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COMPARATIVE ANALYSIS OF GEOTHERMAL POWER PLANT DESIGNS SUITABLE FOR MALAWI'S CHIWETA GEOTHERMAL FIELD

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ABSTRACT

Energy is the engine that drives the economy of a country. Unfortunately, Malawi experiences insufficient electricity generation capacity to support its economic activities. Located within the East African Rift System (EARS), which is one of the hottest geothermal zones in the world, Malawi is deemed to have significant potential geothermal energy resources that could be utilized. However, despite its favourable location, Malawi has been slow in developing production from its geothermal resource. Geological studies indicate that a geothermal system is located in Malawi with a subsurface reservoir temperature range of 169-249°C, which has been manifested through hot springs. Studies of hot springs like Chiweta indicated that the resource could be developed for electricity generation as well as direct utilization. Based on Lindal's diagram of geothermal utilization (Ragnarsson, 2006), the Chiweta geothermal field temperature falls in the category suitable for electricity generation. This report analysed the various geothermal power plant designs suitable for development in Malawi. The analysis covered both technical and economic factors. The report proposes the power plant designs best suited for Chiweta field in Malawi: the basic binary power plant at reservoir temperatures below 210°C; and the basic hybrid power plant at a reservoir temperature of 240°C.

Further studies are proposed to confirm the resource and its subsequent development as well as other potential utilization methods for the resource.

1. INTRODUCTION

1.1 General overview of geothermal energy

Geothermal energy is defined as a natural heat flow from the earth. It is estimated that at the base of the continental crust, temperatures are in the range of 200-1000°C and that, at the centre of the earth, temperatures may be in the range of 3500-4500°C (Fridleifsson et al., 2008). Geothermal energy is considered to be a clean and renewable resource, compared to other sources of energy like fossil fuels and coal, since it emits much less of greenhouse gasses like CO_2 (Hunt, 2001). Geothermal resources are being exploited around the world in a variety of applications and resources. Geothermal resources

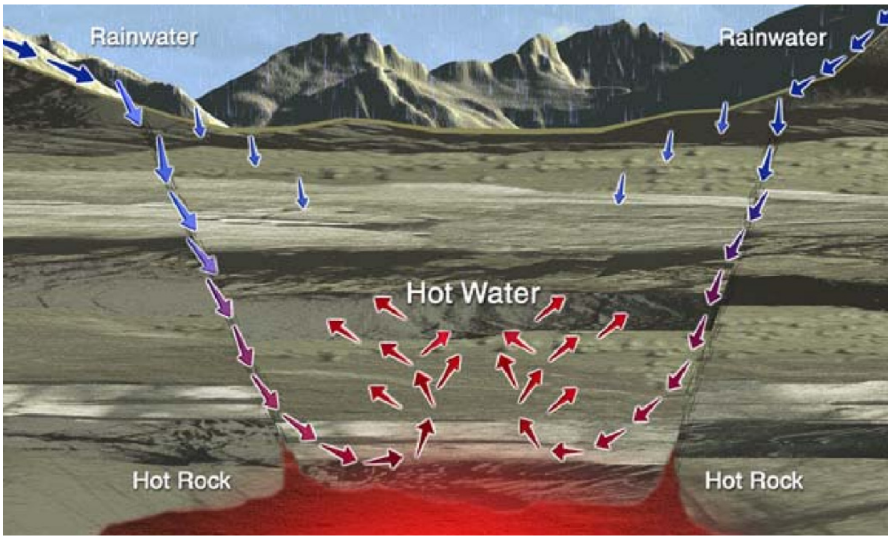

FIGURE 1: Geothermal reservoir formation (Blodgett and Slack, 2009)

can be observed through surface manifestations such as hot springs, fumaroles, surface alteration, geysers, mud pools, etc., depending on the type of reservoir in the subsurface region and the geology of the area. Even though geothermal energy is considered a renewable resource because the heat is transferred from the interior of the earth, which is essentially in abundance, the extent of its exploitation challenges the resource's future exploitation. If the resource is exploited more than the resource's ability to naturally recharge itself, the utilization sustainability of the resource is obstructed.

A geothermal system (Figure 1) consists of a heat source, permeable rock, and an inflow of water. The heat source is mostly an intrusion of magma that is close to the earth's surface. When the water inflow is heated through the heat source, the hot water or steam can be trapped in the permeable and porous rocks, forming a geothermal reservoir. Geothermal reservoir temperature normally increases with an increase in depth into the earth's crust.

Generally, geothermal resources are classified by their temperature or enthalpy as low, medium and high temperature/enthalpy resources, according to their reservoir fluid temperatures. The temperature is used as a classification parameter because it is easy to measure. Temperature also gives an indication of the energy content of the fluid to be extracted from the subsurface. High temperature fields have reservoir temperatures of more than 180°C, and middle to low temperature fields have temperatures below 180°C (Fridleifsson et al., 2008). The theory of plate tectonics states that the earth is made of plates that are floating above the mantle. Where these plates meet, there can be volcanic activity and most of the high temperature geothermal fields are located along these plate boundaries.

1.2 Geology of Malawi

Location: Malawi is a country in southeast Africa, located between latitudes 9° S and 17° S and longitudes 32° E and 36° E. It has boundaries with Tanzania in the north and northeast, Mozambique in the east, south and southwest and with Zambia in the west and northwest.

Geology: Malawi is within the Great Rift Valley which extends from Djibouti to Mozambique and lies at the southern end of the western branch of the East African Rift system (Figure 2). According to Gondwe et al. (2012), the major geological units that make up Malawi are Precambrian to lower Palaeozoic high metamorphic rocks with shaly and semi-shaly affinities. Intercalated within these are calc-silicate units and marbles. Ortho-gneissic rocks include calc-alkaline and ultra-basic rocks. In general, Karoo and Cretaceous to recent sedimentary rocks are distinguished. Karoo volcanism was observed in the form of basaltic and diabasic lava flows. Upper Jurassic to lower Cretaceous magmatic activity is ascribed to the Chilwa alkaline province. This is a suite of alkaline igneous rocks including carbonatites and related rocks, syenites and granites. The province is well developed to the south of the country and is related to the rift system.

Structural control of Lake Malawi Rift is believed to be dominated by a series of segmented N-S rifts controlling normal faults. The Lake has been subdivided into three linked half graben basins, which are the Karonga, Nkhata-bay and Nkhotakota sub-basins; these alternate in polarity along the axis of the lake, each controlled by a major bounding fault system (Gondwe et al., 2012).

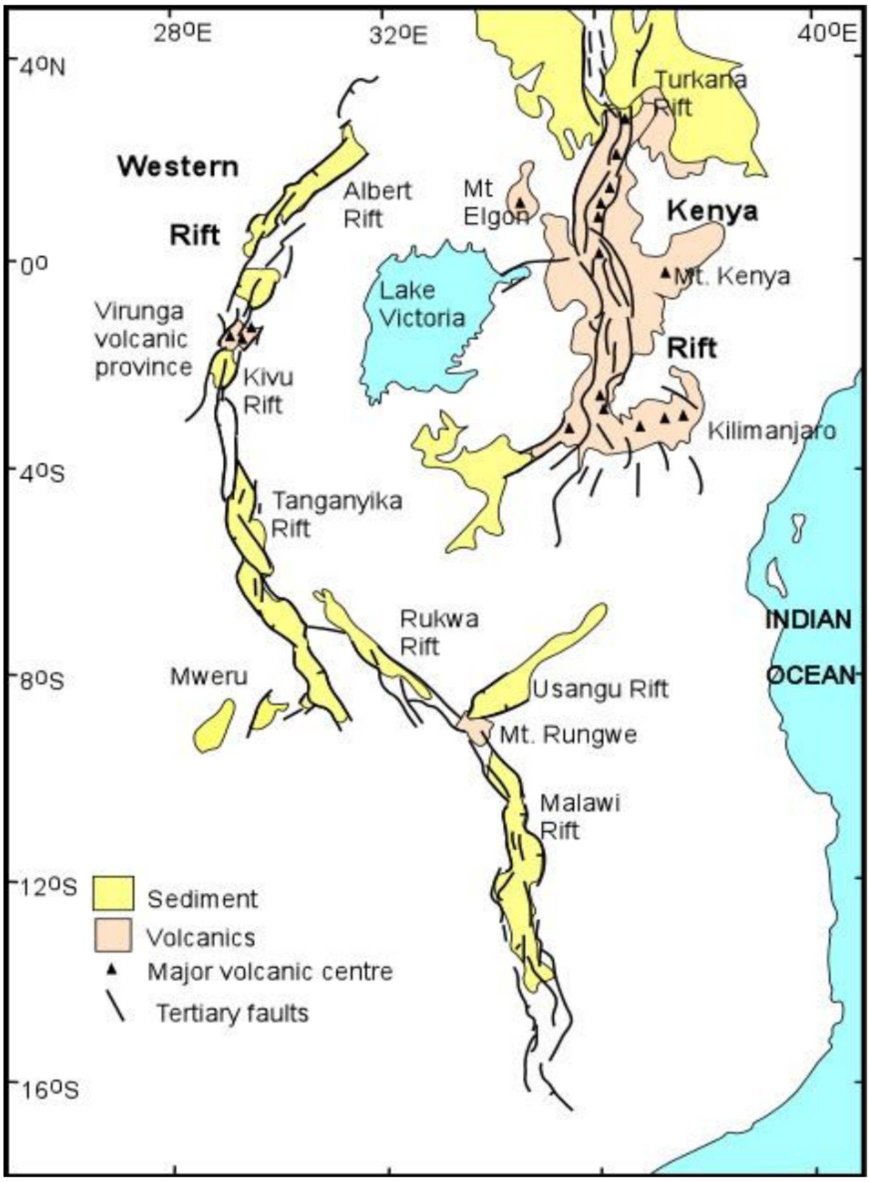

FIGURE 2: The East African Rift System (Omenda, (2005)

1.3 Geothermal resource studies for Malawi

Malawi has porous sedimentary horizons at depth, limited to the small fault-bounded Karoo Basin sediments and the young Neogene rift floor deposits, which hold water and may act as good aquifer. Unpublished studies for Malawi's geothermal potential, conducted by Malawi's geological surveys department, have been going on for some time but are not very detailed. From the studies done, it was stipulated that Malawi geothermal resources are manifested in hot springs that are located mostly along or near the intersections of major faults. There are over 60 hot springs that have been identified and documented and geochemical analyses have been done for some of them in order to understand the nature of the underlying reservoir, its temperature and the origin of the water in the system. Surface temperatures of the hot springs are between 28°C and 79°C. Further, geochemical studies suggest that most of the water, with some isolated exceptions, is immature and has not attained equilibrium, thereby presenting some degree of uncertainty about the system. This might be either a result of thermal water mixing with fresh groundwater or might mean the system is permeable and fast at recharging. Subsurface temperature studies, done with some level of confidence, deduced a reservoir temperature range of 169-249°C. The majority of the hotter springs in Malawi occur in the northern part of the country, with a more promising field in Chiweta. The Chiweta area provides the highest surface temperature of 79°C and the highest geothermometry temperature of 249°C. The chemistry of the Chiweta water shows that the water is rich in chloride, indicating a high input of geothermal fluid. It can, therefore, be concluded that Malawi has a geothermal resource, especially when focusing on Chiweta, but needs further detailed studies to ascertain the resource's size and characteristics.

2. POTENTIAL GEOTHERMAL APPLICATIONS FOR MALAWI

Geothermal utilization involves the extraction of fluid and heat from a reservoir in various ways and means. For many centuries all around the world, geothermal water was used primarily for bathing, cooking and heating. Today's utilization of geothermal resources is done at various ranges of temperature as proposed by the Lindal diagram (Figure 3) by using advances in geothermal utilization technologies. In broader terms, geothermal utilization is divided into two categories, direct utilization and indirect utilization. Direct utilization includes space heating, bathing, agricultural, aquaculture and some industrial uses, where the thermal energy of the fluid is used directly. Indirect utilization of geothermal energy is mostly concerned with the production of electricity, where the thermal energy of the fluid is converted into electrical power. The current common trend in geothermal development is utilizing a geothermal resource through cascading in a power plant along with other possible direct applications.

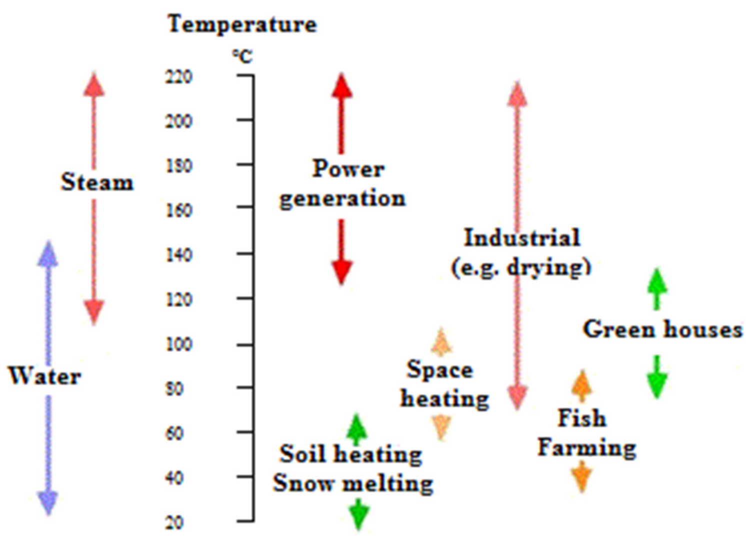

FIGURE 3: Lindal's geothermal utilization diagram

2.1 Power generation

Electricity generation via a geothermal resource is commonly applied to fluid temperatures around 150°C and higher where generation is commercially viable (Figure 3). But with the advancement in technology, considerably lower temperatures could also be used with the application of binary fluids and binary power plants, providing hope for accelerating the development of geothermal energy worldwide (Bertani, 2010).

In Malawi, generally hydro power stations generate the electricity, accounting for 95% of the total electricity generation, which is 285.85MW. All the major power stations are located in the southern part of Malawi along a single river, Shire that runs out of Lake Malawi (Figure 4). One small hydro station is located in the northern part of the country. Because of the geographical locations of the stations, Malawi's electricity system suffers instability due to transmission distances and insufficient generation capacity.

Malawi's electricity sector is dominated by a state owned electric company called the Electricity Supply Corporation of Malawi (ESCOM). The country has an installed capacity of 285.85 MW and mostly operates at 275MW with respect to a non-conventional spinning reserve. The current projected electricity demand is about 340MW, even though this is a suppressed figure rendering to the daily load shedding of electricity. Malawi experiences an average load shedding of 20MW at peak every day. Because of insufficient generation capacity, the Malawi system operates with a spinning reserve of about 10MW, putting a lot of stress on already insufficient generation capacity.

The population of Malawi is estimated to be 13 million people according to population census report of 2008 (NSO, 2010). Of this population, it is estimated that about 7.6% of the population has access to the national grid electricity (MCA – Malawi, 2010). With such enormous numbers of the inhabitants not able to access grid electricity, the majority of the population depends on other alternative sources of energy for their daily needs.

According to the department of energy affairs, the current Malawi energy mix is predominantly dependent on biomass in the form of firewood and charcoal (Table 1). The current status of the energy mix poses a big challenge for the natural vegetation of Malawi as trees are wantonly cut for an energy source. The Malawi government came up with the National Energy Policy (2003) which, among other things, focuses on improving the efficiency and effectiveness in energy supply industries and improving security and reliability of energy supply systems, as well as mitigating environmental impacts of energy production and utilization. The spirit behind the policy is to reduce the dependency of the population on firewood by providing environmentally friendly alternatives so that the energy needs of the population are met in a sustainable manner.

In line with Malawi's energy policy objectives and concern with the power shortage that the country experiences, the country is reviewing the role of generating electricity from sources other than hydro, based on the country's available resources. With geothermal being one of the resources that the country has with the potential for generating power, and with reference to the Lindal diagram in Figure 3, Malawi needs to scale up its studies in order to develop the resource and meet the growing energy demand. This study, therefore, focuses on assessing appropriate power plant designs for Malawi's geothermal resource that the country may adopt for development.

FIGURE 4: Map of Malawi

TABLE 1: Energy mix projections in Malawi 2000 – 2050 (National energy policy for Malawi, 2003)

	2000	**2010**	**2020**	**2050**
Biomass	93%	75%	50%	30%
Liquid Fuels	3.50%	5.50%	7%	10%
Electricity	2.30%	10%	30%	40%
Coal	1%	4%	6%	6%
Renewables	0.20%	5.50%	7%	10%
Nuclear	0%	0%	0%	4%
TOTAL	**100%**	**100%**	**100%**	**100%**

In order to maximise the economies of scale from a given geothermal resource, integration of geothermal power generation projects with agricultural production, farm processing, and distillation or dehydration facilities is rapidly growing in popularity. The trend is as a result of advancements in the generation of electricity from moderate temperature geothermal resources with temperature ranges of 100°-150°C. There is an economic advantage in full utilization of the resource in such a way. Worldwide, geothermal developers are evaluating building projects for optimal resource utilization and a reduction in waste heat rejection, with reference to the various economic activities happening around the prospective geothermal resource.

2.2 Fish farming with geothermal

Located in a tropical region with an abundance of sunlight and fresh water including Lake Malawi, Malawi is home to hundreds of different tropical fresh water species of fish. Among the many species available, tilapia (locally called chambo) is found in Lake Malawi and is the most liked fish from the lake. Chambo have been taken from the lake and bred into various fish ponds across the country, using extensive aquaculture. Thus, the fish are stocked in ponds and then feed on each pond's natural vegetation. Temperature and sunlight enhance the production of aquatic plants through photosynthesis. The aquatic plants, which are mostly algae and related plants, are consumed by smaller animals such as zooplanktons. The zooplanktons are then eaten by the fish, thus making an aquatic ecosystem. Studies have shown that tilapia and other tropical fish breeding, using geothermal heat, has been a success in many areas with examples from Japan, China and USA. A special example is given in the state of Oregon in the USA where chambo from Lake Malawi was successfully bred using geothermal water (Kiruja, 2012). Geothermal water at about 90°C is mixed with colder water into the fish pond for an optimal pond temperature of about 28°C which is maintained year round. Here, geothermal heat is used for better control of pond temperature, thereby leading to optimal fish growth. This results in yields that are encouraging. The quality of water and the control of diseases are critical in the breeding of fish using geothermal resources.

Even though the atmospheric temperatures in Malawi are of a typical tropical type, temperature differences during the day and night, coupled with seasonal changes, are significant. Such factors have an impact on chambo breeding in ponds such that production is not at its best. Malawi could, therefore, incorporate geothermal energy into chambo breeding in various fish ponds for optimal production.

2.3 Other potential applications of geothermal resource utilization in Malawi

One of the industrial uses of geothermal energy is the distillation of ethanol. Ethanol in Malawi is locally produced from by-products of sugar production. Some of the geothermal prospect areas in Malawi are close to the sugar producing area in the central region district of Nkhotakota. Attempts were made in the USA to produce ethanol (alcohol fuel) using geothermal energy. These attempts were not successful, as the economics were marginal (Lund, 2005) in the early days. However, further studies now prove that production using geothermal energy could be viable. Global fuel prices have been on the rise, and that rise is felt by most developing countries' economies. Malawi is a landlocked nation with no direct access to the sea; this factor, with regard to the transportation of goods and services within the country and outside, coupled with rising fuel prices, makes the economy volatile. Currently, Malawi uses a 20:80 blending ratio of ethanol to petrol in its petrol supplies with an aim to reducing carbon emissions, as well as cutting import bills on fuel. With the increase in fuel demand, ethanol production has been challenged as it operates under capacity versus demand. Malawi could, therefore, attempt to increase ethanol production using geothermal energy. Development of ethanol production plants could be done by taking advantage of the proximity of the prospective geothermal areas to the sugar producing factories.

3. GEOTHERMAL POWER PLANT TECHNOLOGIES SUITABLE FOR MALAWI

3.1 Overview of power plant technologies

The power plants that are developed for geothermal resource exploitation are divided into two main categories which are steam cycle and binary cycle (Valdimarsson, 2010). The steam cycle plants are those that utilise the geothermal fluid directly to produce electricity; binary cycle plants are those that use e.g. organic fluid that obtain heat from the geothermal brine in order to produce electricity. The different types of power plants that are commonly developed are: single-flash steam plants, double-flash steam plants, binary organic Rankine cycle, binary Kalina cycle, combined single flash with ORC plant, and combined ORC cascade. The characteristics of a geothermal field are crucial in determining the appropriate type of power plant suitable for the field. Various sources in the literature propose that conventional steam turbines require a particular range of fluid temperatures, depending on field characteristics; the same applies to a binary plant that utilizes a secondary working fluid that requires a certain range of fluid temperature. The temperature ranges are mostly within the proposal of the Lindal diagram. Outside such temperature ranges, the cycles become uneconomical.

One of the good things about geothermal power plants is that when the plant is fully automated, it can operate unmanned and can go through a self-start procedure after they have tripped off line due to faults unrelated to the power plant. The plants can be monitored and started remotely if required. Examples of such plants are the Reykjanes and Svartsengi geothermal power plants in Iceland.

It is estimated that the availability of geothermal power plants, measured with respect to hours in a set time period, is mostly over 95% (Kagel, et al., 2007). This characteristic makes geothermal power plants base load plants.

3.2 Steam-flash plants

In designing a flash steam plant (either single or double flash), it is assumed that the geothermal fluid is a saturated water from the reservoir. This common assumption comes with the fact that, generally, dry steam reservoirs are very rare (DiPippo, 1999). Where vapour dominated reservoirs exist, direct-steam plants are used; otherwise the assumption holds. With reference to Figure 5, as the fluid travels towards the surface through the production well, it experiences a flashing process along the way. Flashing of the fluid means that the fluid pressure decreases and steam forms from the saturated water. The fluid is directed to the power plant from wells via pipelines. The two-phases, water and steam, are separated by a separator directing the steam towards the inlet of a turbine for electricity generation. The separated brine is directed to reinjection or, where need and brine characteristics allow, for further utilization such as for district heating. This is called a single-flash power plant. Even though experimental machines have tried to use two-phase fluid for running the turbine, the general approach has mostly been to separate the two phases (DiPippo, 1999). The water phase from the separator may be flashed again for a low pressure turbine, making the cycle a double-flash power plant. Double-flash power plants are normally associated with high-enthalpy geothermal fields with temperatures in excess of 240°C.

After passing through and driving the turbine for electricity generation, the steam exits into either a condenser, where it is condensed and cooled by a chosen cooling medium for a condensing plant, or is exhausted into the environment for a back-pressure plant.

Experience has shown that the flashing process is an appropriate power generation process where resource temperatures are above 150°C. However, some developments in studies seem to indicate that flashing technology can be employed at temperatures as low as 120°C or less, and at a cost significantly lower than that of a similarly sized binary plant (Pritchett, 1996). Such studies are trying to work out scaling problems that are major barriers to flash plant development at lower temperatures. These technological studies could result in more efficient utilization of geothermal energy in the future.

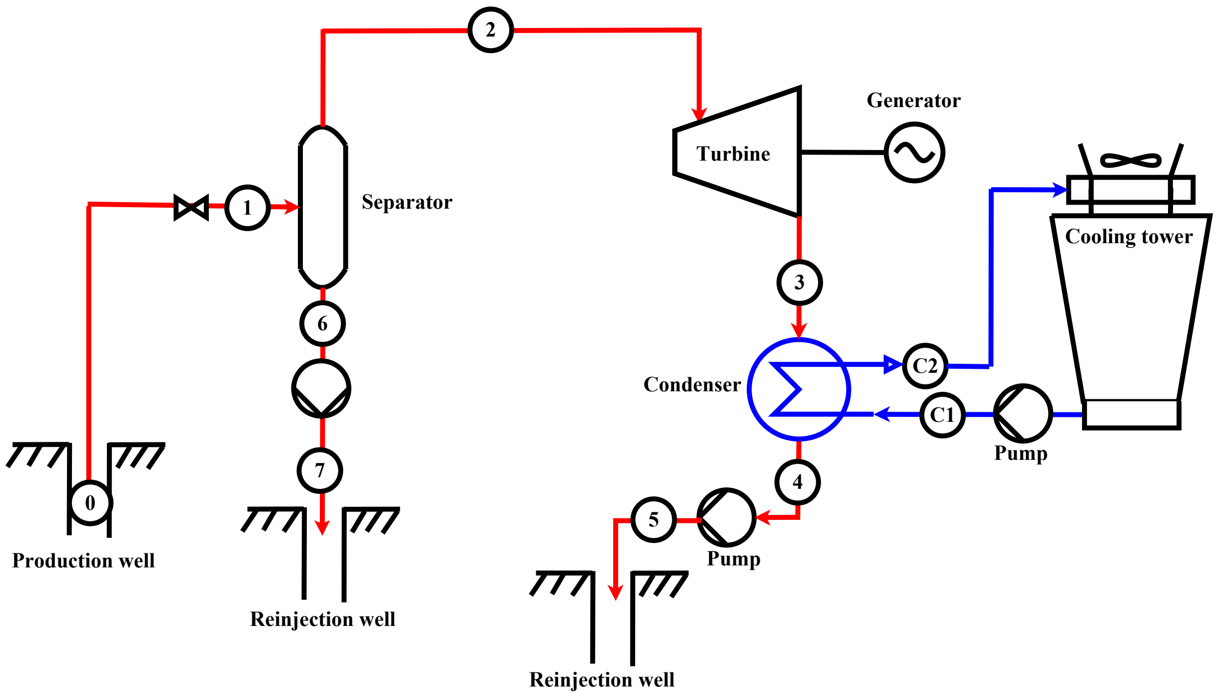

FIGURE 5: Single-flash power plant process diagram

3.3 Binary cycle power plants

The primary objective in developing binary cycle power plants was to generate electricity from low to medium temperature geothermal resources and to increase the utilization of the geothermal fluid through recovery of heat from waste fluid. Binary power plants utilize a secondary working fluid for power generation. The working fluid, which is usually an organic fluid, has a low boiling point and high vapour pressure at low temperatures, when compared to geothermal fluid. Binary power plants are mostly utilized for geothermal resource temperatures of 150°C and less (DiPippo, 2008). From various studies conducted among geothermal energy resources, it is believed that the medium- and low-temperature liquid-dominated systems are the most abundant sources occurring around the world (Franco and Villani, 2009). This makes the use of binary power plants popular in electricity generation applications for geothermal utilization. In a binary plant, the thermal energy of the geothermal fluid in the primary cycle is transferred to the secondary working fluid via a heat exchanger for use in the Organic Rankine Cycle (Figure 6) or the Kalina Cycle (Figure 7). The vaporized working fluid is expanded through a turbine which, in turn, drives a generator for electricity generation. The vapour is then condensed in the condenser and returned to the heat exchanger through a pump in a closed loop, and the process continues in the cycle. Efficient use of heat in the binary cycle can lead to an outlet temperature of the geothermal fluid that can be further utilized in other applications, depending on the fluid's characteristics.

In recent years, there has been development of an improved binary cycle called the Kalina Cycle (Figure 7). Kalina power plants utilize an ammonia and water mixture as its working fluid in the binary cycle with geothermal fluid as its primary cycle just like in the basic binary power plant. The working fluid from the vaporizer passes through a separator which separates liquid fluid and steam. The working fluid steam is expanded through the turbine in a superheated condition. As the steam goes to the condenser from the turbine, it mixes with the fluid from the separator before rejecting some heat in a recuperator. The fluid then passes through a condenser where it is condensed. From the condenser the fluid passes through the recuperator for the first pre-heating and then to the pre-heater and evaporator. The fluid in the recuperator is heated by the fluid (with a higher enthalpy) that comes from the separator and turbine. As such, a Kalina cycle has the advantage in that it allows a higher heat exchange effectiveness to be achieved over and above the traditional binary plant. Literature and studies estimate that Kalina power

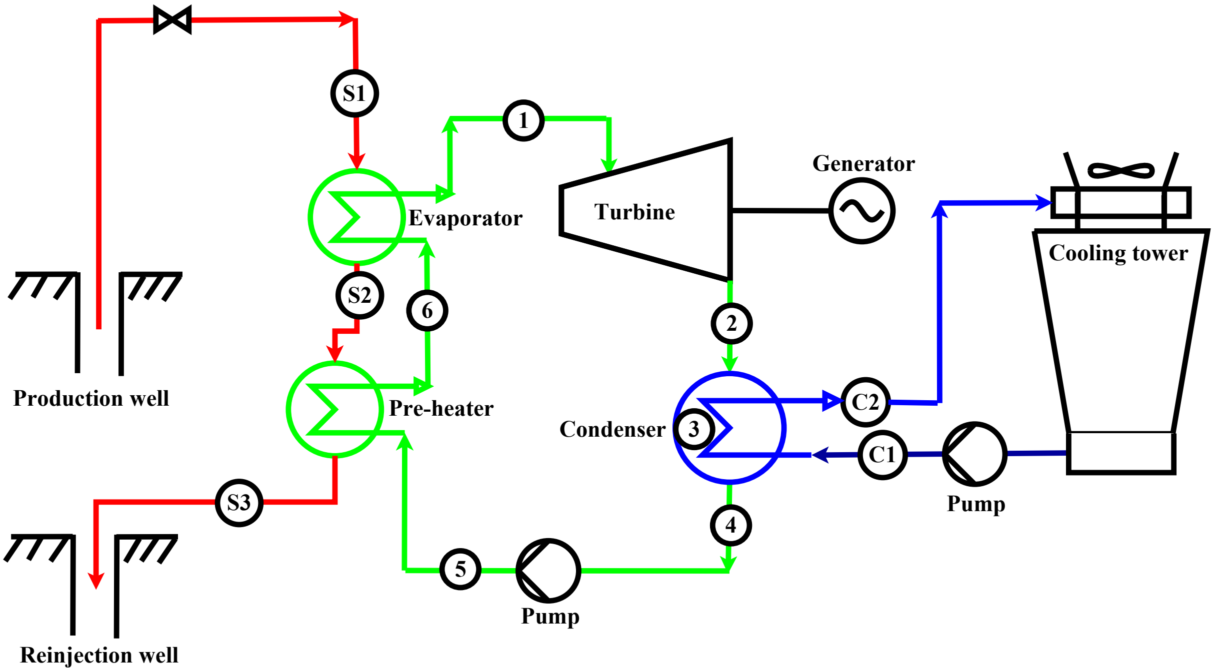

FIGURE 6: Binary power plant process diagram

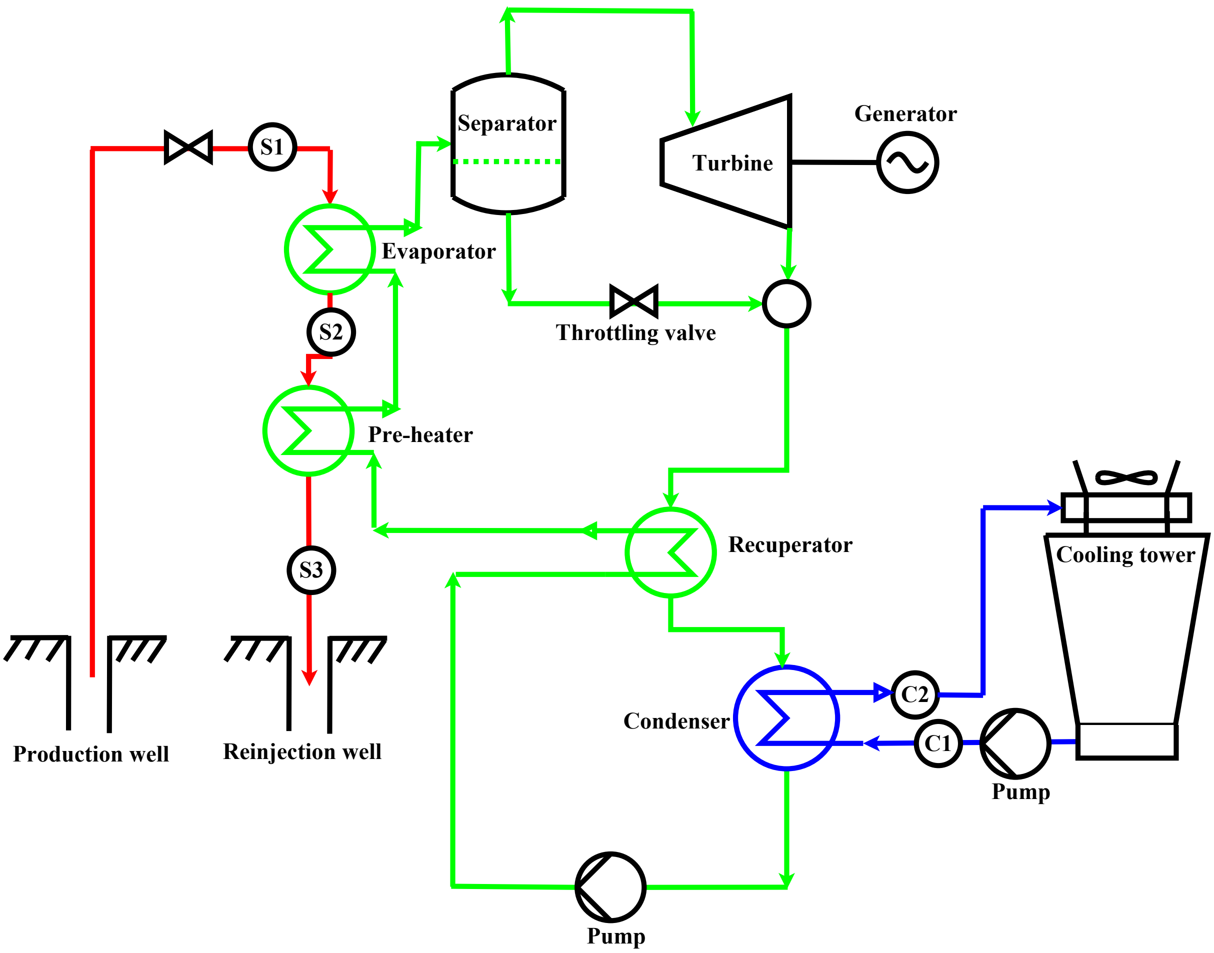

FIGURE 7: Kalina power plant process diagram

plants are about 40% more efficient (Dickson and Fanelli, 2003) compared to the traditional binary power plants, even though they are not yet as popular as the traditional binary plants.

Binary power plants are usually constructed in small modular units of the order of a few kWe to a few MWe capacity which, when added together, create a power plant of a few MWe. This mode makes binary power plants cost effective and a reliable means of geothermal electricity generation for medium to low temperature geothermal resources.

3.4 Hybrid power plants

A hybrid power plant (Figure 8) is a combination of steam flash and binary cycles. The configuration may be such that it combines single flash with a binary cycle or a double flash with binary, depending on the levels of field enthalpy. The cascaded binary cycle may get its primary fluid heat from either brine coming from the flash cycle's separator or from the steam from the exhaust from the turbine of a back pressure steam flash cycle. The binary bottoming that uses steam from a back pressure turbine as a heat source has some advantages, as Thórhallsson (2005) explained, as it would be free of scaling problems. An example is the Svartsengi plant in Iceland. The rest of the cycles are as mentioned earlier.

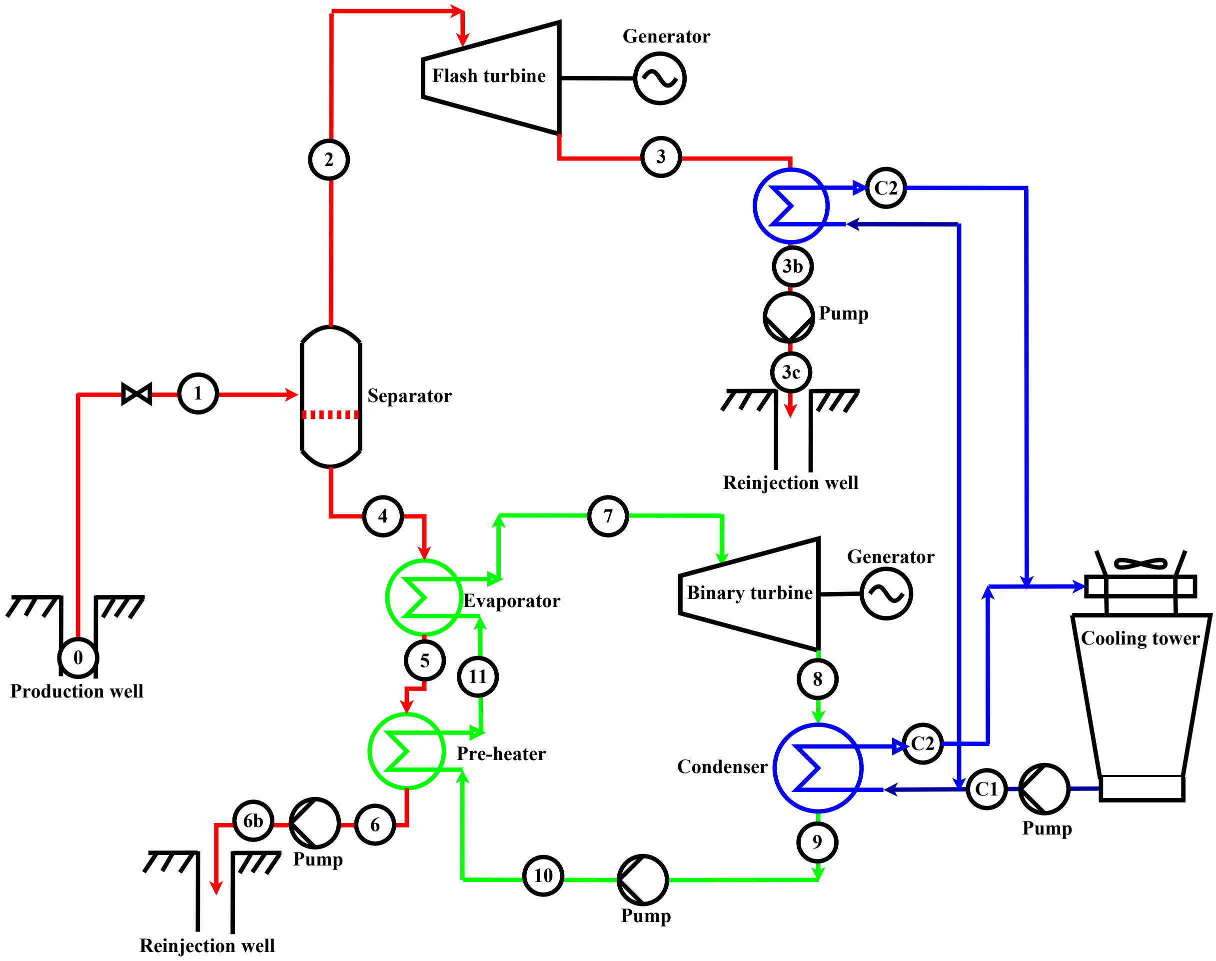

FIGURE 8: Hybrid power plant process diagram

A suitable power plant design for any field is the one that: matches with the expected geothermal production well parameters; is reliable; and is environmentally friendly while giving assurance of its economic viability. Based on the geochemical data available for Malawi and using the Lindal geothermal resource utilization diagram, three possible proposals for Malawi's development of its geothermal resource are: through a single flash power plant, a binary power plant, or a hybrid of the single flash and binary cycle power plant. The power plant could then be cascaded with other direct various applications, depending on the characteristics of the geothermal brine that may come from power plant utilization. The proposed cycles are presented in the assessments below to find the most suitable option for Malawi, in terms of both technical analysis and economic analysis.

4. THERMODYNAMIC DESIGN CONSIDERATIONS FOR POWER PLANTS

4.1 Single-flash power plant - thermodynamic considerations

The assessment of the thermodynamic design considerations for a single flash power plant is based on the single-flash diagram in Figure 5. From Figure 5 it is assumed that, at stage 0 which is the geothermal reservoir, the fluid is in single state liquid form at a saturated pressure with respect to the T-s diagram in Figure 9. This also assumes that there is no heat loss along the way to the surroundings or that the heat lost is negligible; therefore, an adiabatic process from 0 to 1 is assumed. Therefore:

$$h_0 = h_1 \tag{1}$$

It is also assumed that there is no loss of mass along the way from 0 to 1or that the loss is negligible; hence, the mass balance at point 1:

$$\dot{m}_0 = \dot{m}_1 \tag{2}$$

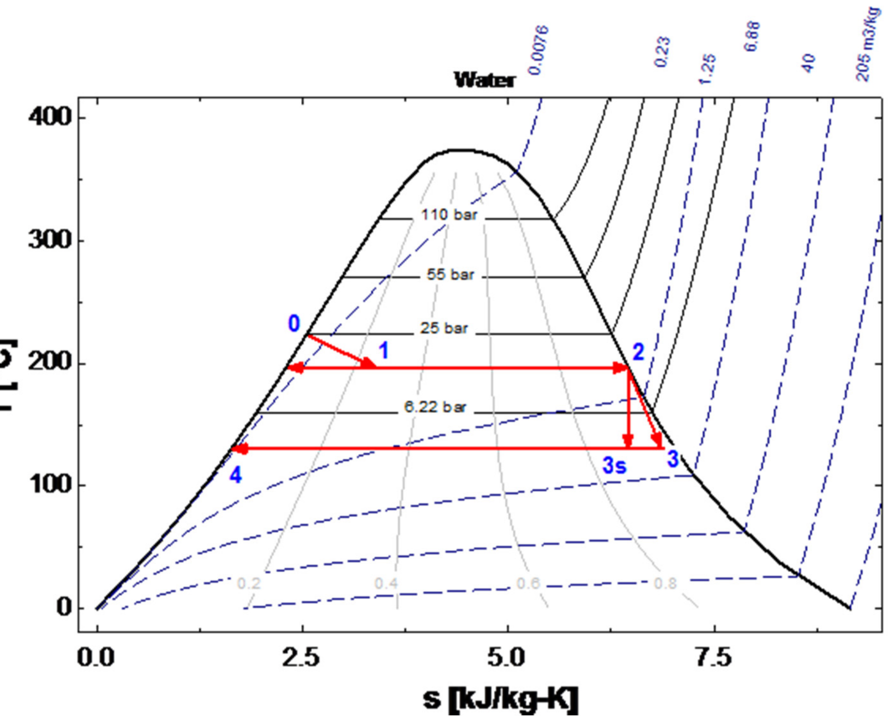

FIGURE 9: T-s diagram for a single-flash cycle

The fluid is throttled into the separator through a valve at the wellhead. The process of throttling the geothermal fluid results in a pressure decrease at point 1 of the T-s diagram in Figure 9. Due to pressure reduction the fluid starts boiling, meaning that the temperature is dependent upon the separator pressure (Valdimarsson, 2011a). At the separator, there is a separation of steam and liquid. The level of the separator pressure and enthalpy determines how much steam is produced. The lower the separator pressure, the more the steam produced, hence there is less liquid. The higher the separator pressure, the less steam is produced, hence there is more liquid. For the single-flash plant, the target is to get the optimum steam flow and enthalpy, so an optimal separator pressure for this purpose was reached by following the relationship of separator pressure and turbine output. This indicates that the selection of the separator pressure is crucial in designing a geothermal power plant. This pressure, coupled with the wellhead pressure, determines whether boiling starts in the formation or not. If boiling starts in the formation, it can lead to scaling along the fluid's path, thereby reducing/blocking the fluid's flow passage in the formation. This may lead to a shorter lifespan of the well.

The steam fraction at the entry point of the separator is defined as follows:

$$x_1 = \frac{h_1 - h_6}{h_2 - h_6} \tag{3}$$

where x_1 is the steam fraction at the separator's entrance,
h_x is the fluid enthalpy at point *x*.

Looking at the mass balance at the separator's entry point, the total mass flow rate entering the separator ($\dot{m}_1$) is equal to the sum total of the mass flow rate of the fluid leaving the separator. This is represented by:

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_6 \tag{4}$$

But at point 2, the fluid is saturated steam and at point 6 is saturated water (Figure 10). Therefore, with the mass flow rate for steam ($\dot{m}_2$) and the mass flow rate for water ($\dot{m}_6$) at these respective points, and with respect to $\dot{m}_1$, the steam fraction becomes:

$$\dot{m}_2 = x_1 \dot{m}_1 \tag{5}$$

$$\dot{m}_6 = (1 - x_1)\dot{m}_1 \tag{6}$$

where x_1 is the steam fraction at the separator's entrance.

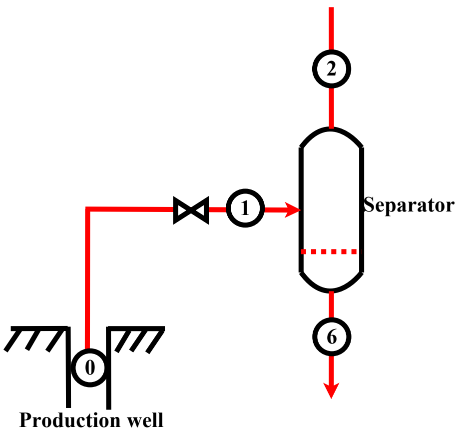

FIGURE 10: Separator point

The fluid from point 6 is either reinjected into the field or further utilized, depending on the fluid characteristics in terms of temperature and chemistry. The steam from point 2 is directed to the turbine entrance through a demistifier/mist eliminator.

The steam from point 2 is expanded through a turbine producing mechanical power that is used in turning the turbine to generate electricity. The steam at the turbine entry is in the same state as when exiting the separator, with some pressure drop due to transportation in the piping system. The work done by the steam, in turning the turbine, causes a drop in enthalpy at point 3 (Figure 11). It is ideally perceived that the process of expansion of steam in the turbine is isentropic, i.e. the entropy at the output of the turbine is the same as the entropy at the turbine inlet. However, in real application, the process is not isentropic since the expansion is irreversible and the process increases fluid entropy. Therefore, both the isentropic enthalpy h_{s3} and the real enthalpy h_3 are assessed at point 3. The relationship between enthalpy and isentropic turbine efficiency is given by the following equation:

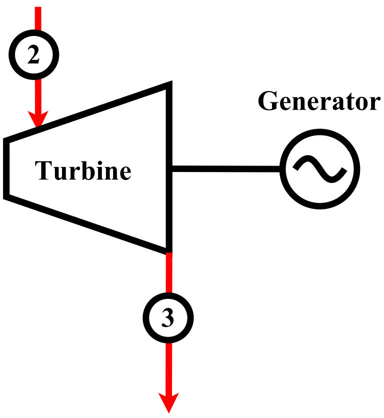

FIGURE 11: Turbine point

$$\eta_{tur} = \frac{h_2 - h_3}{h_2 - h_{3s}} \tag{7}$$

where η_{tur} is the turbine isentropic efficiency;
h_{s3} is the isentropic enthalpy at point 3.

However, in calculating the work done by the turbine, the isentropic enthalpy, together with the isentropic turbine efficiency (η_{tur}), is commonly used. The efficiency is provided by the turbine's manufacturer and, in common practice, this efficiency is 85%.

From the equations above, the work done by the steam which is the mechanical power output from the turbine is given by turbine efficiency, the mass flow rate of the fluid passing through the turbine, and the enthalpy drop across the turbine. This relationship is presented in the following equation:

$$\dot{W}_{tur} = \eta_{tur} * \dot{m}_2(h_2 - h_{s3}) \tag{8}$$

where $\dot{W}_{tur}$ is the mechanical power output of the turbine.

From the turbine, the steam is led to atmospheric exhaust and into the atmosphere for a back pressure system. In a condensing system, the steam from the turbine is led to a condenser which changes the fluid from a vapour state to a liquid state. Pressure at this point is kept as low as possible in order to extract more energy from the turbine process. The condenser is one of the most important facilities in the cycle because it assists the turbine in obtaining maximum efficiency in its energy conversion. The condenser is coupled to a cooling system which commonly either uses 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.

Basically, there are two types of condensers, the direct contact condenser and the surface condenser (most often a shell and tube heat exchanger). The direct contact condensers are designed in such a way that production steam directly contacts the cooling water which cools the steam down and forms liquid. This condenser is applicable in flash plants but not in binary plants since a closed loop secondary fluid is used there. The surface condenser allows for two separate fluids to exchange heat without directly coming into contact with each other. In the case of geothermal plant, such condensers require more fresh water for the effectiveness of the system. The surface condensers are more applicable in binary cycles where secondary fluid does not come into contact with the water. They can also be used in flash systems, depending upon the characteristics of the fluid in use.

The cooling system can either be water cooled or air cooled. The air cooled system uses fans that are electrically driven to cool the working fluid. The water cooled system uses water that can either be sprayed in direct contact condensers or passed through the shell and tube condensers. It is more economical to use a water-cooled system in the case of a flash power plant; in a binary power plant, the air cooling system can be considered where access to water is limited. In Malawi, where a source of cooling water is not a problem as water bodies are close to the geothermal prospective areas, the water cooled system is proposed. Therefore, in this study, the cooling system will use the water cooling tower.

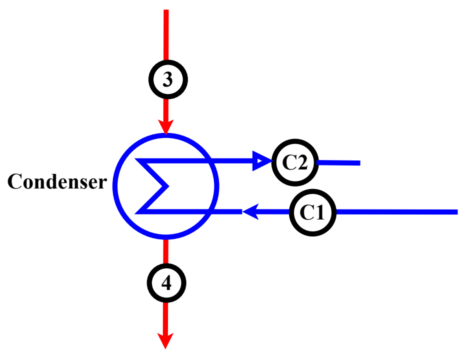

FIGURE 12: Condenser point

The heat rejected ($\dot{Q}_{wf\_cond}$) from the working fluid to the cooling medium in the condenser is found by the mass flow rate of the fluid and the enthalpy drop across the condenser (Figure 12). In a single flash plant, the working fluid is the geothermal steam itself. The relationship is presented in the following equation:

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

The rejected heat from the working fluid is transferred to and accepted by the cooling water as $\dot{Q}_{cw}$, hence the relationship is as follows:

$$\dot{Q}_{wf\_cond} = \dot{Q}_{cw} \tag{10}$$

Where $\dot{Q}_{cw}$ is a relationship between the cooling water mass flow rate and the enthalpy change in the cooling water across the condenser. This relationship is given by the following equation:

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

Or

$$\dot{Q}_{cw} = \dot{m}_{cw}cp_{cw}(T_{c2} - T_{c1}) \tag{12}$$

where h_{cx} is cooling water enthalpy at point x;
cp_{cw} is the specific heat capacity for cooling water;
T_{cx} is the cooling water temperature at point x.

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 vapour which is released into the environment and, hence, there is an exchange of both heat and mass between the water and the air.

In direct contact condensers, during the condensing process, part of the cooling water is sent back to the condenser after it is cooled by air in the cooling tower. The excess water may be sent for reinjection for sustainable production and environmental mitigation just like the brine from the separator, or it may be directly rejected into the environment, depending on the fluid chemistry.

The cooling water is sourced from various sources like nearby streams, boreholes for cooling water and part of the condensed steam from the geothermal fluid in the direct contact condensers, as mentioned earlier.
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.

4.1.1 Consideration of potential scaling

When the geothermal fluid is flashed, non-condensable gases (NCGs) emerge. The natural characteristics of these gases are such that they do not change state; neither do they dissolve, so some attention is required. If left unattended, the NCGs collect in the condenser steam space and generally increase pressure at the turbine exit side which, in effect, reduces the efficiency of the turbine, resulting in low generation capacity and can lead to a turbine trip if left unattended. It is for this reason that the NCGs are supposed to be removed. The gasses, therefore, must be extracted from the condenser by a vacuum gas extractor which should not affect the turbine efficiency through pressure increase.

Reinjection needs to be done with proper studies of the field and the fluid. The field studies are supposed to suggest an appropriate location for reinjection wells where reinjection will not cause short-circuiting of cold water into the reservoir, thereby lowering the production temperature. Tracer testing is one of the tools used to understand the connection between the production wells and the reinjection wells.

Studies of the fluid chemistry are meant to provide knowledge about the chemical composition of the fluid. This assists in ascertaining the probability of scaling at various temperature levels, both in the surface equipment and in the reinjection wells. It is recommended that the silica solubility curve (Figure 13) be consulted to ascertain safe working reinjection temperatures, with respect to the silica content in the geothermal brine. For Malawi, with reference to Figure 12, and a sub-surface temperature range of 169-249°C, the safe reinjection temperature that can avoid silica scaling is around 70°C for 169°C, and around 110°C for 249°C when both flashing the brine and using a binary cycle. The project has observed these considerations where necessary.

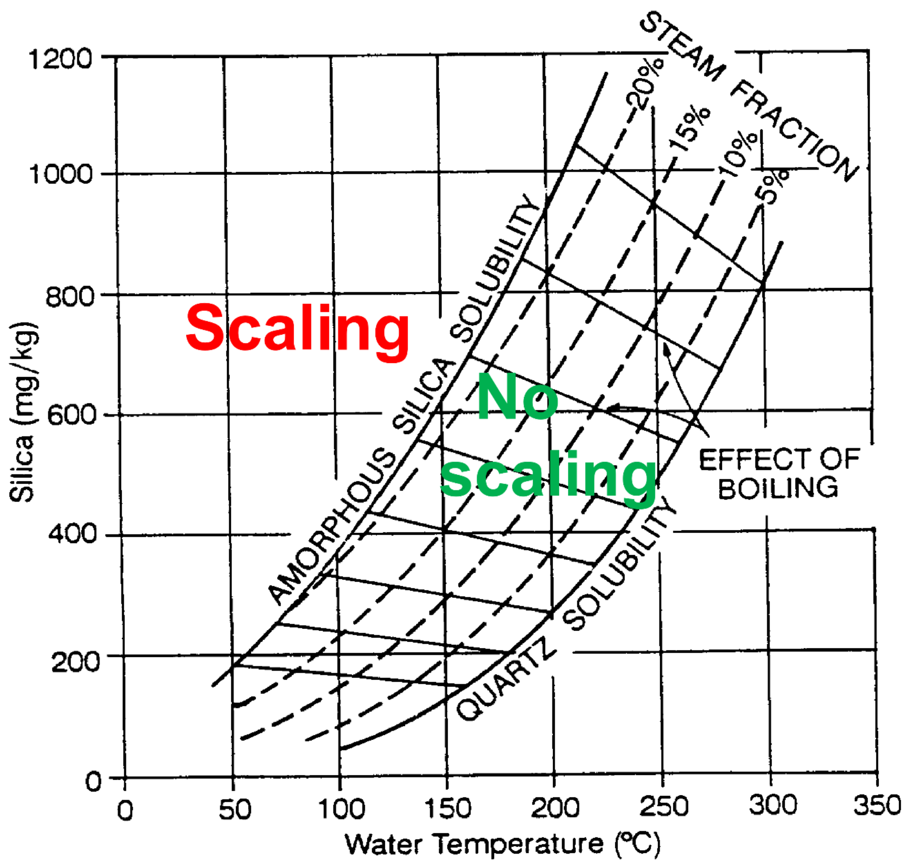

FIGURE 13: Amorphous silica solubility curve (Thórhallsson, 2013)

4.2 Binary power plant thermodynamic design considerations

With the advancement in technology and the demand for cleaner energy that geothermal resources offer, Binary power plants (or Organic Rankine Cycle units – ORC) are becoming popular in areas where the reservoir has low-enthalpy characteristics. Binary plants are also being implemented for further utilization of geothermal brine from flash power plants where temperature allows. They are mostly considered to be viable energy conversion systems, both technically and environmentally, in the cases above. A binary cycle power plant consists of two fluid systems for the generation of electricity, i.e. the primary and the secondary systems. The primary system is the hot open loop geothermal fluid system which is the source of the energy. The secondary system is the closed loop working fluid system that is in contact with the turbine and gets its heat from the hot geothermal fluid of the primary system. The fluid used in the secondary system is usually an organic fluid that has a low boiling point and a high vapour pressure, when compared to water, at a common given temperature.

The thermodynamic analysis of a binary power plant is based on the basic binary diagram in Figure 6. The heat from the geothermal water is transferred to a secondary working fluid through heat exchangers and the cooled geothermal water is reinjected back into the reservoir.

The geothermal fluid enters the primary cycle at point S1 (Figure 14), and vaporizes the working fluid in the evaporator. The geothermal fluid then leaves the evaporator and enters the pre-heater through point S2. The geothermal fluid heats the working fluid in the pre-heater and then leaves the pre-heater through point S3 (Figure 14).

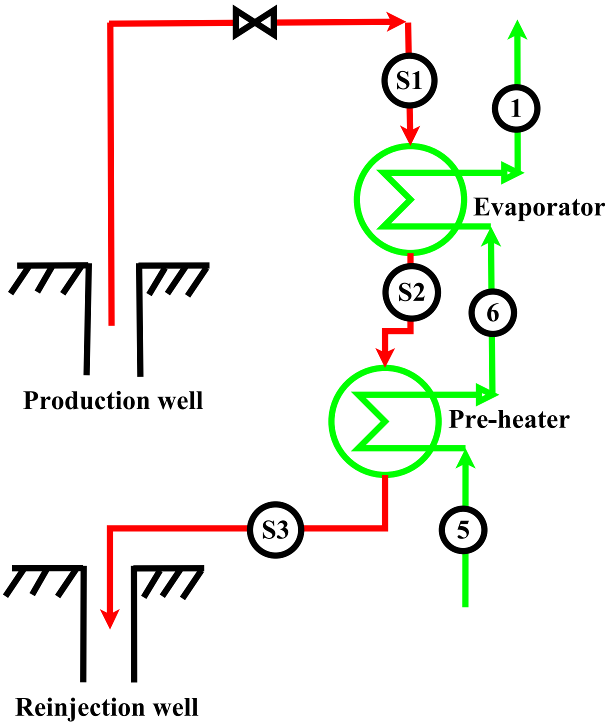

FIGURE 14: Pre-heater and evaporator point

Conversely, the working fluid in the secondary cycle enters the pre-heater through point 5 and is heated by the geothermal fluid. The working fluid then leaves the preheater as saturated liquid and enters the evaporator through point 6. In the evaporator, the fluid is vaporized and leaves the evaporator through point 1 directed towards the turbine (Figure 14).

The process of heat exchange is designed such that the heat rejected by the geothermal fluid in both the evaporator and the pre-heater is received by the working fluid at these respective points. The thermodynamic assessment is, therefore, as follows:

$$\dot{Q}_b = \dot{Q}_{wf} \tag{13}$$

where $\dot{Q}_b$ is the total heat rejected by geothermal brine; and
$\dot{Q}_{wf}$ is the total heat received by the working fluid.

The total heat rejected by the brine is the sum of the heat rejected in both the evaporator and the pre-heater and is given by the equation:

$$\dot{Q}_b = \dot{m}_b(h_{S1} - h_{S3}) \tag{14}$$

where $\dot{m}_b$ is the brine mass flow; and
h_x is the enthalpy at point *x*.

Using temperatures instead of enthalpy, Equation 14 becomes:

$$\dot{Q}_b = \dot{m}_b * c_{pb}(T_{S1} - T_{S3}) \tag{15}$$

where c_{pb} is the brine specific heat capacity;
T_x is the temperature at point *x*.

The mass balance across the primary and secondary cycle then becomes:

$$\dot{m}_b * c_{pb}(T_{S1} - T_{S3}) = \dot{m}_{wf}(h_1 - h_4) \tag{16}$$

where $\dot{m}_{wf}$ is the working fluid mass flow.

The mass balance across the pre-heater and the evaporator then becomes:

Pre-heater: $$\dot{m}_b * c_{pb}(T_{S2} - T_{S3}) = \dot{m}_{wf}(h_5 - h_4) \tag{17}$$

Evaporator: $$\dot{m}_b * c_{pb}(T_{S1} - T_{S2}) = \dot{m}_{wf}(h_1 - h_5) \tag{18}$$

Temperatures at point 5 and S2 recognise the effect of the pinch point in the heat exchanger. Their relationship is, therefore, given with respect for the heat exchanger pinch as follows:

$$T_{S2} = T_5 + T_{pp} \tag{19}$$

where T_{pp} is the heat exchanger pinch temperature as provided by the heat exchanger's manufacturer:

Beyond the evaporator, the thermodynamic assessment of the binary cycle is similar to that of the basic flash cycle, as discussed in the single-flash assessment. It must be mentioned, though, that binary power plants do not use direct-contact condensers, as the secondary cycle is a closed loop.

An ideal binary power plant is considered to have no emissions to the atmosphere, hence it is environmentally friendly. However, where the secondary fluid is not handled properly, in terms of leakages, emissions into the atmosphere become significant. The geothermal fluid never comes into contact with the turbine and is fully re-injected after heat extraction. By not letting the geothermal fluid come into contact with the turbine, it provides the turbine and the associated equipment a corrosion free operation, hence guaranteeing a longer life span. It also helps the binary power plants avoid the release of greenhouse gasses and related toxic elements, such as CH_4 and CO_2, which are common in flash power plants.

4.2.1 Choice of working fluid in binary plant

The type of working fluid to be used in a binary power plant is of importance and the process of choosing it requires the consideration of several factors. The working fluid's thermodynamic properties have a large effect on the performance of the plant, and its cost also affects the overall cost of the power plant. The parameters that need to be considered when choosing a working fluid include: the critical temperature of the fluid, critical pressure, the environmental impact of the fluid, health and safety of the fluid and the cost of the fluid. DiPippo (2008) compared different working fluids that could be used in a binary power plant. The fluids were compared according to their critical temperature, critical pressure, toxicity, flammability, Ozone Depletion Potential (ODP) and Global Warming Potential (GWP). The GWP was considered to be relative to the amount of heat that could be trapped by a similar mass of carbon dioxide as to the working fluid being analysed. The choice of an appropriate working fluid is based on a best fit with the thermodynamic conditions and the cost, with a preference for retrograde fluids (fluids with a positive slope saturation curve in a T-s diagram). The comparison of the fluids is summarized in Table 2.

The fluids in Table 2 show that they have lower values for the critical temperature and pressure than those for water.

TABLE 2: Properties of binary plant working fluids (modified from DiPippo, 2008)

Fluid	Formula	Critical temp. [°C]	Critical pressure [bar]	Toxicity	Flammability	ODP	GWP	Molecular wt.
Propane	C_3H_8	96.6	42.36	Low	Very high	0	3	44.09
i-Butane	$i\text{-}C_4H_{10}$	134.9	36.85	Low	Very high	0	3	58.12
n-Butane	C_4H_{10}	152	37.18	Low	Very high	0	3	58.12
i-Pentane	$i\text{-}C_5H_{12}$	187.8	34.09	Low	Very high	0	3	72.15
n-Pentane	C_5H_{12}	193.9	32.4	Low	Very high	0	3	72.15
Ammonia	NH_3	133.65	116.27	Toxic	Lower	0	0	17.03
Water	H_2O	374.14	220.89	Non-Toxic	Non-flam.	0	0	18

Working fluids are further divided into three types according to their saturation vapour curves in the T-s diagram (see Figure 15). The three types are: wet fluids, isentropic fluids and dry fluids. According to Bao and Zhao (2013), the dry fluids exhibit a positive slope of a saturation curve in a T-s diagram (Figure15c) while the wet fluids have a negative slope of the same, with examples of ammonia and water as the wet fluids. The isentropic fluids exhibit a nearly infinitely large slope, which is almost vertical (Figure 15b). Examples of isentropic fluids include flourinal 85 and R11. The isentropic fluids remain in a vapour saturated state while expanding through the turbine, since the expansion occurs along the vertical line of the T-s diagram. This results in the fluid not condensing at the turbine outlet; hence, there is an absence of liquid droplets inside the turbine.

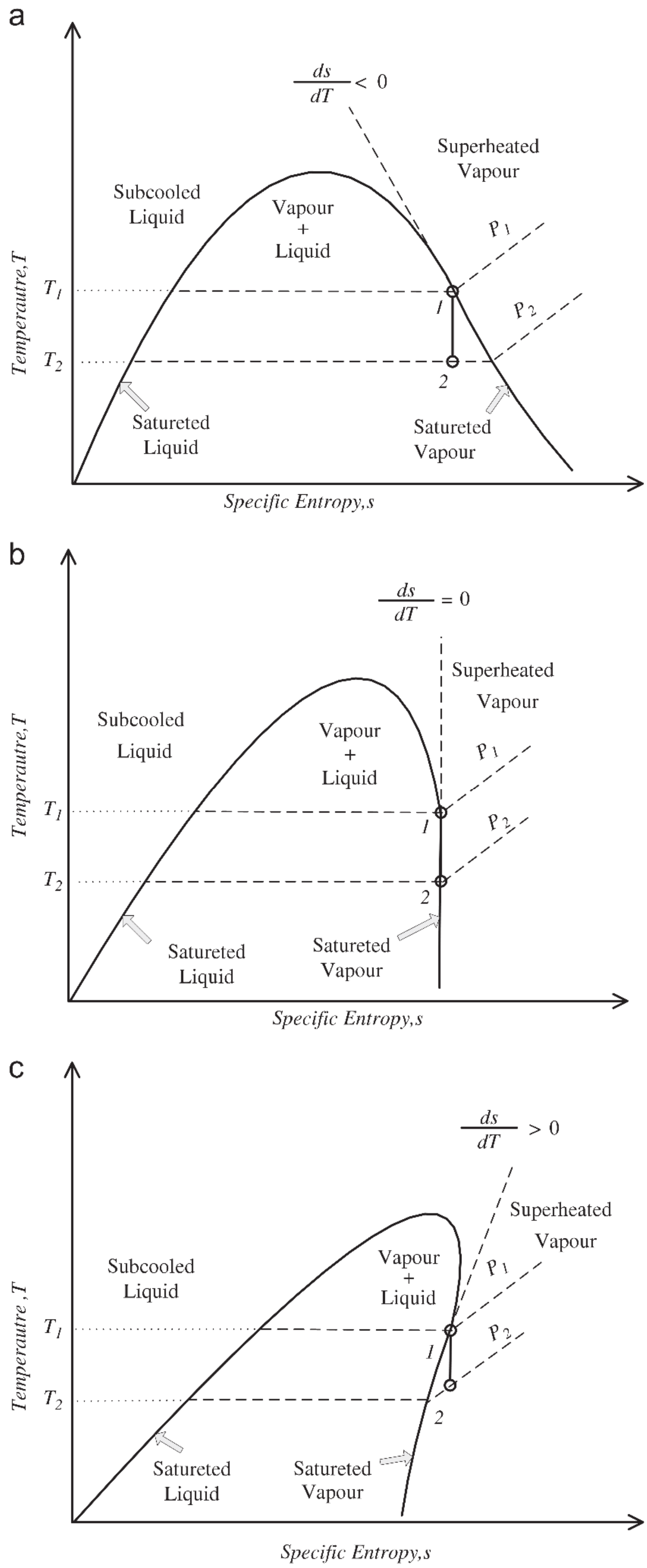

FIGURE 15: T-s for working fluids, (a) wet fluid, (b) isentropic fluid and (c) dry fluid (Bao and Zhao, 2013)

For the wet fluids, the outlet of the turbine normally contains some level of saturated liquid. This is due to their negative saturation vapour curve (Figure15a); these could damage the turbine blades. To sustain operations with wet fluids, the fluid is normally superheated at the turbine inlet and the dryness fraction of the fluid is kept at a minimum of 85%, beyond which damage to the turbine blades becomes severe. The isentropic and dry fluids do not need superheating and a minimum dryness fraction since they are already in the vapour saturated phase at the turbine exit. This is the reason why, in most binary applications, the dry fluids and the isentropic fluids are the ones commonly used; they do not condense after going through the turbine.

The choice of a working fluid is then a function of its critical temperature in relation to the geothermal fluid temperature, and the state of the fluid after exiting the turbine, as it is not desirable to have a fluid that condenses as it expands through the turbine.

The process of choosing a working fluid for this project was based on a literature review which recommended retrograde fluids (dry fluids). Isopentane and Isobutane have been frequently used in many instances. These two fluids were tested in a binary model, at 6 bar well head pressure and reservoir temperature of 180°C, to determine the better choice. The analysis varied the turbine inlet pressure. With this analysis, it was observed that Isopentane reached its maximum work output at a lower turbine pressure than Isobutane. This meant that Isopentane exhibited a higher turbine work output than Isobutane at lower pressures, while Isobutane exhibited a higher turbine work output than Isopentane at higher pressures. Beyond some critical pressure, Isobutane's behaviour was unpredictable (Figure 16). However, reinjection temperature analysis revealed that the peak turbine work for Isobutane appears at a lower reinjection temperature than the peak turbine work for Isopentane (Figure 17). As the silica solubility curve has already been alluded to, the use of Isobutane to get optimal turbine work within the reservoir temperatures of Chiweta would require the introduction of scaling inhibitors in the reinjection process. Isopentane turbine work output appears to be within the safe working zone for scaling. With this outcome, the choice of Isopentane was made as a working fluid for all the binary models under study in this project.

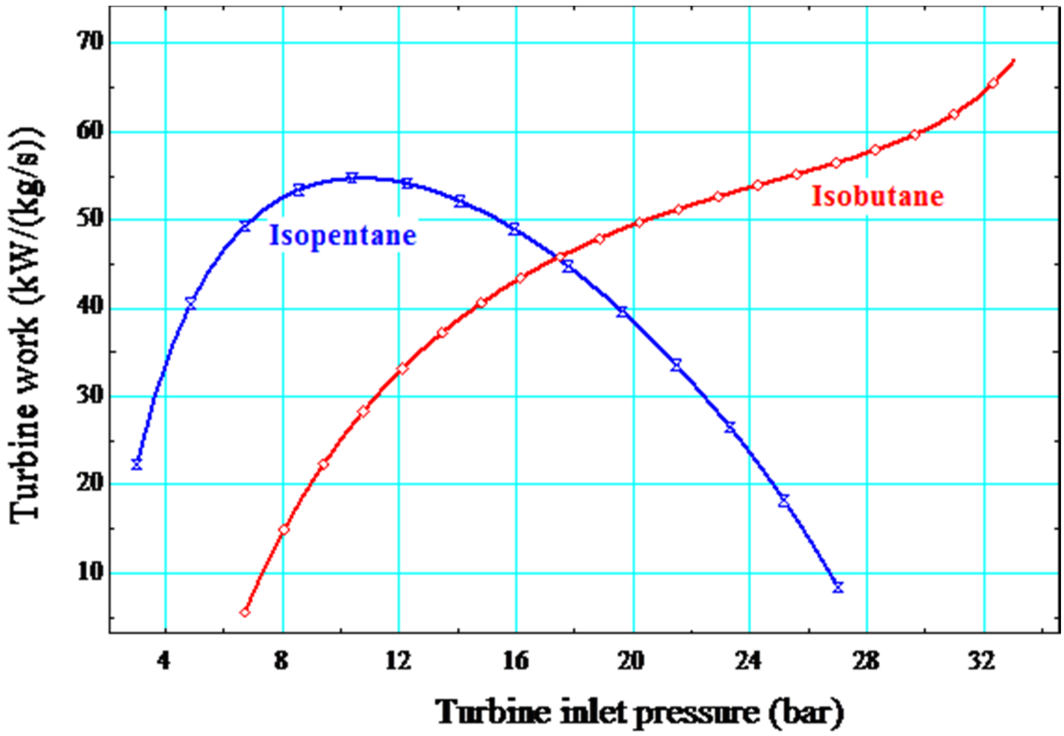

FIGURE 16: Working fluid turbine inlet pressure

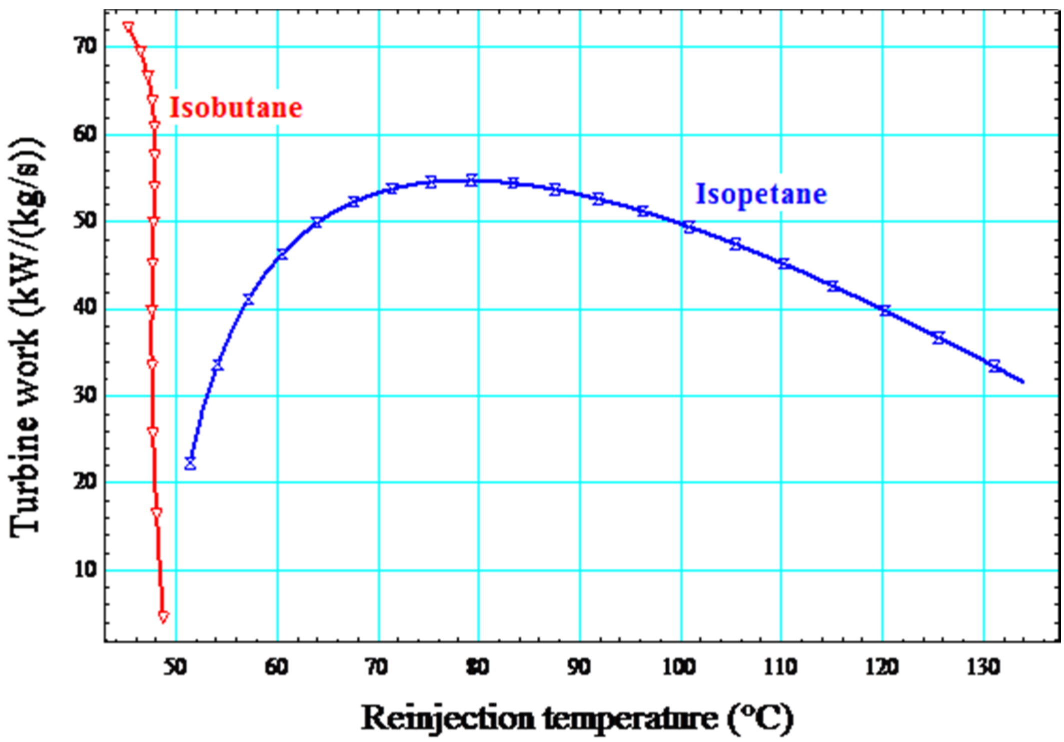

FIGURE 17: Working fluid reinjection temperature

4.3 Recuperator effect in a binary power plant

When a recuperator was incorporated into the binary model, two things were observed about its behaviour in the new binary cycle. The parameters observed were the brine reinjection temperature and the turbine inlet work. These parameters were observed with varying turbine inlet pressure. When the temperature difference in the primary cycle, between the reservoir and reinjection point, was controlled to be common in both a binary model with a recuperator and in a binary model without a recuperator, it was observed that the turbine work output for the recuperative model was higher than the work output from the basic binary model without a recuperator while the turbine inlet pressure was varied (Figure 18). When the reinjection temperature was not controlled but the turbine inlet pressure was varied, it was observed that the model with a recuperator reached its maximum turbine work at a higher reinjection temperature than the model without a recuperator. Based on these observations, in both models the maximum turbine work was the same (Figure 19), with a shift in reinjection temperature.

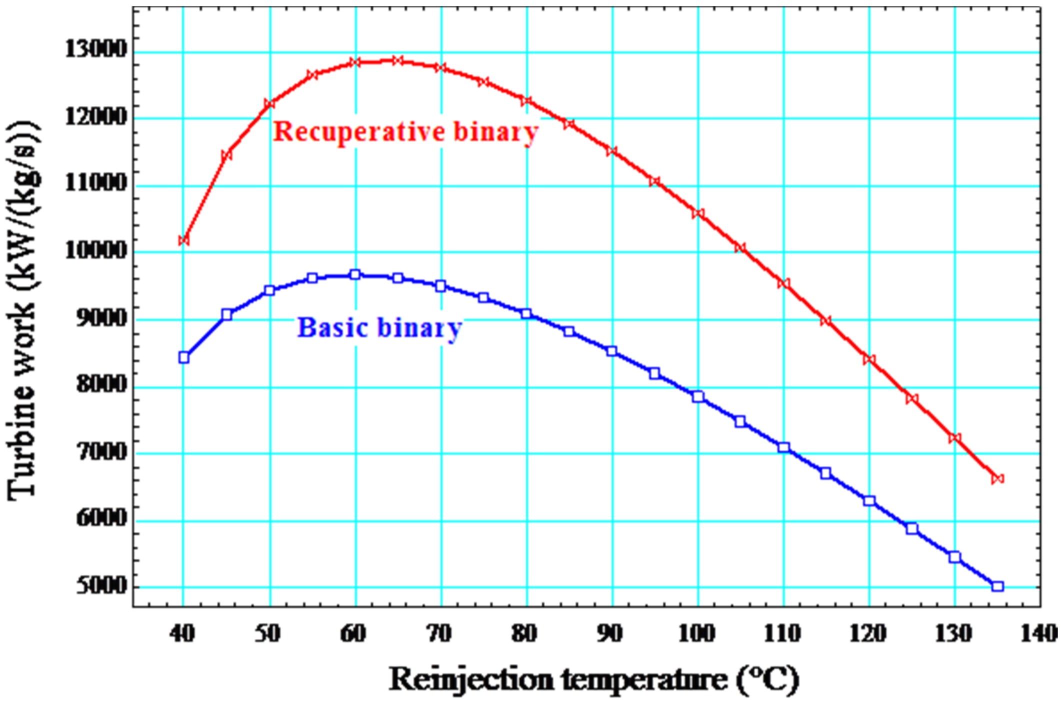

FIGURE 18: Impact of a recuperator on models under controlled reinjection temperature

It can be concluded, therefore, that depending on the desire of the model, the recuperator can either be used for improved turbine work output or to reinject brine at a higher temperature, while maintaining turbine work output where chemistry restrictions prevail. Valdmarsson (2011a) suggested that a recuperator be used where chemical conditions demanded a higher reinjection temperature in order to get optimal benefits from a resource. The addition of a recuperator to a system increases the capital cost of the system in the sense that additional heat exchanger area is needed in the recuperative model than in the basic model.

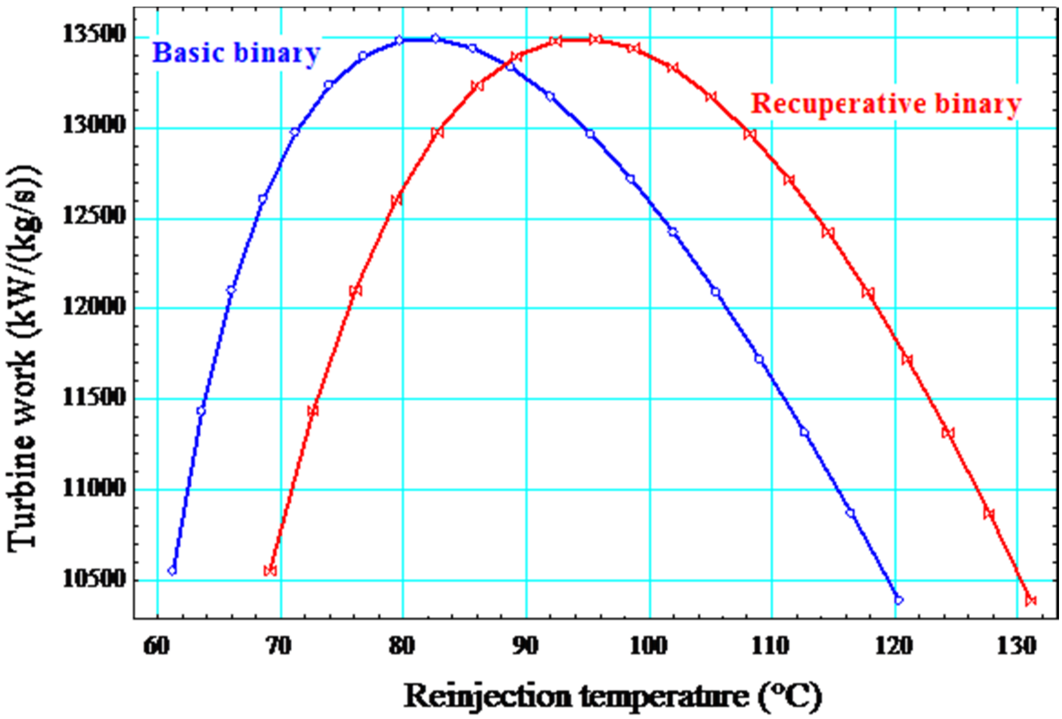

FIGURE 19: Impact of a recuperator on models under free reinjection temperature

5. MODELLING OF GEOTHERMAL POWER PLANTS USING EES

From the discussions above, the power plants were modelled using Engineering Equations Solver (EES) software. This software assists in analysing the thermodynamics of various fluids in a power plant to give desired outputs in terms of turbine work, cycle efficiency and more. Programmes for each power plant model, as mentioned earlier, were produced and analysed. Since Malawi has not done many studies to ascertain field characteristics that would fully satisfy in creating model parameters, some assumptions were used in all the analyses. Wherever applicable, the assumptions followed the general characteristics of the Chiweta field. The following are the parameters and assumptions used in the analyses:

- Heat exchanger pinch temperature: 4°C
- Ambient temperature: 25°C
- Geothermal fluid mass flow: 1 kg/s *(in order to calculate specific power output)*
- Turbine efficiency : 85%
- Pump efficiency : 75%
- Binary working fluid : Isopentane
- Heat transfer coefficients (U) (Ahangar, 2012)
  - $U_{Evaporator}$ = 1600 W/m^2°C
  - $U_{Pre\text{-}heater}$ = 1000 W/m^2°C
  - $U_{Recuperator}$ = 400 W/m^2°C
  - $U_{Condenser}$ = 800 W/m^2°C
- Plant lifespan: 30 years
- Discount rate: 15%
- Operation and maintenance cost: 4% of gross income
- Cost of steam gathering system: US$250/kW (Hance, 2005)
- Electricity tariff: US$0.09/kWh (ESCOM, 2013)
- Plant components Unit Cost (UC) (Ahangar, 2012)
  - $UC_{Evaporator}$ = US$500/m^2
  - $UC_{Pre\text{-}heater}$= US$450/m^2
  - $UC_{Recuperator}$ = US$400/m^2
  - $UC_{Condenser}$= US$600/m^2
  - $UC_{Turbine}$= US$500/kW
  - UC_{Pump}= US$450/kW

The reservoir temperature was split into three levels for the model analyses. The three reservoir temperature levels were at 180, 210 and 240°C in accordance with the range of subsurface temperatures in Malawi. The reinjection temperatures, according to the amorphous silica solubility curve in Figure13 were, therefore, 70, 110 and 130°C, respectively.

All the models were first optimised to get the best fit of parameters at a given point with optimal model output. The process of optimization involved the turbine inlet pressure and the wellhead pressure while observing the conditions that gave the highest possible turbine output within the allowable reinjection temperature range of a given reservoir temperature. The pinch temperature was conveniently assumed for the sake of the analyses. Of interest to the observations were the thermal efficiency, exergetic efficiency, turbine work output and the specific gain from the model. Thermal efficiency is the ratio of the power produced in a power plant to the heat transferred to that power plant (Valdimarsson, 2011b). Thermal efficiency is given by Equation 20.

$$\eta_{th} = \frac{\dot{W}_{tur}}{\dot{Q}_b} \tag{20}$$

Exergy is the portion of heat from a heat source which can be converted into work (Valdimarsson, 2011b). Therefore exergetic efficiency is the ratio of the power produced in a power plant to the portion of heat available which can be converted into work. The heat available for work conversion is given as a function of the local environmental conditions. Exergetic efficiency (η_{ex}) is given by Equation 21.

$$\eta_{ex} = \frac{\dot{W}_{tur}}{\dot{Q}_{av}} \tag{21}$$

where $\dot{Q}_{av}$ is the available heat as a function of local environmental conditions.

The turbine work output is the amount of energy (kW) obtained from the turbine in a given model. Since hybrid models consist of two turbines, the sum of the work of the two turbines was considered; the gross turbine work was used in the analysis. A specific turbine work was obtained in a given model as a result of using a unit mass flow from the well of 1kg/s, hence the specific work was given by kW/(kg/s). The specific gain defines the amount of work that can be obtained per dollar of the cost of the total power plant cost (kW/US$). Specific gain is given by the total cost of a model and the turbine work output of the model as given in Equation 22.

$$Specific\ gain = \frac{\dot{W}_{tur}}{Plant\ cost} \tag{22}$$

In all the observations above, the principle of 'the bigger the better' applied in selecting a suitable model. The following were the findings from the analyses.

5.1 Technical comparative analysis of power plants

5.1.1 Single-flash plant model - technical analysis

From the single-flash model analysis, it was observed that the plant improved its performance with an increase in reservoir temperature (Figure 20). The thermal efficiency and exergetic efficiency of the model increased in the same proportion as the resource temperature increased. Of significant note was that turbine work output increased more as reservoir temperature increases from 210 to 240°C. It was also observed that the specific gain of the plant was relatively higher at high temperature with an increase in work output compared to lower temperature. This is because the plant becomes efficient at higher temperatures and more economical than at lower temperature. This confirms the understanding that single-flash models are more viable at higher reservoir temperatures than at lower reservoir temperatures.

5.1.2 Basic binary plant model - technical analysis

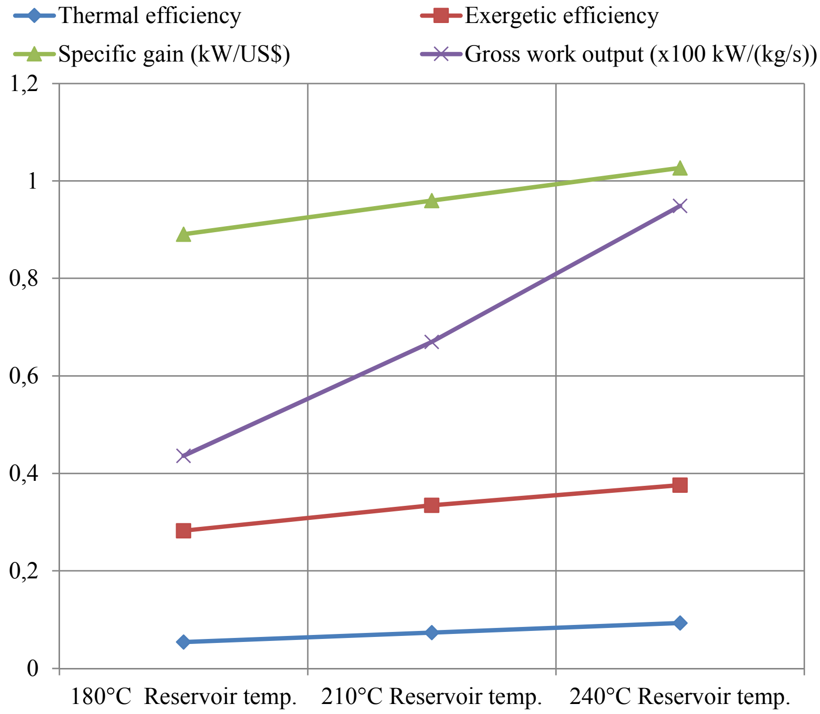

FIGURE 20: Single-flash performance with reservoir temperature

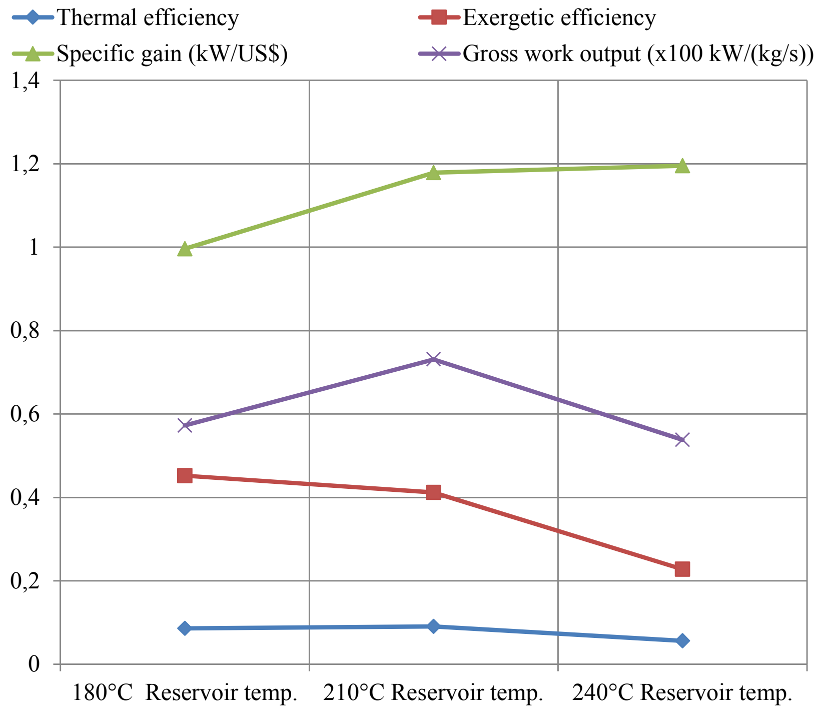

FIGURE 21: Basic binary cycle performance with reservoir

From the analysis of the basic binary plant, the model showed that its performance increased with the first increase in reservoir temperature from 180 to 210°C (Figure 21). At this level, the thermal efficiency as well as the turbine work output increased. The exergetic efficiency slightly decreased because at this point the reinjection temperature was fixed as opposed to a reinjection temperature of 180°C. The cost of generation at this level is relatively lower and there is more benefit of work from a dollar input, thus an increase in specific gain. As the reservoir temperature increased from 210 to 240°C, the performance of the cycle decreased in such a way that thermal efficiency, exergetic efficiency and turbine work reduced. The reinjection temperatures observed at the three reservoir temperature level were 78, 110 and 130°C. The cost of generation at these levels was relatively lower and the specific gain was almost the same to what was gained at 210°C, signifying that the cost of the power plant at this level was higher than at 210°C. This confirms the understanding that binary cycle models are more economically viable at low to medium reservoir temperatures than at higher reservoir temperatures.

5.1.3 Recuperative binary plant model - technical analysis

From the analysis of the impact of a recuperator on a basic binary and a recuperative binary plant, the analysis of a recuperative binary plant model showed that at a reservoir temperature of 180°C, the

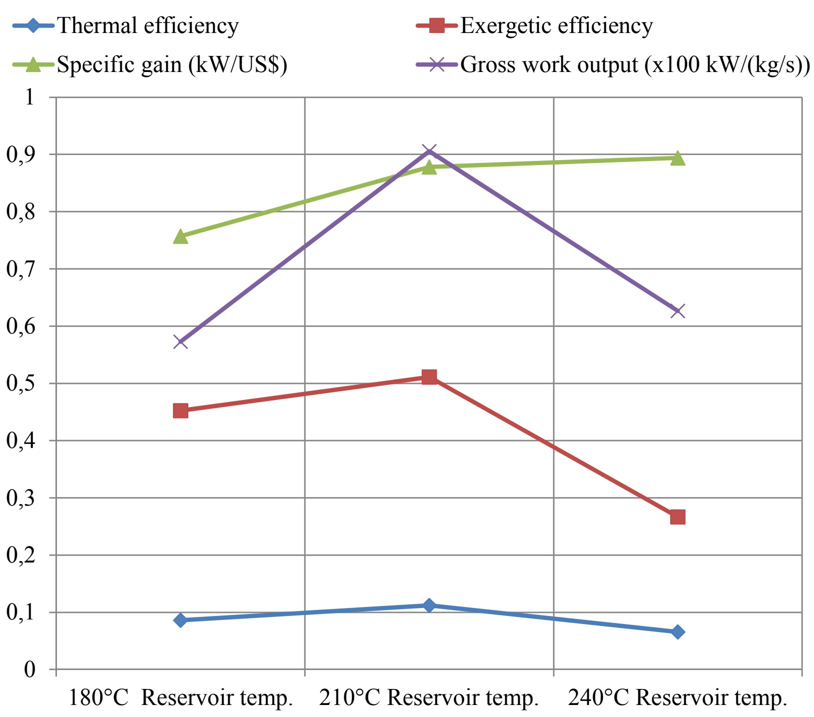

FIGURE 22: Recuperative binary cycle performance with reservoir temperature

performance exhibited the behaviour seen in Figure 15. The reinjection temperature at 180°C was higher than the reinjection temperature of a basic binary plant with the same turbine work output. The recuperative reinjection temperature was 89°C. As the reservoir temperature increased from 180° to 210°C, the performance improved more than in the basic binary plant (Figure 22). At this level, the thermal efficiency as well as the turbine work output increased and their increase was much higher than in the basic binary cycle. At this level, the exergetic efficiency was also observed to increase. Even though the turbine work was high at this level, compared to the basic binary cycle, the specific gain at this level was relatively lower as there was less benefit of work per dollar input with regard to the basic binary cycle. This signifies that the cost of a recuperative power plant is higher than the basic binary plant. With further increase of reservoir temperature from 210° to 240°C, the performance of the cycle decreased such that thermal efficiency, exergetic efficiency and turbine work reduced in the basic binary cycle. However, in the recuperative binary plant, there was slightly higher exergetic efficiency and turbine work than in the basic binary plant. The reinjection temperatures observed at the three reservoir temperature levels were 89°, 110° and 130°C. The specific gain in the recuperative plant was observed to be lower than in the basic binary plant, signifying that the cost of the recuperative plant was higher than for the basic binary. The overall general analysis showed that the recuperative binary cycle models were more viable at low to medium reservoir temperatures than at higher reservoir temperatures and that the benefits of that model over the basic cycle were generally traded in. The areas for the condenser and the pre-heater in the recuperative binary plant increased compared to the basic binary plant and this caused the overall cost of the cycle to increase, thus reducing the benefits.

5.1.4 Basic hybrid and recuperative hybrid power plant - model technical analysis

The hybrid that was used in this project was the one with binary bottoming, using brine from the separator of a single-flash plant, taking into consideration the fact that the proposed Chiweta field is a medium to low-enthalpy field and flashing is at low pressure. The hybrid under study used both a basic binary cycle and a recuperative binary cycle. The principle behind the hybrid cycle under study was to optimise the use of the geothermal resource even further, after flashing. Therefore, the first line of optimization is the single-flash cycle cascaded with the binary cycle.

From the model's analysis, it was observed that the basic hybrid plant's performance was better than that of the single-flash plant (Figure 23). The hybrid plant exhibited more turbine work output and higher exergetic efficiency than the single-flash plant at 180°C reservoir temperature. However, at this level of temperature, the specific gain was almost the same as for the single-flash plant. This is because of the simultaneous increase in turbine work output with increase in plant cost. The basic hybrid plant's performance and specific gain improved with an increase in reservoir temperature. The thermal efficiency and exergetic efficiency of the model tended to be relatively stable unlike the increase observed in the single-flash cycle. This is the result of a combination of a single flash that increases efficiency with an increase in reservoir temperature, and a binary plant that decreases in efficiency with an increase in temperature. As in the single-flash cycle, of significant note was that the turbine work output increased more as reservoir temperature increased from 210° to 240°C with a corresponding increase in plant specific gain. The hybrid plant becomes cheaper at higher temperatures than at lower temperature as it is delivered more turbine work than at lower temperature while maintaining efficiency.

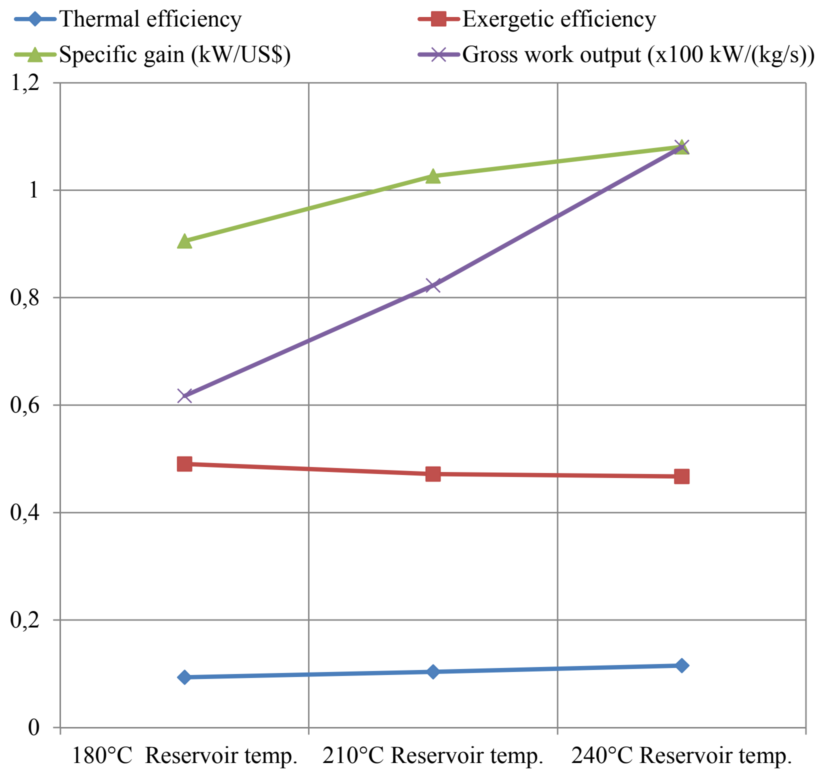

FIGURE 23: Basic hybrid cycle performance with reservoir temperature

Similar observations were noted when a recuperative hybrid cycle was analysed (Figure 24). Notable changes in behaviour were that a recuperative hybrid was more stable in efficiency than the basic hybrid across reservoir temperature changes. It was also observed that the recuperative hybrid delivered slightly higher turbine work output at higher reservoir temperatures of 210° and 240°C than the basic hybrid plant. However, the specific gain in the recuperative hybrid model was lower than for the basic hybrid model. This was caused by the addition of a recuperator to the plant, which generally increases the plant's cost.

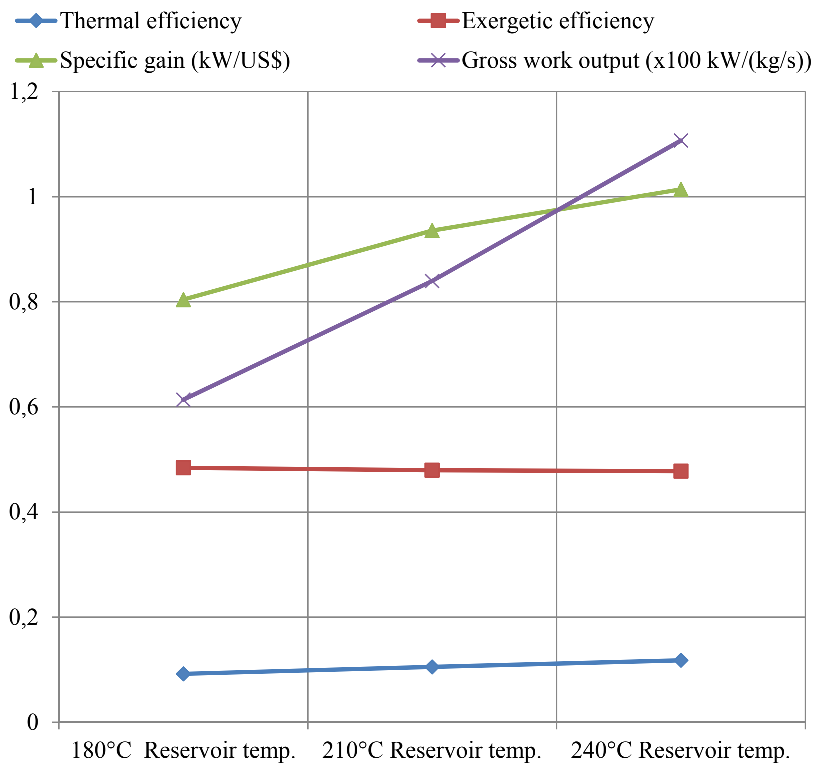

FIGURE 24: Recuperative hybrid cycle performance with reservoir temperature

5.2 Economic analysis of the modelled power plants

The electricity tariff regime for Malawi segregates customers depending on the type of use implemented by the country's sole electricity service provider ESCOM. Among others, the segregation considers whether the customer is connected at either a single-phase for domestic use, or connected at a three-phase for domestic and industrial uses. The current electricity tariff in Malawi, with respect to the customer type, is in the range of US$0.06 – 0.12 per kWh (ESCOM website). This report used the mid-range tariff for economic analysis which is US$0.09. The economic analysis compares the payback period of the models as well as the Net Present Value (NPV) of the models. The analysis assumes a uniform tariff over a 30 year life span of the power plant; thus, a constant annual cash income was assumed and not all cost factors were included.

5.2.1 Payback period analysis

Payback period is the length of time required for a project's cash inflow to recover the original cash outlays required by the project's initial investment (Bejan, et al., 1996). This is considered the period where the net cash inflow of the project is zero. The principle of a payback period advises choosing a project that gives the least payback period among projects under consideration. The payback period is found by using Equation 23:

$$T_{PB} = \frac{TDI}{ANCF} \tag{23}$$

where T_{PB} is the payback period;
TDI is the total depreciable investment;
ANCF is average annual net cash inflow (Bejan, et al., 1996).

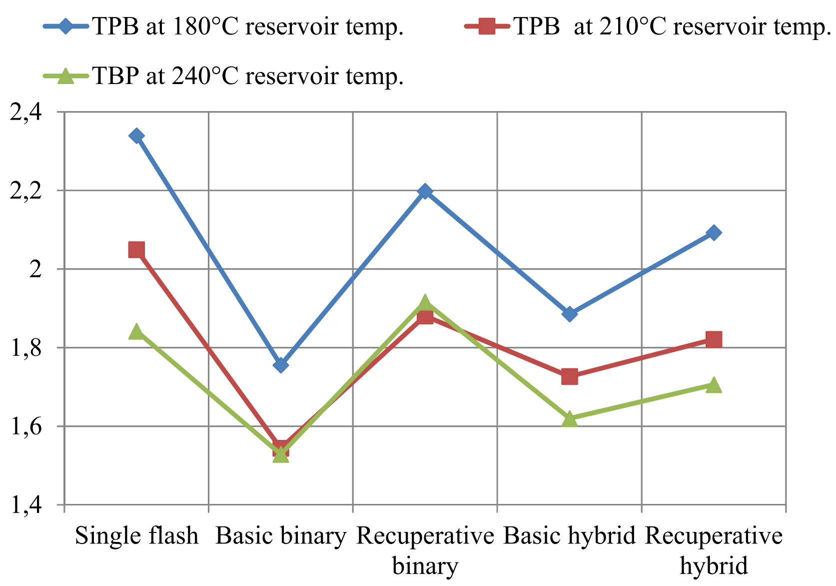

FIGURE 25: Payback period analysis

For purposes of comparison in this analysis, *TDI* was assumed to be the cost of the power plant and *ANCF* is the plant's annual net income. The analysis focuses on power plant components and the unified cost of steam gathering. The net cash inflow does not considered tax deductions, loan interest payments and related expenses. Subjecting all the models at every reservoir temperature level to the payback period analysis, it was observed that basic binary plants and the basic hybrid plants are the ones that exhibit a relatively lower payback period at all levels (Figure 25). It was also observed that there is a bigger variation in the payback period at lower reservoir temperature than at higher reservoir temperature. This is due to the fact that there is more work delivered at higher reservoir temperature than at lower reservoir temperature, thereby significantly increasing the annual revenue and thus reducing the payback period.

5.2.2 Net Present Value (NPV) analysis

Where the NPV principle is used, it advises that a project should be chosen if it has a positive NPV, otherwise the project should be rejected. It is also further recommended to choose a project with a higher NPV among projects with positive NPV under consideration. The NPV formula is given in Equation 24:

$$NPV = \sum_{z=0}^{BL} Y_z (1-i)^{-z} \tag{24}$$

where Y_z is the net cash flow at the end of z^{th} time period;
BL is the book life of the project;
i is the effective discount rate (Bejan, et al., 1996).

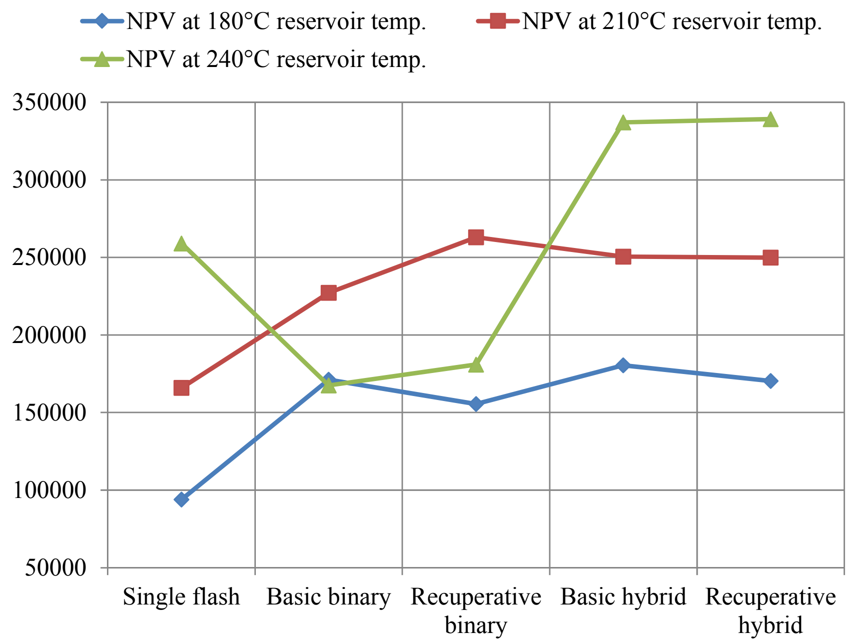

FIGURE 26: NPV analysis

The net cash flow does not consider tax deductions, loan interest payments and related expenses. The book life of the project is assumed to be 30 years and the discount rate is 15%. From the NPV analysis, all the power plants exhibited a positive NPV (Figure 26). At 180°C, a single-flash plant showed the lowest NPV of all the models, while the rest of the models showed NPV within the same range of US$150,000-200,000. At 210°C reservoir temperature, the single-flash plant had the least NPV followed by a basic binary, while the rest were within the same range around US$250,000. At 240°C reservoir temperature, the basic binary and the recuperative binary plants exhibited the lowest NPV, while the basic hybrid and the recuperative hybrid plants exhibited the highest NPV. The single flash was observed to be in between the two ranges.

6. RECOMMENDED DESIGN FOR CHIWETA FIELD

Based on the analyses done, recommendations are given for the three values of reservoir temperature.

- At a reservoir temperature of 180°C, the recommended design is the basic binary plant. The design has a higher specific gain than the other models; it also requires the shortest payback period and has a relatively higher NPV. The thermal efficiency and exergetic efficiency of a basic binary plant at this level do not vary significantly from that of the other models, however it was more efficient than the single flash. Overall, the model turbine work output was almost the same as for recuperative binary, basic hybrid and recuperative hybrid plants but the basic binary is the cheapest of them all.

- At a reservoir temperature of 210°C, the recommended design is the basic binary plant. The design has the highest specific gain of all the models; it also requires the shortest payback period among the models. Even though the model does not give the highest NPV, the model's NPV is higher than that of a single flash cycle and is also closer to the higher NPV of the other models. The thermal efficiency and exergetic efficiency of the basic binary cycle at this level do not vary significantly from that of the other models.
- At a reservoir temperature of 240°C, the recommended design is the basic hybrid plant. The design has a higher specific gain than the other models; it comes in second after the basic binary plant but offers more turbine work output than the basic binary model. The model also gives a shorter payback period among the models, coming in second best after the basic binary model. The model exhibits a higher NPV, second best after the recuperative hybrid model but relatively cheaper than it. The thermal efficiency and exergetic efficiency of the basic hybrid at this level were relatively higher than for the other models, almost the same as the recuperative hybrid model.

7. CONCLUSIONS

From the preceding study, it can be concluded that Malawi could develop either a basic binary or a basic hybrid power plant for the utilization of its Chiweta geothermal field. These power plant models proved to be more technically and economically viable than the other plants that have similar development potential in Malawi. In as much as the study has suggested the mentioned power plants for development, there is a need for Malawi to conduct detailed studies for the fields to obtain meaningful data that could lead to development of the resource. Since geothermal development is multi-disciplinary, there is need for further studies to be carried out using MT and TEM soundings to find the geophysical properties of the Malawi resource. Exploratory wells could then be drilled to confirm the obtained data from the geochemical and geophysical explorations.

The integration of power production with other direct utilization programmes does significantly improve the economic viability of using lower temperature geothermal fluids and could result in a much higher overall efficiency than could be achieved with just producing power or just direct use projects. The proposed utilizations should be studied further for potential integration and for optimizing resource efficiency.

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