperature and vaporizer pressures for the working fluid of this study model.

Isopentane has been used in a number of binary power plants applications. Some of the power plants that are currently using Isopentane as their working fluids in their power plants include Orpower in Kenya, Svartsengi in Iceland, Tulza in Turkey, Aluto in Ethiopia and Berlin in El Salvador. Therefore, this this gives a better backing for our choice of our model working fluid.

3.3.4 Vaporizer pressure optimization

The model is given Isopentane as the working fluid and the vaporizer pressure is optimized for this working fluid. This is achieved by setting the reinjection temperature and generating the turbine power output as the vaporizer is varies. We then plot the varying vaporizer pressure against the turbine work output as seen in the curve below.

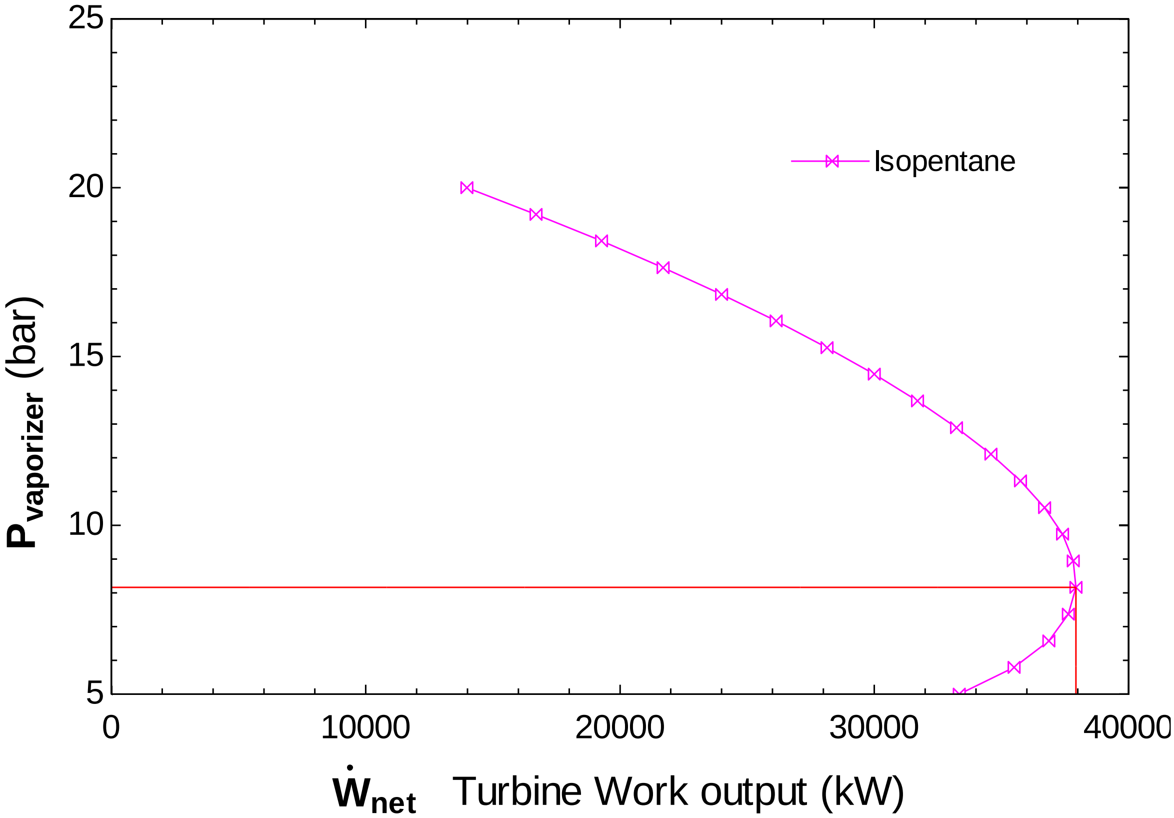


Figure 3.5 - Vaporizer Pressure optimization curve.

From figure 3.5 above we obtain a maximum power output of 37MW at 8.158bar with a reinjection temperature of 73.96°C. However, at this maximum turbine power output is way below the 80°C recommended reinjection temperature. Therefore, to optimize the vaporizer pressure we vary it up to the pressure that will be in line with the reinjection temperature as shown below. In this model the vaporizer pressure used is 9.3 bar to achieve a reinjection temperature of 80°C however we can set and work within a range of 9.3 to 11 bar for vaporizer pressure. This can be clearly seen on the curve below of the reinjection temperature against the vaporizer pressure.

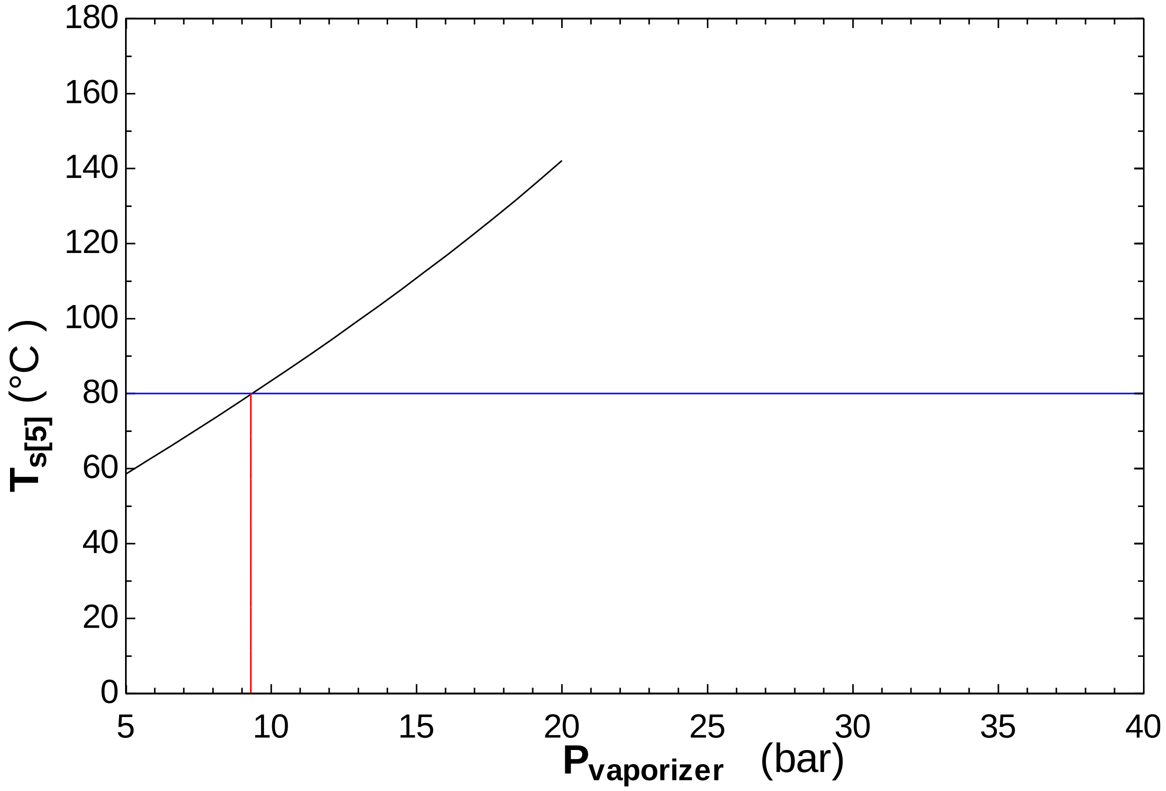


Figure 3.6 - Optimal vaporizer pressure for dry basic binary model.

3.3.5 Efficiencies of the associated parameters and general assumptions.

Generally, the efficiency of turbines is within the range of 81-85% [42] therefore for the model the turbine efficiency used is 85% as this ensures that we have the best performing turbine which is energy efficient. The motor efficiency for all the pumps and equipment is 95%. Feed pump efficiency was 80% while the cooling fun efficiency was 70%. The overall heat transfer coefficients for the heat exchangers in this model was based on Ahangar [41] where the preheater has 1000W/m^2°C, the vaporizer has 1600 m^2°C, the recuperator 400 m^2°C and lastly the condenser 800 m^2°C.

The pinch condensation temperature for this study is 10 °C however this is usually a range from 8- 10°C while the change in the condensation temperature dT_c is 12°C. The condensation temperature used in this modeling is calculated as ambient temperature. However, this can be optimized by considering the efficiency of the cycle and the cost of condenser. In this work we use a condensing temperature of 40°C that is used in calculating the condenser parameters. This is used to find the temperature range of the condenser and also helps in determining the condenser size.

For the heat exchangers the pinch temperature used is 4°C. The choice of the pinch is also an optimization just like the condenser with a consideration on the efficiency and the cost of the heat exchangers. However, this pinch selection is usually given by the manufactures of the heat exchangers in this study we use VERKÍS Consulting Engineers [43].

The local climatic conditions of the Olkaria area is well known subject considering the existence of the geothermal plants its altitude above sea level is about 1505m a.s.l. It is located near the Lake Naivasha region in the Great Rift Valley area.

The higher you go the cooler it becomes and the higher you go from the sea level the lower the atmospheric pressure. Therefore, atmospheric pressure of a given place varies with the altitude in meters above sea level. The atmospheric pressure for an area is given by

$$P_{air,alttitude} = (P_{atm,Zero} - \rho air * g * altitude)/100{,}000 \qquad (30)$$

Where $P_{air,alttitude}$ the atmospheric pressure at altitude is, $P_{atm,Zero}$ is the atmospheric pressure at sea level. While Altitude is the site elevation above sea level and ρ_{air} is the density of air

Thus this gives the atmospheric pressure of Olkaria as 0.86 bar and a mean ambient temperature of 20°C that is used in this work [1].

The table below shows a summary of the boundary conditions for the model used in this work.

Table 3.5 – Boundary and input conditions for the model.

Parameter	**Value**	**Unit**
Working Fluid	Isopentane	
Geothermal Fluid Pressure	9.23	bar
Atmospheric Pressure	0.86	bar
Vaporizer Pressure (Basic and recuperative	11	bar
Pressure change in fan	100	Pa
Geothermal fluid source temperature	168-180	°C
Condenser temperature	40	°C
Vaporizer preheater pinch temperature	5	°C
Condenser pinch temperature	10	°C
Ambient temperature of Olkaria	23	°C
Feed pump efficiency	80	%
Fan efficiency	70	%
Motor efficiency (for the pump and fan)	95	%
Turbine efficiency	85	%
Preheater heat transfer coefficient	1000	W/m2°C
Vaporizer heat transfer coefficient	1600	W/m2°C
Recuperator heat transfer coefficient	400	W/m2°C
Air cooled Condenser heat transfer coefficient	800	W/m2°C

CHAPTER FOUR:

4. BINARY POWER PLANT MODEL RESULT, SCENARIOS AND ANALYSIS.

The model is based on the following scenarios with the following performance model

4.1 Basic Binary Model with Dry Cooling.

For the model we use 11 bars as the vaporizer for both basic and recuperative model. On average Binary power plants range from the 10-20MW [27]. To illustrate the effect of the required mass flow for the geothermal fluid that will generate for instance, the model power plant of 13MW with a working fluid at 168°C. A plot of the required mass flow rate of the geothermal fluid and the net power output is represented by the graph below.

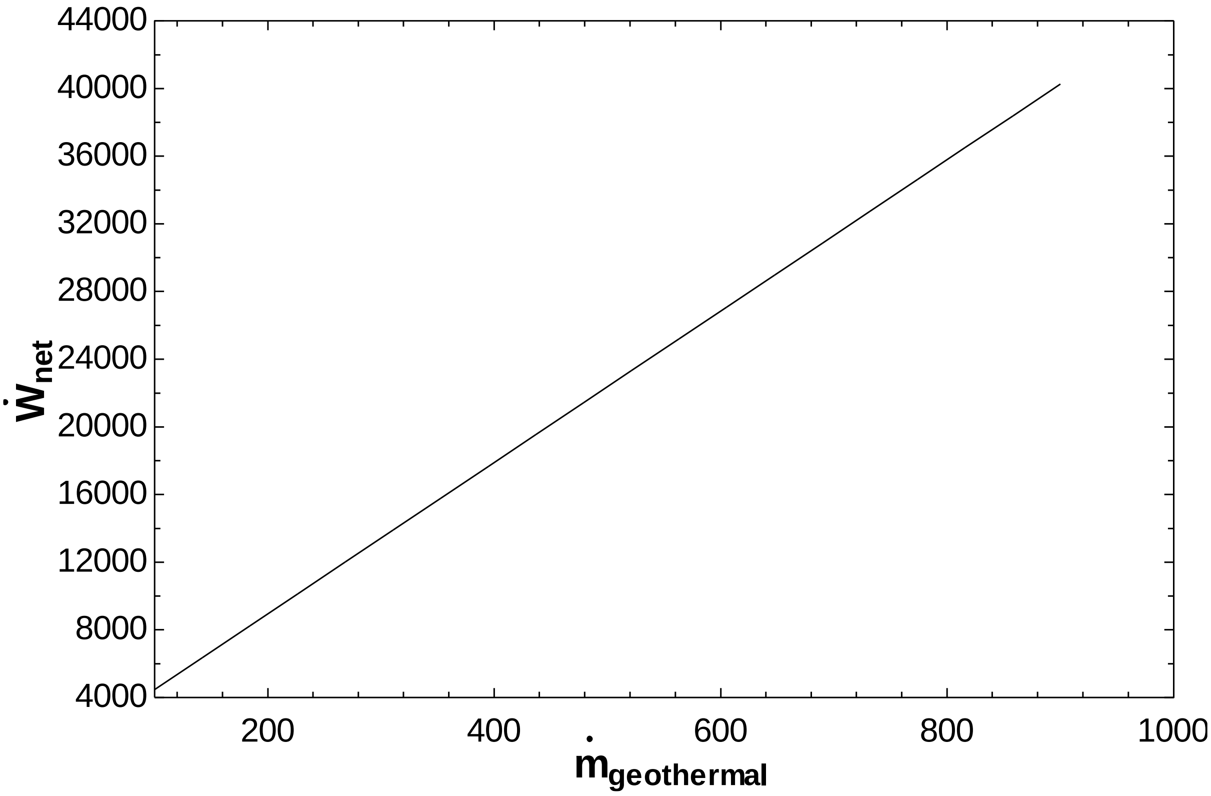


Figure 4.1 - Relationships between geothermal mass flow and turbine work output

From figure 4.1 above a direct proportional relationship between the turbine work output and the required geothermal mass flow rate is seen for both dry and wet cooled binary power plants. That is as the mass flow rate for the geothermal increases there is an increase in the power plant of the binary power plant. Therefore, there is a direct proportional increase in the net generator power output with respect to the required mass flow of the geofluid. The model requires a mass flow of 300 kg/s geothermal fluid to produce13MW generator power at 168°C for dry cooled model.

The process flow diagram of the dry cooled model is as shown below. This includes the process diagram of the T-s, T-h and P-h using Isopentane as the working fluid in all the graphs

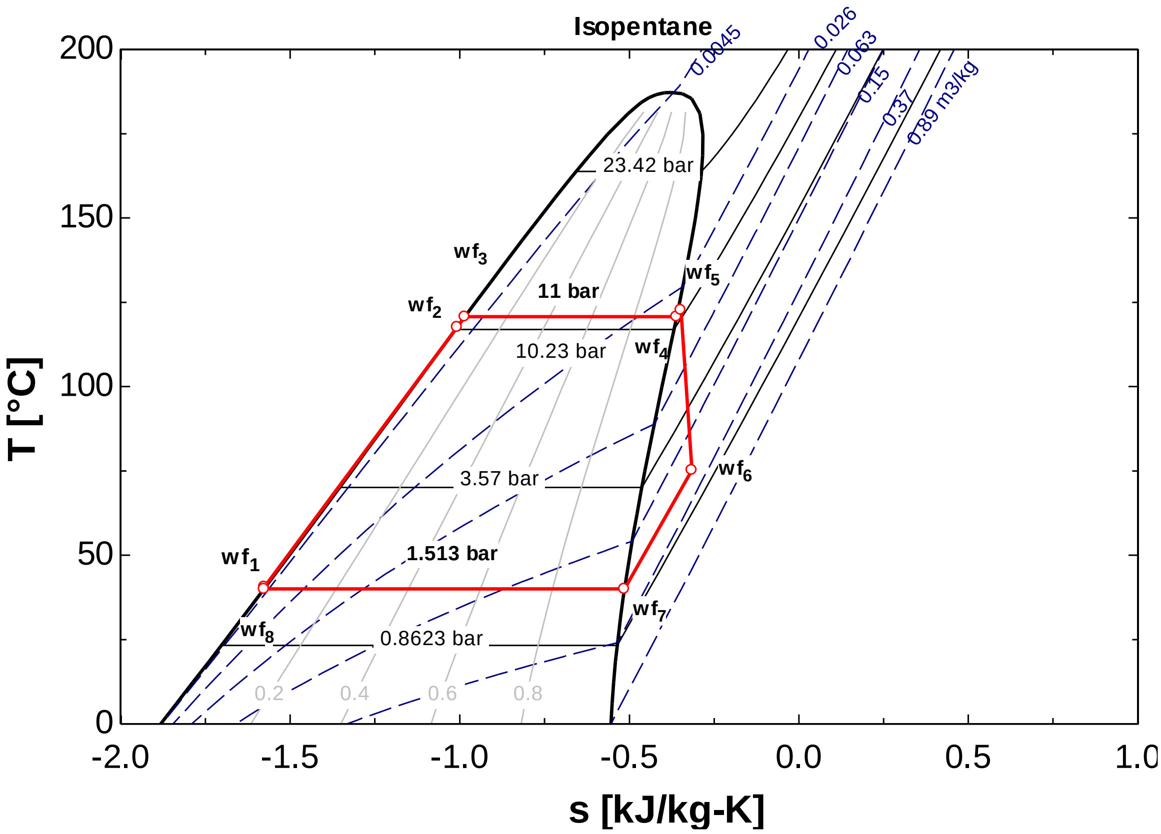


Figure 4.2 – T-s curve for the basic air cooled model.

The figure 4.2 above represents the T-s curve of a dry cooled binary model. At point wf_8 the working fluid has just left the condenser and it enters the circulation pump at point wf_1. The pressure at the entry point wf_1 of the circulation pump is at 1.513bar. The circulation pump adds the needed pressure up to 11 bar to point wf_2 with some very slight increase in temperature between wf_1 and wf_8. The working fluid enters the preheater at point wf_2 and gains enthalpy as shown in the T-h curve below from the geothermal fluid and entropy changes from s_2 to s_3.

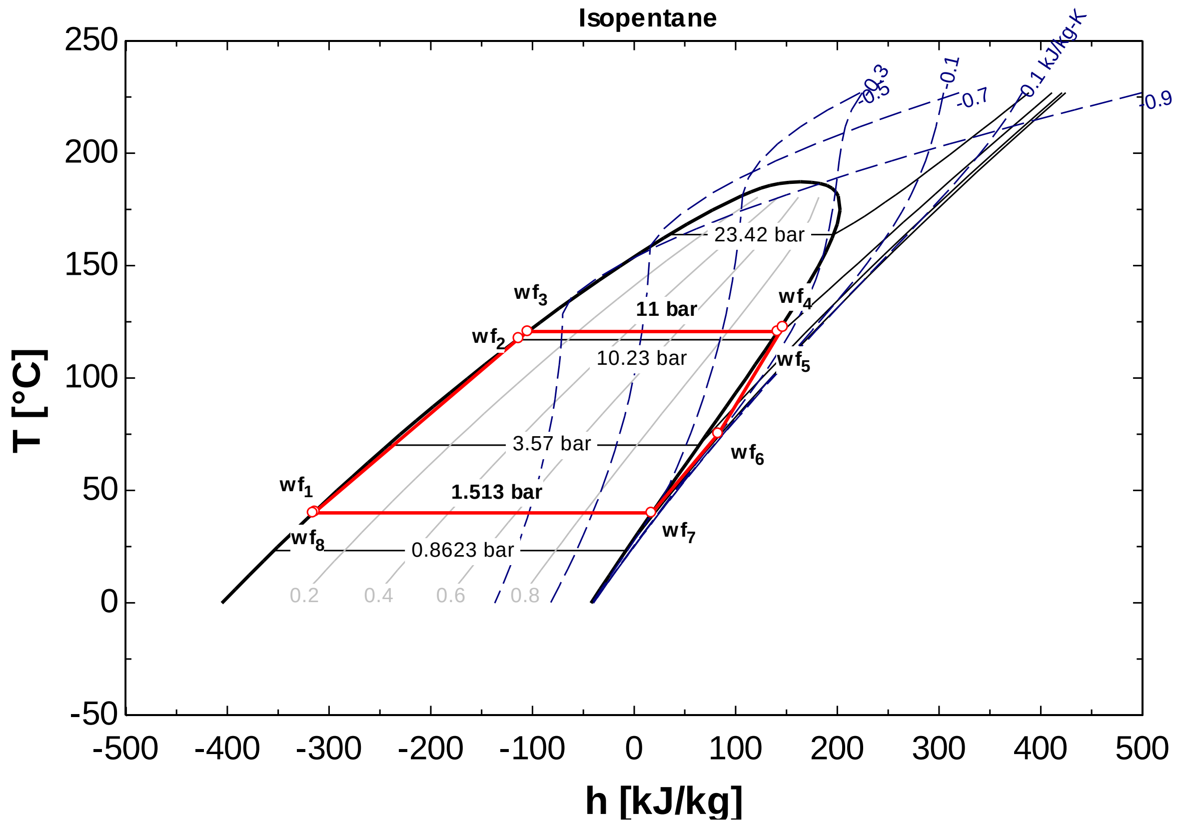


Figure 4.3 – T-h curve for the basic air cooled model.

At point wf$_3$ from figure 4.3 there is bubbling (boiling point) of the working fluid. The fluid is saturated and it enters the vaporizer as saturated vapor point wf$_3$. To ensure that the vapor has no moisture as it is existing the vaporizer point wf$_4$ and entering the turbine wf$_5$; as vapor in the turbine has a catastrophic effect on the turbine. The saturated vapor is superheated a point wf$_4$ to 5°C more than the vaporizer temperature.

The saturated vapor enters the turbine and is expanded through wf$_5$ to wf$_6$. It's expanded and moves from high pressure 11 bar to wf$_6$ lower pressure 1.513 bar (condensing pressure). From the model we have two regions, regions that are on high pressure that is wf$_1$, wf$_2$, wf$_3$, wf$_4$ and wf$_5$ and regions on lower pressure or condensing pressure that is wf$_6$, wf$_7$ and wf$_8$. The P-h curve for the dry cooled model is shown on the figure 4.4 below.

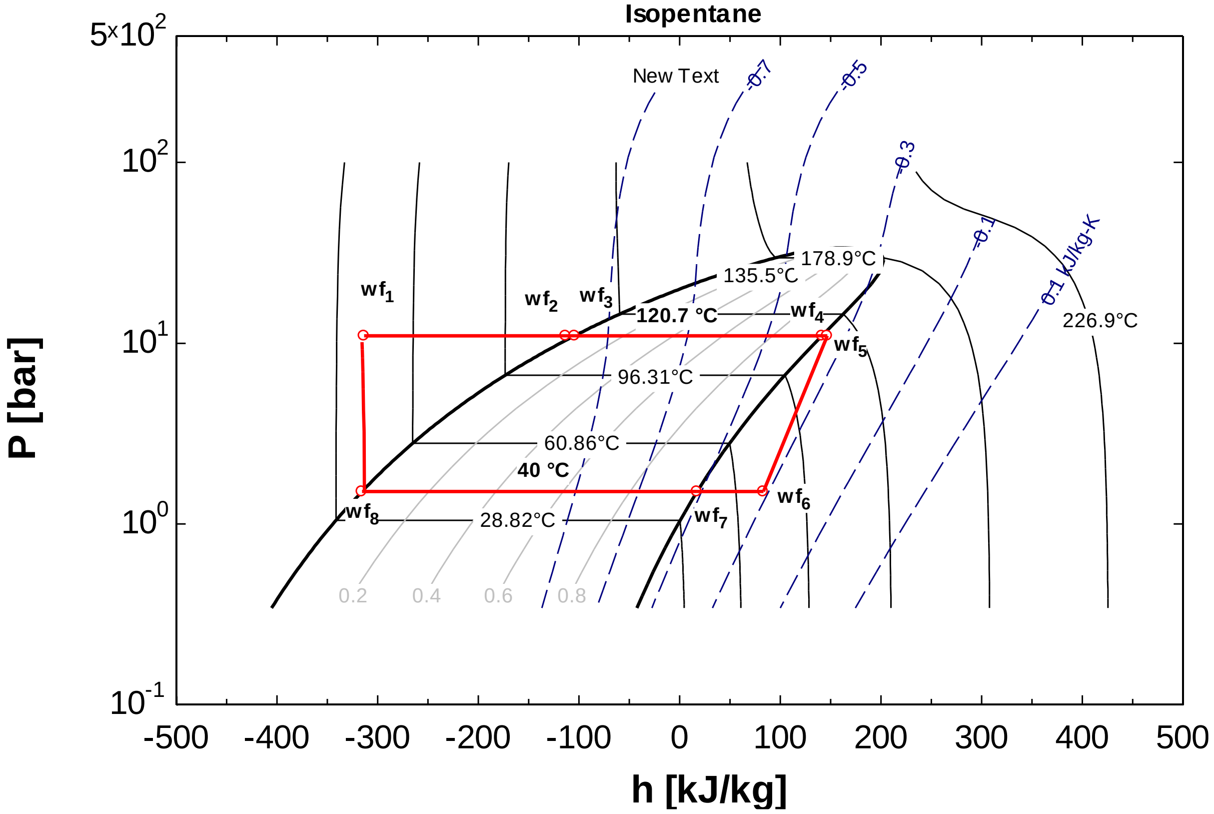


Figure 4.4 – p-h curve for the basic air cooled model

The model performance of the heat exchangers (preheater and vaporizer) is represented below. The heat exchangers preheater and vaporizer for the dry cooled model has the geothermal fluid entering the vaporizer at s_1 at 168°C while superheating the working fluid at 5°C between the point's s_2 and s_3. The working fluid is vaporized at a constant temperature between s_2 and s_3. Pre heating of the working fluid occurs from s_3 and s_4 in the pre heater. This leads to the exit of the geothermal fluid at point s_5 for reinjection at 90.45°C. The heat that is exchanged in the heat exchangers (pre heater and vaporizer) is gained by the working fluid from wf_1 at 40.6°C to 122.7 °C wf_5. The wf_1 is pumped from the circulating pump from point wf_8. The working fluid gains the temperature from the geothermal fluid from wf_1 at the entry of the preheater is at 40.6 °C. It then heated and gains heat to wf_2 at 117.7 °C then vaporized to wf_3 to 120.7 its super saturated by 5 °C to 122.7°C. The heat exchanger process is similar for the both models that is the basic and recuperative with only difference being slight difference in the temperatures. The heat transfer curves are shown on figure 4.5 and 4.6 for the preheater, vaporizer and condenser respectively.

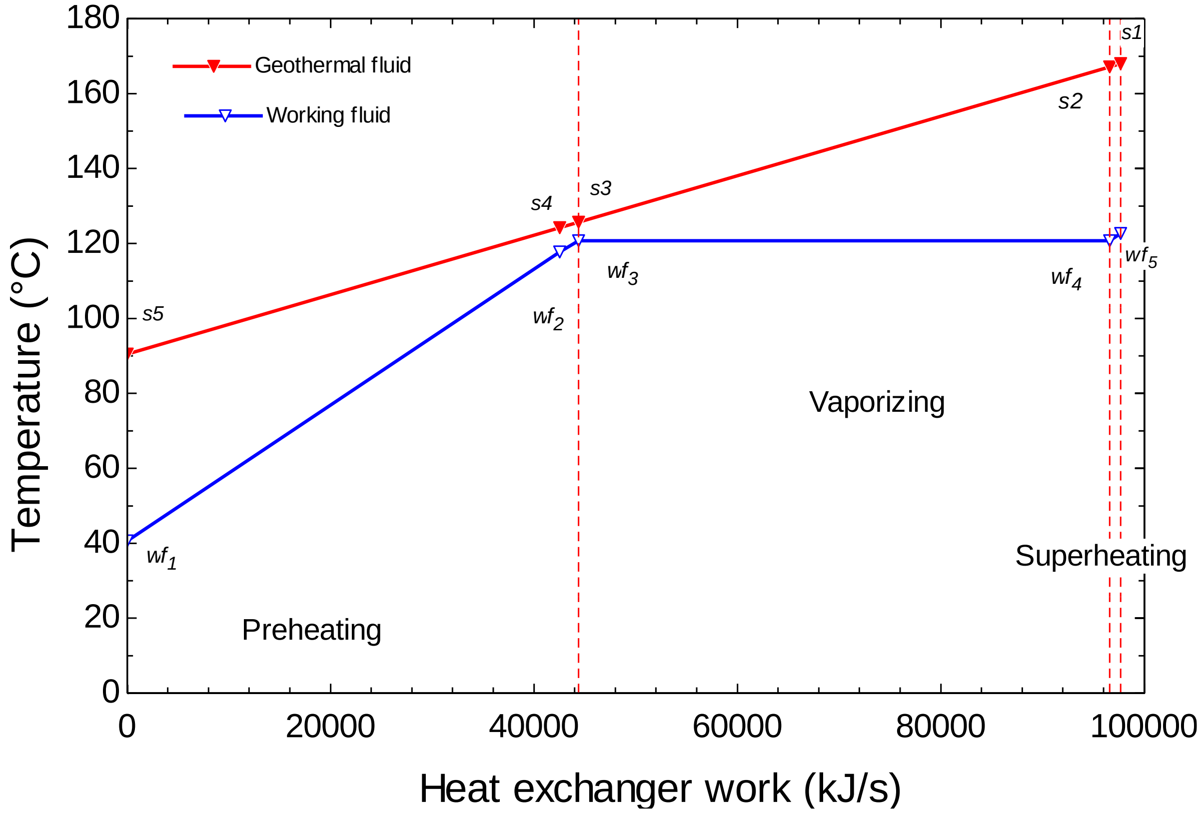


Figure 4.5 – Heat transfer for the preheater and vaporizer for the basic aoir cooled model.

For the cooling of the model the heat exchanger which is the condenser in the model the working fluid exist the turbine at wf_6 at 75.22°C and enters the condenser. It is condensed by air in the air cooled and water in the water cooled model. For the air cooled model, it enters the condenser air cools and condense the working fluid at wf_7 to 40°C at a constant temperature since the fluid is saturated at point wf_7. Lastly, the working fluid undergoes condensation from wf_7 to wf_8 until it is saturated liquid as it enters the circulating pump at wf_8 at still 40°C. As this is taking place the cooling media in this case air is gaining the heat from c_1 to c_3 (19.98 to 31.98) °C. This heat transfer for the heat exchanger of the condenser is represented in the curve below.

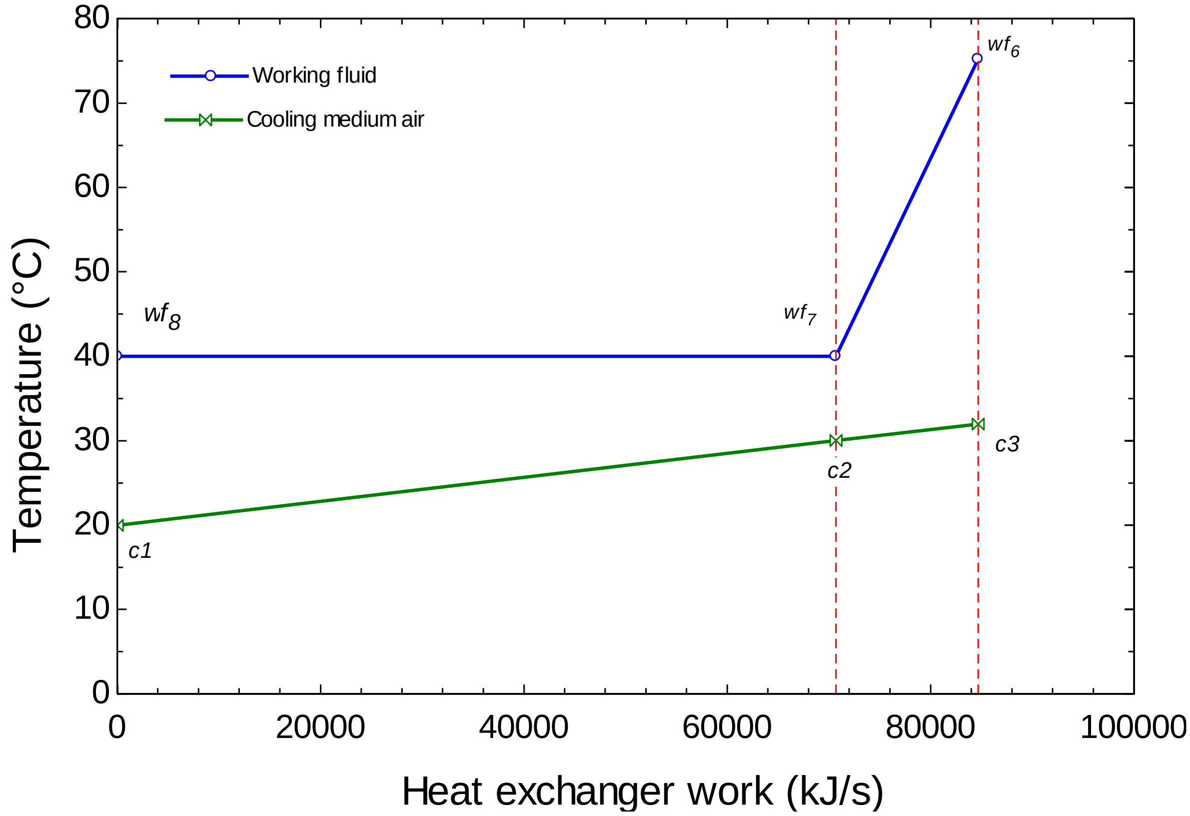


Figure 4.6 – Heat transfer process in the condenser for the basic air cooled model

4.2 Recuperative Binary Model with Dry Cooling.

The recuperative binary model is one of the configuration of binary plants whereby it uses the concept of waste heat recovery. The model uses the exhaust gases from working fluid that exists the turbine. Once the steam from the working fluid has turned the turbine before it is cooled it is passed through a recuperator that heats up the incoming working fluid as it gets into the preheater. This study uses an optimal vaporizer pressure of 11 bar and geothermal fluid at a temperature of 168°C at a mass flow rate of 300kg/s with Isopentane as the working fluid at a flow rate of 219.71kg/s to produce 13.4MW. It also considers that 40% of heat required for condenser de-superheating, is rejected in the recuperator (expert opinion). The 40% de-superheating duty provides a temperature drop across the recuperator for the working fluid coming from the turbine [27].

The T-s, T-h and P-h curves are represented below. The three curves exhibit the typical characteristic of the recuperative binary model.

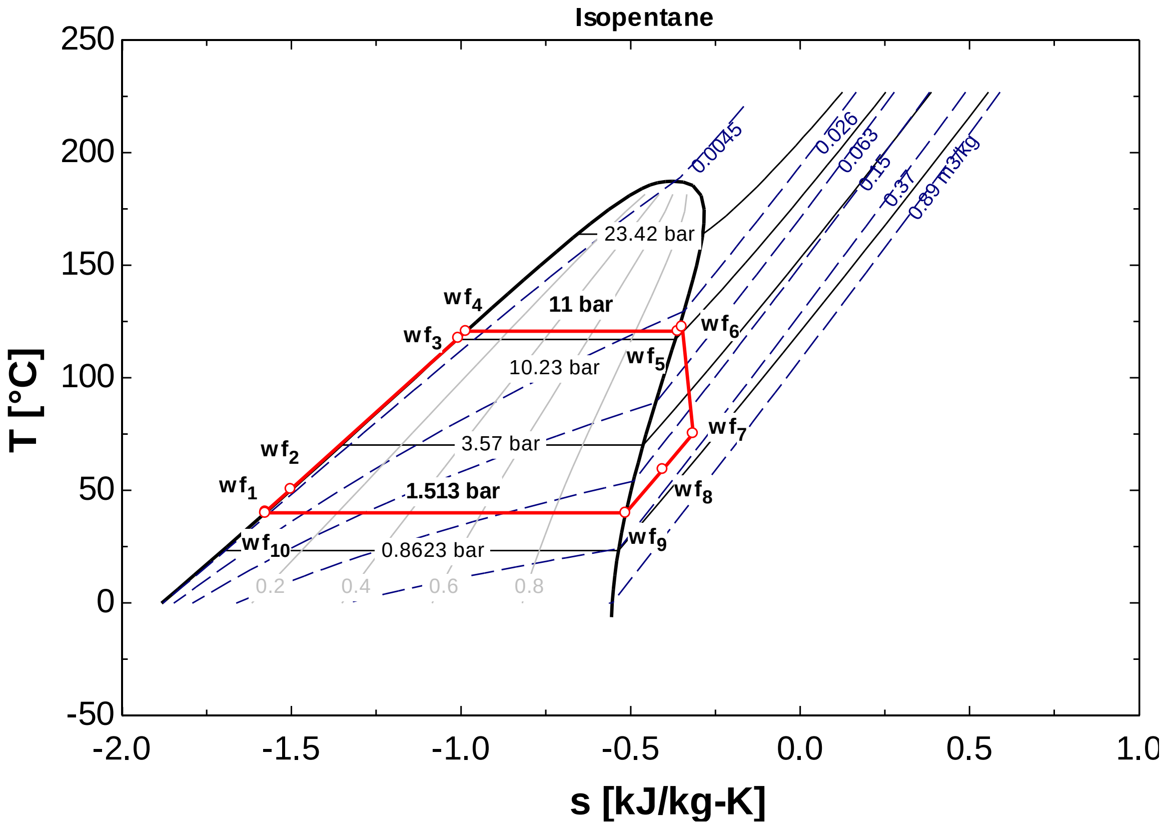


Figure 4.7 – T-s curve for the recuperative air cooled model.

The figure 4.7 represents the T-s curve of a recuperative dry cooled binary model. At point wf_{10} the working fluid has just left the condenser and it enters the circulation pump at point wf_{1}. The pressure at the entry point wf_1 of the circulation pump is at 1.513bar. The circulation pump adds the needed pressure up to 11 bar to point wf_{3}. At point wf_2 gains some temperature from wf_1 (40.06°C) to wf_2 (50.6°C). This gain in temperature is as result of the waste heat recovery via the recuperator. The working fluid enters the preheater at point wf_3 and gains enthalpy as well as its entropy changes as it enters the preheater at 120.7°C it maintains this temperature until it attains saturation level so as to enter the turbine as saturation vapor. The changes in enthalpy is represented on T-h curve below.

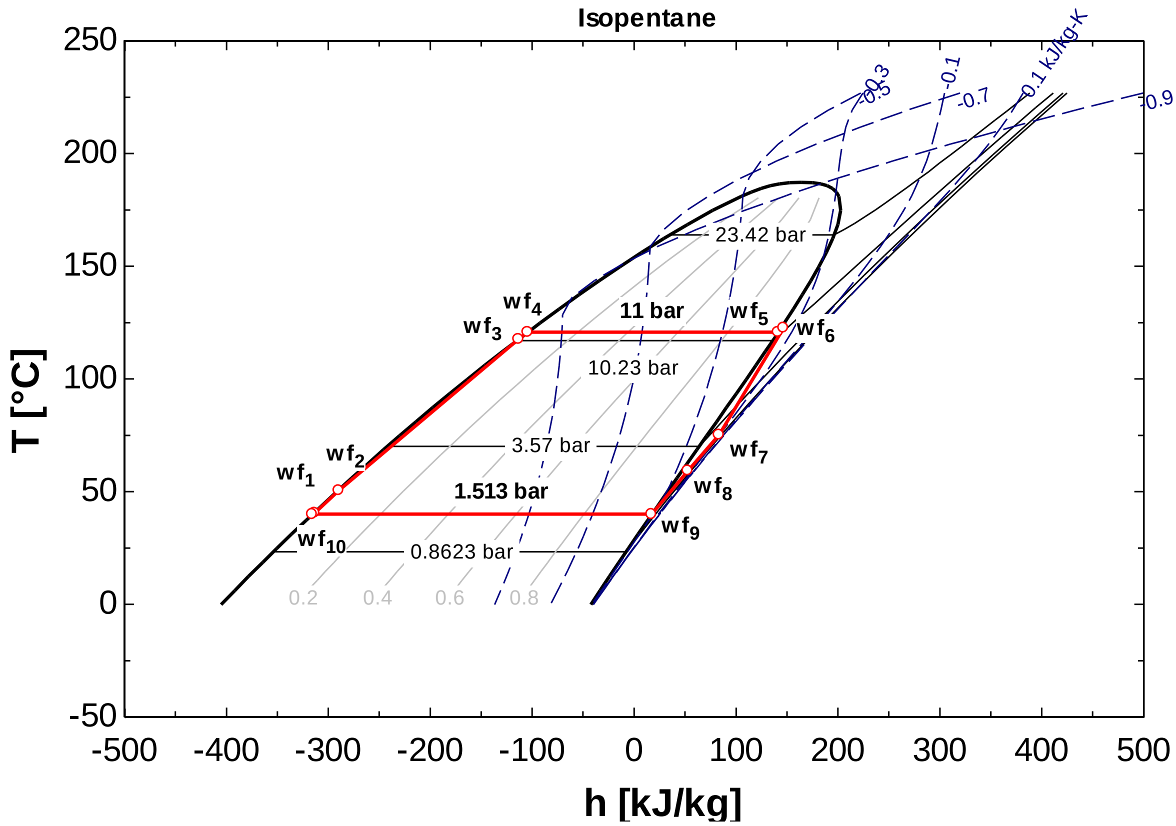


Figure 4.8- T-h curve for the recuperative air cooled model

Just as in the basic model even in the recuperative model care is taken so that the vapor has no liquid as it enters the turbine by super heating at wf_5 by the same margin of 5°C. The steam is then expanded in the steam turbine via from wf_6 to wf_7. As the working fluid is expanded through the steam turbine the recuperator recovers some of the exhaust heat that the turbine rejects and it is used to heat the working fluid that is coming from the condenser across the recuperator through wf_7 and wf_8.The fluid exists the turbine at wf_7 at 75.22°C and the recuperator at 56.3°C then it is set to the condenser. The use of the recuperator is quite advantageous as it uses waste heat thus releasing the working fluid at lower temperature this reduces the work done by the condenser in turn reducing its size as a results its cost also. This is illustrated and represented on the P-h curve below. The curve for the wet cooled is just similar to the dry cooled recuperative model.

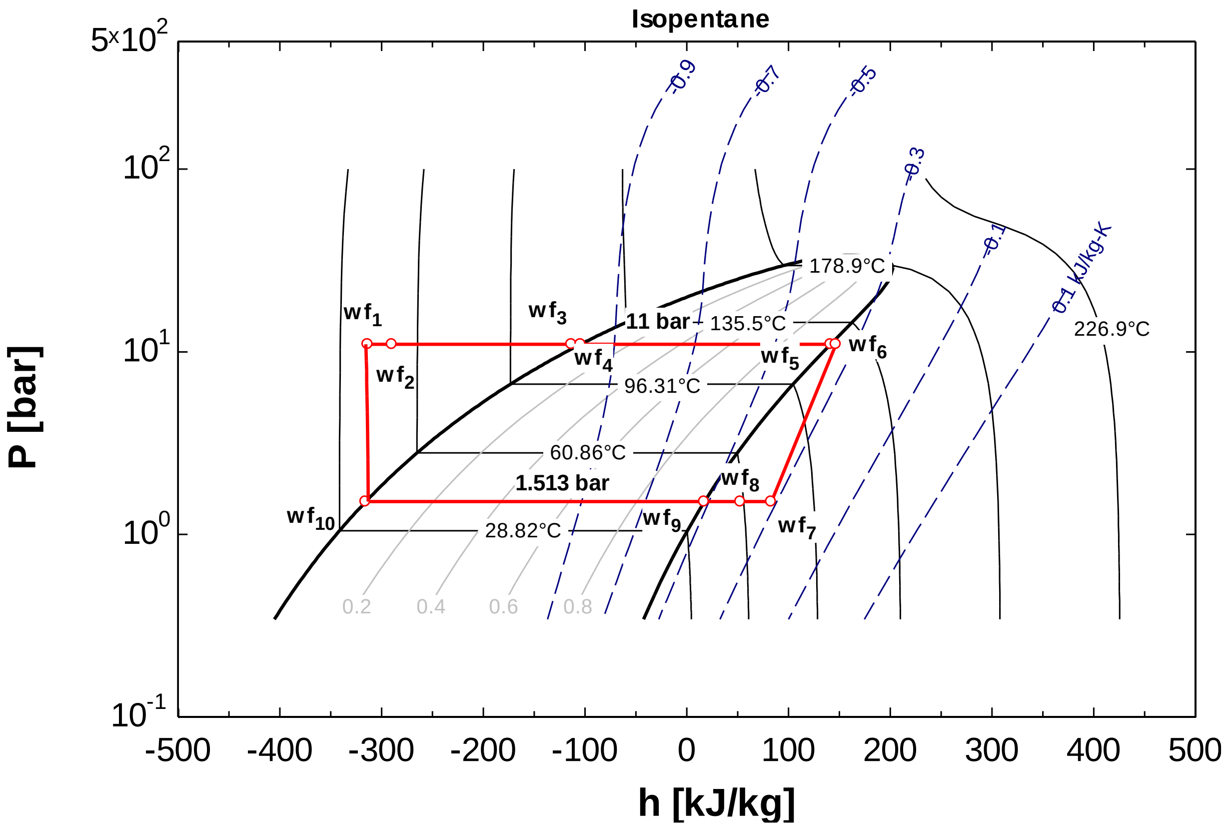


Figure 4.9 – p-h curve for the recuperative air cooled model

4.3 Results and Technical Analysis of the Model.

The table below shows the results of the two binary models modelled by EES. The size, area and heat transfer of the preheater, vaporizer, fan, pump were calculated using the following equation and substituting the values from the ones gotten on EES program

$$Q = UA * LMTD \tag{31}$$

Where U is the Overall heat transfer coefficient (°C/m^2), while A is the Heat transfer area (m^2) and LMTD is the log mean temperature difference °C which is given by:

$$LMTD = \left(T_{hot,in} - T_{cold,out}\right) - \frac{(T_{hot,out} - T_{cold,in})}{ln[(T_{hot,in} - T_{cold,out})/T_{hot,out} - T_{cold,in}]} \tag{32}$$

The area and heat transfer for the heat exchangers gotten are shown below.

Table 4.1 – Heat transfer for the heat exchangers.

MODEL	Q_{REGEN}	$Q_{SUPERHEAT}$	$Q_{PREHEATER}$	$Q_{VAPORIZER}$	$Q_{CONDENSOR}$
RECUPRATIVE	11867	1141	38806	44013	73134
BASIC	0	1103	42539	53298	70686

Table 4.2 – Heat transfer area for the heat exchangers

	A_{REGEN}	$A_{SUPERHEATER}$	$A_{PREHEATER}$	$A_{VAPORIZER}$	$A_{CONDENSER}$
REGENAROTOR	925	495.4	17223	5501	6808
BASIC	0	469.46	18502	6662	6581

From the heat transfer calculation, the surface area of the basic model is larger compared to the recuperative model as seen on table 4.2 above this is due to the incorporation of a regenerator that uses the waste heat from the turbine thus heating up the working fluid before it enters the preheater. Consequently, also the size of the vaporizer is smaller for the recuperative model as compared to the basic model.

Table 4.3 – Results for the model.

Parameters	Basic Binary	Recuperative
Net power	13.044 **MW**	13.496 **MW**
Working fluid mass flow	212.3 **kg/s**	219.7 **kg/s**

The table 4.3 above shows power produced by the two models same mass of geothermal fluid was used that is 300kg/s at the same temperature of 168°C.and the same vapor pressure of 11 bar. The basic air cooled binary a net power of 13.044Mw while the recuperative air cooled binary produced 13.496MW. The mass of the working fluid for the recuperator was 212.3kg/s for the Basic model while 219.7kg/s for the recuperative model and that of the basic was 230.5kg/s. The recuperative model produces more turbine network output with a better efficiency as it utilizes waste heat. The efficiency of the regenerative model is 14% while that of the basic model is 13.5%.Technically, the recuperative dry model performance is the best as compared to the basic binary.

4.4 Economic Overview and Analysis of the Model.

For geothermal projects the capital cost of geothermal projects are very site and resource specific. The geothermal resource temperature will determine the power conversion technology and in turn the conversion technology has an overall effect on efficiency of the power system. Other factors that are considered in costing of geothermal power plants are site accessibility, its topography, the local weather conditions, land type and ownership [27].

This section addresses the question whether binary power plants are economically feasible in Kenya considering majority of the geothermal power plants in Kenya are of flash (single) technology. It also tries to see how best we can make it financially attractive to Kenya. In order to assess the costing, the following were considered

The case study chosen for this project is the well-known Olkaria geothermal field and the best resource selected is the brine from existing power plants. Some of the costs that are considered when producing power plants include

i. Cost of field development – Considering our case study region this cost is quite minimal as most of the exploration of the field as been done and drilling of wells. However, one major cost needs to be was considered in this study is the fluid gathering system. However due to lack of sufficient data we shall not so much dwell on this Piping needs to be done so that the fluid is gathered to the power plant and the reinjection system.
ii. Civil, Electrical and controls costs **-** Cost of putting up civil structures and related electrical and control equipment, generally corresponds to the capacity of the power plant. The bigger the power plant, the higher the civil works and electrical and control equipment associated with it and hence the higher the costs.
iii. Cost of the power equipment – The major binary power plant equipment for a binary are vaporizer, preheater, condenser, turbine and fun. However, a binary plant may or may not have a recuperator. For this study we shall compare the costing of both a dry cooling binary power plant with basic and recuperator

model. As a rule of thumb we shall use the table below for estimating the cost of the model power plant equipment. However, for a more accurate costs quotations need to be obtained from the vendors.

Table 4.4- Assumed thumb values for cost of power equipment [41]

Equipment	Unit Size	Base cost/Unit size USD ($)
Vaporizer	m^2	500
Preheater	m^2	450
Recuperator	m^2	500
Condenser	m^2	400
Turbine	kW	500
Fan	kW	400
Pump	kW	450

iv. Total cost of the power plants – This is a summation of all the three above cost.

However, for this study we shall only focus on the cost of the power equipment to give an indicative of how economical feasible binary power plants are in Kenya. This is because of lack of sufficient data to be able to analysis the other two costs mentioned above.

4.4.1 Cost estimation of the Model

The cost estimation of the model is done by costing of the major components of the model binary power plants of the models major components was is represented on the table4.5 below.

Table 4.5 - Estimated cost for major power plant equipment in **USD**

Parameter	Basic dry	Recuperative dry
Vaporizer	3, 331,000.00	2, 750,500.00
Preheater	8, 325,900.00	7, 750,350.00
Super heater	234,500.00	247,500.00
Recuperator	-	555,000.00
Condenser	2, 632,400.00	2, 723,200.00
Turbine	6, 725,000.00	6, 855,500.00
Pump	189,000.00	195,300.00
TOTAL	21, 437,800.00	21, 077,350.00

Generally, binary power plants are much more expensive as compared to flash technology this is so due to the use of heat exchangers that is preheater and vaporizer that are made of high quality stainless steel. From table 4.5 the recuperative model is much cheaper as compared to the basic air cooled model by 350,450USD. Other economic analysis done between regenerative and basic models show that the cost of equipment of regenerative model are generally cheaper as compared to basic model [27].This is so due to the use of a regenerator that utilizes waste heat thus reducing the size of the preheater and vaporizer. We can also see that the regenerator doesn't cost so much just shy of half a million USD thus the cost is so insignificant as compared to its benefit and making binary power plants more efficient.

CHAPTER FIVE:

5. CONCLUSION

Production of electricity would be economically unjustified without a properly chosen binary model for geothermal power production in Olkaria, Kenya that is greatly gaining momentum in Kenya. Kenya is slowly moving from hydro based power plants and investing more on geothermal. Investing more on binary power plants for Kenya will help it work on in the inefficiencies that is associated with the current flash technology used in Olkaria that makes the existing power plant ejected brine that has sufficient power to use. Recuperative model has an added advantage to the traditional binary power plants that uses the waste heat from the turbine.

In this paper, we have assessed the potential of binary power plants by keenly looking at the geothermal resources in Kenya. Olkaria in Naivasha Kenya was identified as the case study location for this study. Brine from the existing power plants in the region was chosen as the best possible candidate for binary power plants. In addition, to the brine of the drilled wells that are not currently connected to geothermal power production that were not having such high enthalpy was seen as the second most possible resource for binary power plant. This unattached wells can also be used in connection the brine from the existing power plants. The unattached wells also had a lot of brine as compared to steam ratio.

From the technical and economic analysis of the binary model we have seen that the recuperative model is the best option for binary for Kenya. Both models were given same conditions that is mass flow rate of geothermal fluid of 300kg/s at 11bar at 168°C. Technically, the recuperative model produces more net turbine work as compared to the basic binary model. The recuperative model produces 13.496MW with 219.7kg/s mass flow of the working fluid while the basic model produces 13.044 with 212.3kg/s mass flow of the working fluid. Both models were air cooled this was so because the Olkaria region is near the lake Naivasha however, most recently the waters of the lake have been reducing therefore an air option model was more feasible as air is free of charge as compared to water that will need more legal permission to use. In addition, air cooled power plants have a better aesthetic as compared to water cooled power plants.

Whereas, economically the regenerative model costs of the power plant equipment costs cheaper as compared to basic binary by around 360, 450USD.This is due to the reduction of size of the preheater and vaporizer. In conclusion the recuperative model is both economical and technically feasible binary model for Kenya. Binary power plant technology is not only a reasonable way for power production for Kenya which has a great potential for geothermal but a very energy efficient method of power production that will be able to supply the much needed electric for Kenya and in turn improve the local people's living standards and quality of life in general.

CHAPTER SIX:

6. RECOMMENDATIONS.

This study has shown that binary power plants can and are feasible geothermal technology that Kenya can venture into however some of the recommendations include

i. Detailed and a wholesome costing be done as this study has only majorly focused on only one part of the costing which is only the cost of the power plant equipment
ii. Assesment of the feasibility of combined cycle power plants in Kenya. That is binary power plants combined to the existing single flash plants as combined cycle power plants have a much higher efficiencies and they have not yet been exploited for geothermal power generation in Kenya.
iii. A detailed environmental impact assessment test for binary power plants should be taken to assess their impacts in Kenya and the location
iv. Binary power plants are an emerging technology for geothermal exploration. Therefore, the government of Kenya should see and find a way of making them financially attractive. Considering as it stands now the technology is very expensive and not attractive to investors yet binary power plants are more efficient as compared to the conventional methods of geothermal power production.

7. REFERENCES

[1] Kwambai, B.C., "Exergy Analysis of Olkaria I Power Plant, KENYA," *Geothermal training Programme*, 2005.

[2] Kenya National Bureau of Statistics, "Economic Survey 2015," Author, Nairobi, 2015.

[3] World Bank, "The World Bank," 2016. [Online]. Available: http://www.worldbank.org/. [Accessed 6 March 2016].

[4] Omenda, P. & Simiyu, S, "Country Update Report for Kenya 2010-2014," in *World Geothermal Congress*, 2015.

[5] T. Mwagomba, "Comparative analysis of geothermal power plants designs suitable for Malawi Chimweta geothermal field," vol. 22, no. 22, pp. 501-530, 2013.

[6] Kenya Electricity Generating Company, "KenGen," 2016. [Online]. Available: http://www.kengen.co.ke/. [Accessed 7 April 2016].

[7] Omenda, P. , Simiyu, S. & Muchemi, G., "Status of geothermal exploration in kenya and future plans for its development," *Geothermal Training programme*, 2014.

[8] Kopuničová, M., "Feasibility Study of Binary Geothermal Power Plants in Eastern Slovakia: Analysis of ORC and Kalina power plants," 2009.

[9] Martha, M., "Feasibility study on direct utilisation of energy from geothermal brine - A case study of Olkaria geothermal power plant, Kenya," in *World Geothermal Congress*, Bali, Indonesia, 2010.

[10] Ouma, A.P., "Geothermal exploration and development of the olkaria geothermal field," in *UNU-GTP & KENGEN*, Nairobi, 2007.

[11] Geothermal Energy Weekly, "Geothermal Energy Associaion," 8 March 2013. [Online]. Available: www.geo-energy.org. [Accessed 4 April 2016].

[12] World Energy Council, Renewable energy projects handbook, London: Author, 2004.

[13] Mburu, M., "Geothermal energy utilization," *UNU-GTP*, November 2013.

[14] Saemundsson, K., Axelsson, G., & Steingrimsson,B., "Geothermal systemsin global Perspective," *El Salvador*, p. 13, 2011.

[15] Matek,B.,, "2015 Annual U.S. & Global Geothermal Power Production Report," Geothermal Energy Association, 2015.

[16] Geothermal Development Company, "Geothermal Development Company," 2016. [Online]. Available: http://www.gdc.co.ke/. [Accessed 20 April 2016].

[17] Were,O.J. & Mwangi, N. M.;, *An Overview of Geothermal Development in KenyaDevelopment Kenya.*

[18] Ouma,A. P., "Geothermal Exploration in Kenya," 2010.

[19] Nigusse, A.H., "Performance assessement of model Orgenic Rankine Cycle power plant components for application at Olkaria I- Geothermal power plant," 2014.

[20] DiPippo, R., "Small geothermal power plants:Design,perfomance and economic," pp. 1-8, June 1999.

[21] Bronicki, Y. L., "Geothermal power stations".

[22] Valdimarsson,P., "Geothermal utilization – Production of power," 23-29 March 2014.

[23] Franco, A. & Villani, M., "Optimal design of binary cycle power plants for water dominated, medium- temperature geothermal fields," Pisa.

[24] Maghiar, T. & Antal, C. , "Power generation from low enthalpy geothermal resources," GeoHeat Center Bulletin, 2001, pp. 35-37.

[25] Eliasson,E., Thorhallsson, S. & Streingrimsson, B., "Geothermal power plants," 2008.

[26] Hettiarachchi,H. et al, "Optimum design criteria for an Organic Rankine cycle using low temperature heat sources," pp. 1698-1706, September 2007.

[27] Mwagomba, T., "Preliminary technical a,d economic feasibility study of Binary Power Plant for Chiweta geothermal field, Malawi," 2016.

[28] Quoilin,S. ,Van Den Broek, M., & et al, "Techno-economic survey of Organic Rankine Cycle (ORC) systems," *Elsevier,* vol. 22, pp. 168-186, 2013.

[29] N/A, "Geothermal technologies".

[30] DiPippo, R., Geothermal powerplants, London: Oxford, 2008.

[31] Thórhallsson, S., "Common problems faced in geothermal generation and how to deal with them," in *Paper presented at "Workshop for Decision Makers on Geothermal Projects and Management,* Naivasha, Kenya, 2005.

[32] Saitet, D. & Navas, H.F., "Valorization of Olkaria brine resources for secondary power generation," in *World Geothermal Congress*, Melbourne,Australia, 2015.

[33] Chandrasekhharam, D. & Bundschuh, J., Low-enthalpy geothermal resources for power generation, Netherlands: CRC Press/Balkema, 2008.

[34] Brown,K., "Mineral scaling in geothermal power production," UNU-GTP, Reykjavik,Iceland, 2013.

[35] Yanagisawa, N., "Case study of Calcium Carbonate scale at EGS and hot spring binary sysem," Proceedings of World Geothermal congress, 2015, Melbourne,Australia, 2015.

[36] Utami, W., Herdianita, N.,& Atmaja, R., "The effecct of temperature and pH on the formetion of silicascaling of Dieng geothermal field," in *Proceedings of the 39th workshop on the Geothermal Reservoir Engineering*, Central Java, Indonesia, 2014.

[37] Fournier, R. & Rowe, J., "The solubility of amorphous silica in water at high temperatures and high pressure," *American Mineralogists,* vol. 62, pp. 1052-1056, 1977.

[38] A. Nugroho, "Optimization of electrical power production from high temperature geothermal fields with respect to silica scaling problems," UNU-GTp, Iceland, 2011.

[39] Bao, J. & Zhao, L., "A review of working fluid and expander selections for organic Rankine cycle," *Renewable and sustainable energy revews,* no. 24, pp. 325-342.

[40] Marcuccilli, F. & Thiolet, D., "Optimizing binary cycles thanks to radial inflow turbines," in *Proceedings of the World Geothermal Congress, 2010*, Bali, Indonesia, 2010.

[41] F. Ahangar, "Feasibility study of developinga binary power plant in low temperature geothermal feild in Puga ,Jammu and Kashmir, India," UNU-GTP, Iceland, 2012.

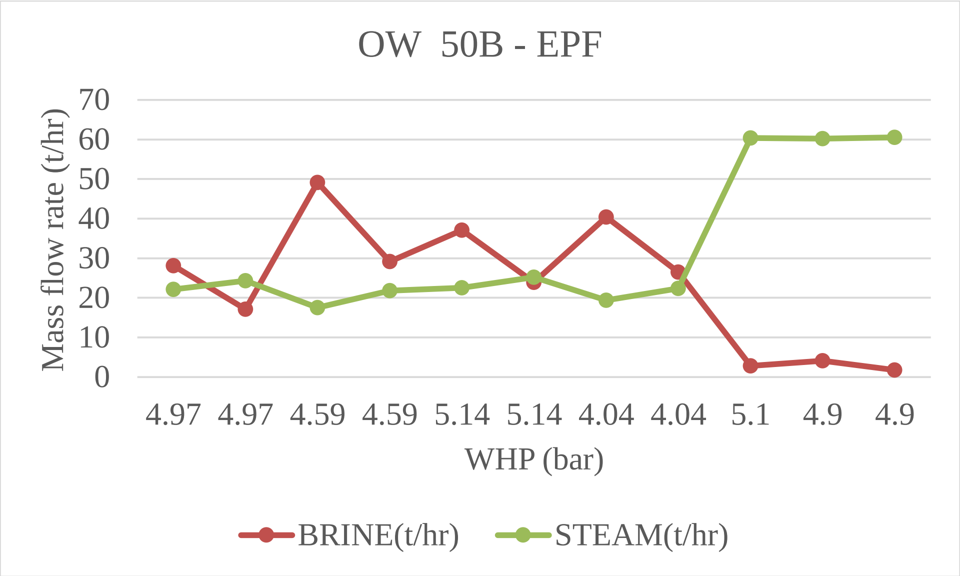
[42] Dickson, M. & Fanelli, M., "Geothermal energy: Utilization and technology," UNESCO, Paris, France, 2003.

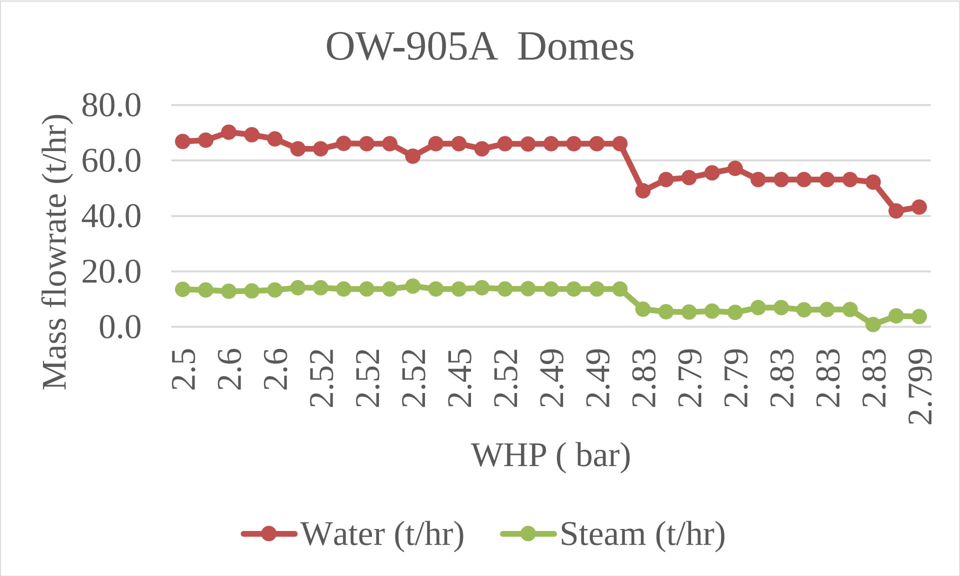
[43] VERKÍS Consluting Engineers, "Binary power plants:Preliminary study of low temperatureutilizaton,cost estimates and energy costs," VERKÍS, Reykjavik,Iceland, 2014.

[44] Mannvit Eng., "A software to evaluate financial viability of geothermal project," Author, Reykjvaik, 2012.

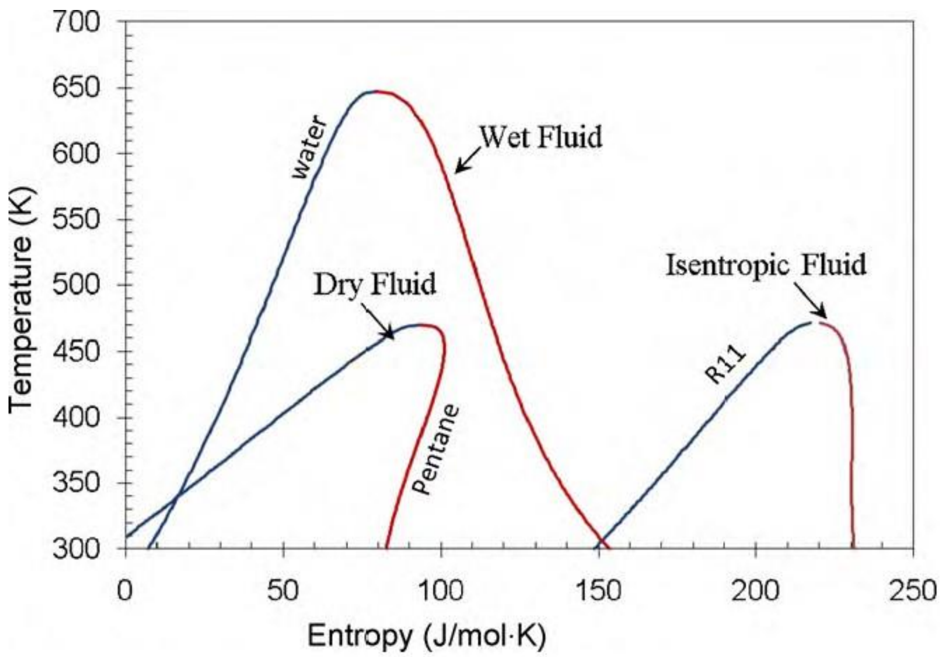
APPENDIX

Appendix I: Discharge and well monitoring curves for the unattached Olkaria wells.

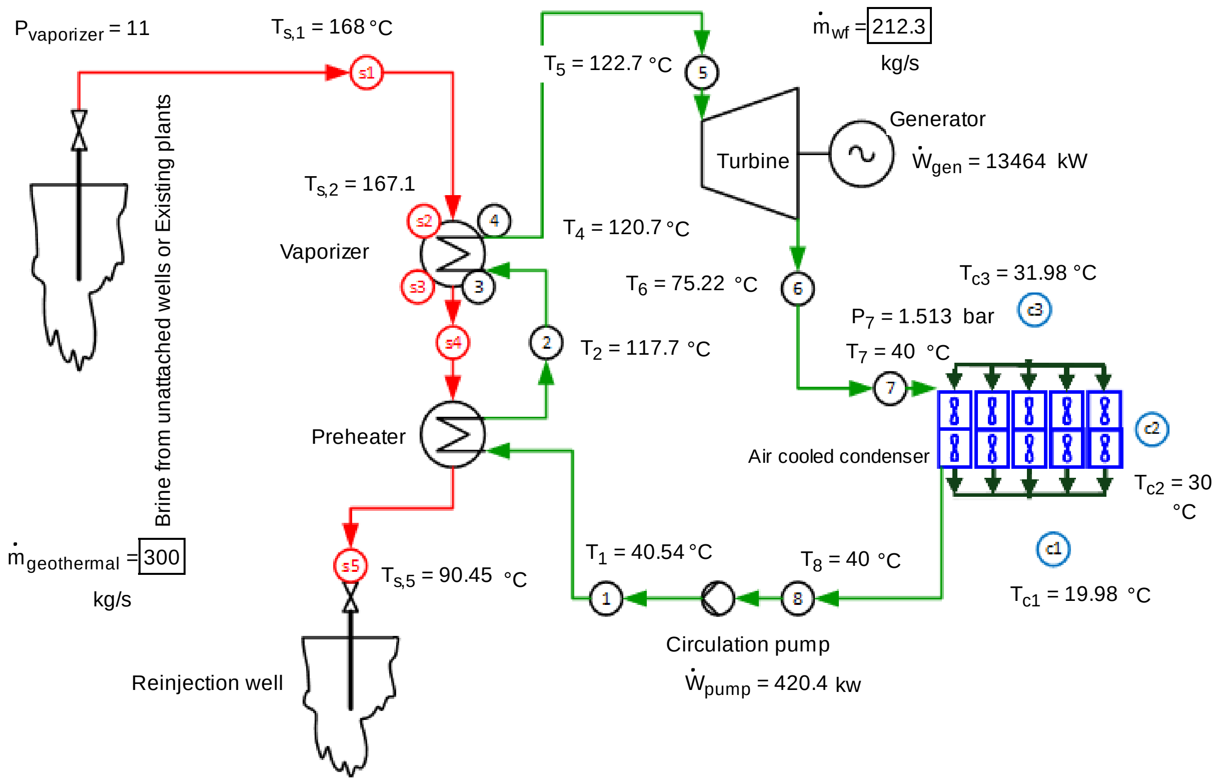




Appendix II: Thermodynamic property curve for working fluids.



Appendix III: Flow diagram for Dry Cooled Basic binary plant Model.



Appendix IV: Flow diagram for the Recuperative dry cooled binary model.