Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Efficiency and Cost Benefit Analysis of Combined Heat and Power in Geothermal Energy Utilisation: A case study of the low enthalpy fluids from the Menengai Geothermal Field-Kenya

By Martha Mburu

Geothermal Development Company, P.O Box 100746-00101-Nairobi Kenya

mmburu@gdc.co.ke

Keywords: Integrated Energy Systems, Cascaded Uses, Direct Use

ABSTRACT

After successfully drilling a productive geothermal well, various parameters are evaluated to establish its energy potential as well as other factors that may affect the well outputs during exploitation. The energy potential of a geothermal well depends on the fluid's thermodynamic characteristics and quantity. The fluids can either be dry steam, two-phase or just hot water. Geothermal energy can be used both for electricity generation and direct use applications. While high enthalpy fluids are best suited for electricity generation, low enthalpy fluid is mostly used for direct applications. Hot geothermal brine, separated from high enthalpy resources is also a good candidate for direct applications such as industrial processes, agro-processing and for leisure. Such applications can be cascaded to various applications depending on the energy requirements. GDC has done production drilling at the Menengai geothermal field and proved about 170MWe equivalent of steam. The field produces predominantly high enthalpy fluids with an average dryness fraction of 70%. Also, a few of the drilled wells have low wellhead pressure and cannot, therefore, be connected to the steam gathering system. The separated brine, as well as fluids from the low enthalpy wells, have a substantial amount of energy which can be used to generate power using binary technology and thereafter cascaded to direct applications.

This paper analyses the energy potential of the low enthalpy fluids at the Menengai geothermal field and the potential for utilizing the energy for combined heat and power. A cost benefit analyses of the proposed development is also evaluated.

1. INTRODUCTION

In its mandate of developing geothermal resources, Geothermal Development Company (GDC) will develop steam and sell to the Power Producers. Fluids from Low enthalpy wells and separated brine have substantial thermal energy which can be utilised for direct applications such as preservation of farm produce, growth enhancement for plants and animals or value addition. This process is referred to as "*Direct Uses of geothermal energy"*. Geothermal fluids with favourable chemistry and be used directly for irrigation. Such direct applications can be in small scale by individual investors such as small domestic swimming pools or larger-scale as district heating found in Iceland or greenhouse complexes in Hungary, or major industrial uses such as Kawerau Pulp and paper in New Zealand, (Lund, and Boyd, 2015)

Menengai phase one has three power-plants scheduled. The three plants will produce a total of 105 MWe. About 560t/hr of 8 bara separation pressure brine will be generated from the wells to generate electricity. In addition, 390 t/hr of low enthalpy brine (2-7 bars) is also available.

This paper computes the energy available in the separated brine and low enthalpy wells and evaluates how much of that energy can be harnessed for electricity and direct applications. The fluids from the power plants also have energy that can be harnessed for direct applications depending on the energy requirement and availability. This can further improve the profitability of such a project.

Cascading geothermal energy to the various uses should be considered in all developments to increase efficiency and profitability of the investments.

2. CHARACTERISTICS OF FLUIDS FROM MENENGAI GEOTHERMAL FIELD

The Menengai geothermal field is the 3rd field to be developed in Kenya, First being the Olkaria field and the 2nd being the Eburru field. Detailed surface exploration was done between 2004 and 2006 and the 1st well drilled in 2011. Currently, more than 150MWe steam equivalent has been proven for Menengai phase 1 (105 MWe) and Menengai phase 2, 60 MWe is still ongoing. Menengai field is a high temperature field producing mainly high enthalpy fluid.

2.1 Temperature and Pressure

Temperature and pressure data indicate Menengai as a high temperature field with most of the wells recording bottom-hole temperatures in excess of 300 °C with some close to 400 °C. Two main reservoirs were identified; (a) shallow reservoir occurring at around 800-1,200 m depth dominated by low enthalpy fluids and (b) a deeper reservoir occurring below 1,600 to around 2,000 m depth, dominated by high enthalpy fluids. The reservoir fluids are both two-phase and single phase with wells at the central dome area being predominantly steam and wells outside the central dome area being two-phase to single-phase liquid.

Menengai wells have well head pressure (WHP) ranging from 1.6 bara to 19 bara. Based on the WHP, the wells can be classified into three broad categories, category-1 (C-1) are those with WHP above 8 bara and, Category-2 (C-2) are those with WHP 5-8 bara and Category-3, (C-3) are those with WHP below 5 bara.

Category C-1 wells have an average WHP of 10.7 bars and are mostly located at the centre of the field where the upflow of the system is. Their average enthalpy is 2010 kJ/kg and is mostly steam dominated with an average dryness fraction of 0.65. Category C-2 wells have an average WHP of 5.8 bars and an average enthalpy is 1114 kJ/kg and are mostly liquid dominated with a dryness fraction of 0. 28. Category C-3 wells have an average WHP of 2.2 bars and an average enthalpy is 863 kJ/kg and are mostly liquid dominated with a dryness fraction of 0.13.

When designing the steam gathering system (SGS), the separation pressure at Menengai was set to 8 bara, meaning that wells with WHP below 8 bara cannot be connected to the steam gathering system. This leaves category C-2 wells "idle". These wells can be used for conventional electricity generation but on a separate SGS or as wellhead units. Due to their location, putting up a separate SGS would be expensive and therefore they are ideal for connection to wellhead units (WHU). Category C-3 wells are ideal for binary power plants and for direct uses.

Though one well, MW-06 has a C-2 category in terms of WHP, it is a high enthalpy well producing dry steam, dryness fraction of 0.96 at 7.35 bara. To obtain the full benefit if this well, it is advisable to use it for WHU generation either alone or with others having similar characteristics.

2.2 Mass Output

The cumulative amount of fluid available from Menengai wells as at April 2019 is estimated at 1190 t/hr of steam and 1050 t/hr of brine from low and high enthalpy wells. Breakdown of the mass output from the wells are as shown in Table 1 below

Table 1: Average parameters of Menengai wells depending on the WHP

Category	WHP (Bara)	Mass Flow (T/hr)	Steam (t/hr)	Water (t/hr)	Average Enthalpy (kJ/kg)	Average Dryness fraction	Classification
C-1	10.7	1523	991	451	2010	0.65	Vapour dominated
C-2	5.8	465	89	336	1115	0.28	Liquid dominated
C-3	2.2	332	36	266	864	0.13	Liquid dominated
Well 6	7.4	80	77	0.00	2675	0.96	Vapour dominated

2.3 Chemistry of the Fluids

Fluid samples collected during flow tests shows that the chemistry of discharge fluid exhibits widely varying chemical properties from well to well. This observed variability points to heterogeneity of the reservoirs feeding Menengai wells. The fluid discharge is sodium bi-carbonate waters with significant chloride concentrations. The gas content in the steam ranges from 1.5 to 12.5 w/w%, of which over 90% is CO2 being the major constituent of the steam.

Calcite scaling occurs in some of the wells as a result of flashing and mixing of fluids of different enthalpies. Three of the tested wells in the Menengai geothermal field exhibited scaling potential indicated by the decline in well output as well as high calcite saturation indices. Low calcium in the discharged water further supports the formation of calcium carbonate upon flashing of the geothermal water.

3. ENERGY FROM THE FLUIDS

The energy contained in the fluid is a factor of its enthalpy, quantity and chemistry and evaluation will be based on these parameters.

3.1 Separated Brine

Steam from C-1 and C-2 wells will be used for conventional electricity generation, the separated brine from these two categories and total fluid from C-3 will be used for generation of electricity using binary technology and then cascaded to direct use projects. Energy from the fluids is computed from WHP, mass flow (m) and fluid enthalpy (h). Silica concentration determines how low the fluids should be cooled, exit temperature of the brine (T_2). The schematic diagram of the flash binary system is shown in Figure 1.

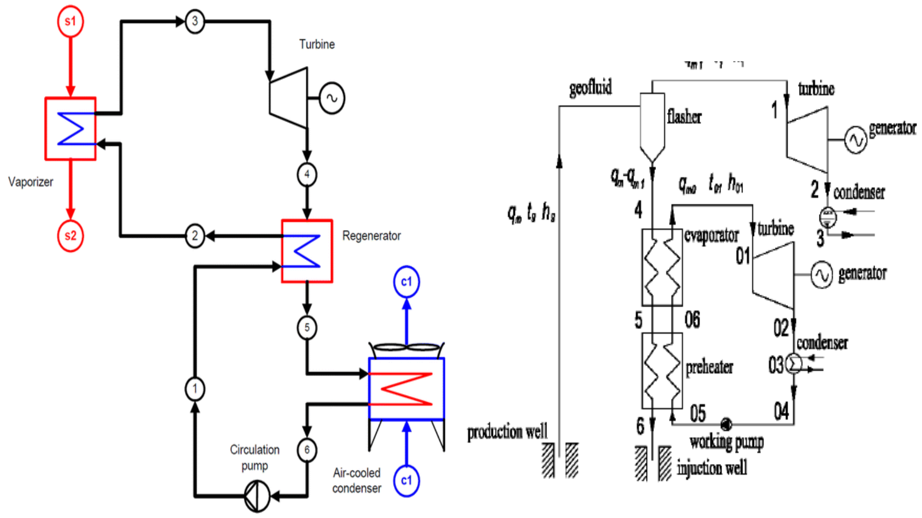

Figure 1: Schematics of the Geothermal Flash-Binary cycle, (DiPippo; 1980)

The fluids are at saturation conditions and energy that can be generated from the fluids is computed either using enthalpy or temperature.

Energy E= mCpΔT or mΔh

- m=mass of brine (kg/s)
- Cp = Specific Heat capacity (kJ/kgK)
- ΔT = temperature difference (Initial (T_1) and final conditions (T_2) K)
- Δh = Enthalpy difference (Initial (h_1) and final conditions (h_2)

Table 2: Average parameters of Menengai wells depending on the WHP

Wells Category	Separation pressure (bara)	Conditions	Enthalpy Jk/kg	Specific Heat Capacity Kj/kgK	Temp (°C)	Mass flowrate (kg/s)	(T1-T2	(h1-h2) kJ/kg	mΔh (MW)
C-1	8	Initial (1)	775.5	4.4198	183	125	74.84	322.84	40.4
		Final (2)	452.66	4.2344	108				
C-2	5	Initial (1)	664.42	4.3331	158	93	71.52	304.47	28.4
		Final (2)	359.95	4.2112	86				

3.2 Low Enthalpy wells

Low enthalpy wells have both steam and brine which can be used for power generation and direct applications. But for them to be connected to the steam gathering system, they have to have the required WHP, without that, the fluid can only be used for binary power production or used for direct application. The steam can also be used in a double flash condensing unit where the fluid is introduced downstream of the turbine (Figure **).

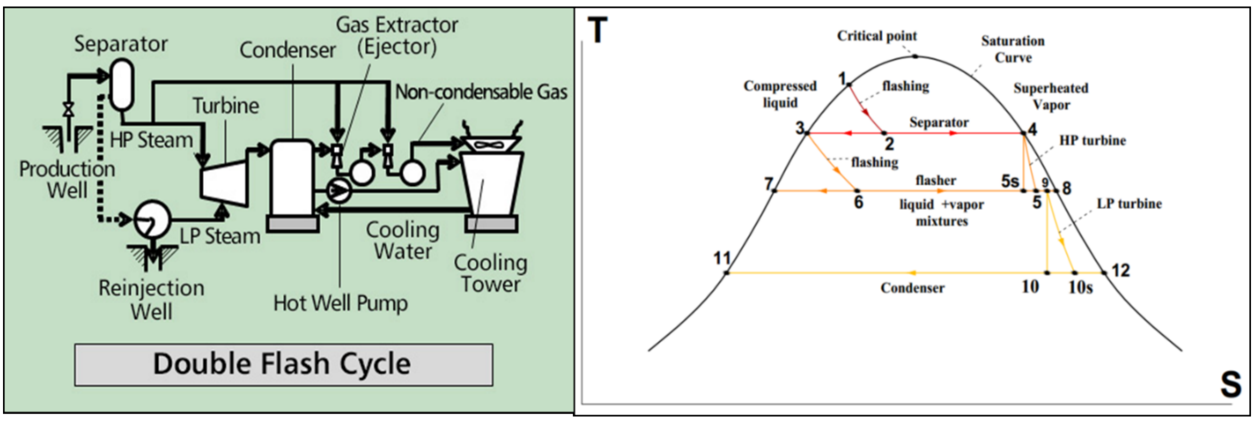

Figure 2: Double flash schematic and T-S diagram, (Cukup, et al)

Binary plants use Organic fluids to run the turbines. In this type of power plant, a secondary fluid such as hydrocarbon or fluorocarbon is used instead of water to run the ORC turbine. In ORC, the geothermal fluid is circulated in a vaporizer and sent back to the reinjection well. The secondary fluid is heated and vaporized in the vaporizer by the heat exchange between the geothermal fluid and the secondary fluid. The generated vapor from the secondary fluid is directed to the turbine for electricity production. The vapor leaving the turbine passes through a regenerator where the superheated steam is used to heat the condensed fluid leaving the condenser before it enters the vaporizer, (Chao, et.al 2015)

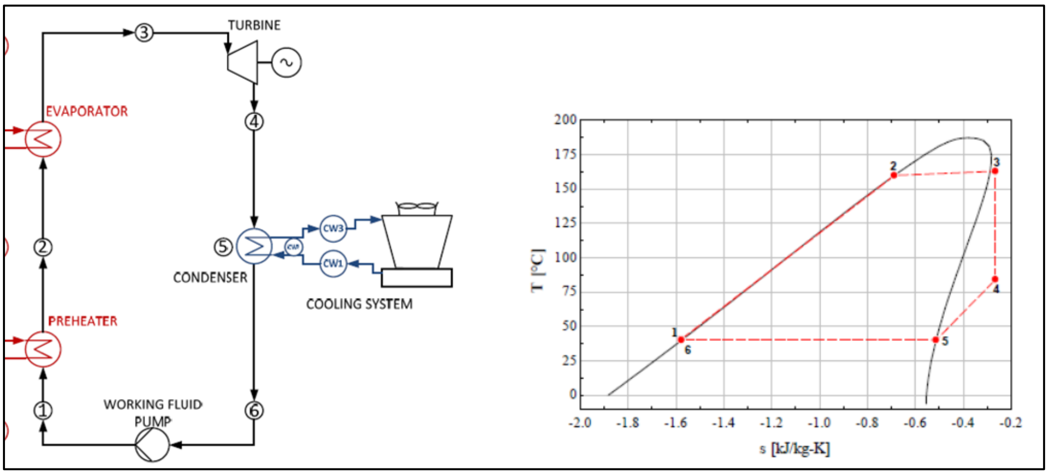

Figure 3: Binary flash schematic and T-S diagram, (DiPippo 1980)

Steam and Brine from C-3 wells will be used to generate electricity using binary power plants, and then cascaded to direct use projects. Just as the case of C-1 and C-2, the energy from the fluids is computed using parameters of WHP, mass flow (m) and fluid enthalpy (h) and silica concentration determine the exit temperature of the brine (T_2).

The Menengai planned plants are all single flash and therefore such fluids cannot be used in the upcoming plants. The low enthalpy fluids are therefore proposed for use for binary generation and direct uses.

Table 3: Energy computations from C-3 fluids

Wells Category	Conditions	Enthalpy Jk/kg	Specific Heat Capacity Kj/kgK	Temp (°C)	Mass flowrate (kg/s)	(T1-T2	(h1-h2) kJ/kg	MW
C-3	Initial (1)	517.45	4.257	123	74	43.28	182.69	13.5
	Final (2)	334.76	4.2065	80				

3.3 Steam Wells that cannot be connected to SGS-MW-06

This is the simplest and oldest type of geothermal plant. It directly uses steam from the reservoir to operate the turbine. The steam is collected from the production well and used to operate low-pressure turbines. Hence, the working fluid is steam. The used steam is then condensed and injected back through the injection well. Wells that have high enthalpy fluids but cannot be connected to the steam gathering system due to their WHP being lower than the SGS pressure can be used for electricity generation using wellhead technology.

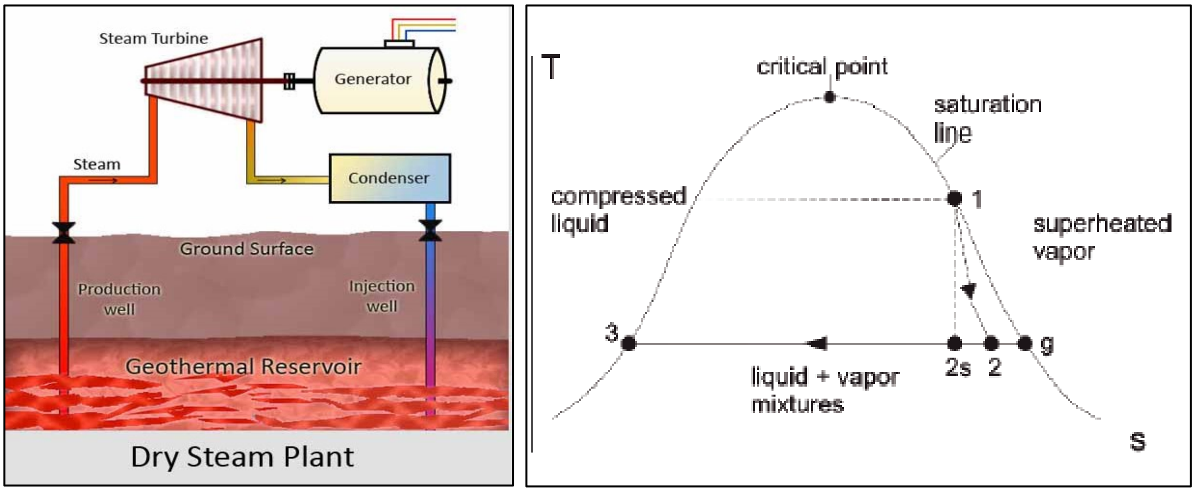

Figure 4: Binary flash schematic and T-S diagram (Gong, et. al, 2010)

Table 4: Energy from MW-06

Wells Category	Conditions	Initial Enthalpy Jk/kg	Final Enthalpy (h2)	Mass flowrate (kg/s)	(h1-h2) kJ/kg	MW
MW-06	Initial (1)	2762.8	188.29	21	2574.51	9.6

3.4 Direct Uses and Cascading

The energy present in the fluids of all low and medium enthalpy fluids can be cascaded from power generation to direct applications. Applications requiring temperatures from 100oC to 30oC can utilise the energy rejected by the power plants. Clean cold water to be heated using a heat exchanger to generate thermal energy. The amount of energy is a factor of temperature and fluid quantity. The cost of such energy can be computed using exergy or using volume.

Different thermal processes demand hot water at different temperatures. A thermal process demanding water at high temperature should pay more for the same volume of hot water than a thermal process demanding water at a lower temperature. The differentiation in the price of hot water with respect to the temperature is based on the exergy available in the hot water at that temperature. Exergy refers to the work which can be recovered from a stream of hot water and is determined by two factors:

- Inlet temperature – the temperature at which the hot water enters into a thermal process.
- Outlet temperature – the temperature at which hot water exits from a thermal process.

A thermal process that demands hot water at a high temperature will have higher exergy at its disposal relative to a thermal process that demands hot water at a lower temperature. Therefore, the price that each of the thermal processes is charged for the hot water is proportional to the exergy availed to it. If a thermal process only extracts some energy from a stream of hot water and passes the remaining energy to another thermal process, it is charged in proportion to the exergy it will have extracted from the hot water

Volume based tariff assumes is based on the utilisation per cubic unit irrespective of the temperature of the fluid. This method is easier to monitor since it is similar to cold water municipal tariff, but it does not account for the content of the fluid nor does it encourage cascading, hence more revenue. Fresh water at 100oC cooled to 30oC can generate

4. DISCUSSIONS

When wells are drilled for electricity generation, only steam can be utilised in the turbines if the plants are condensing units. This leaves fluids from wells with lower wellhead pressure, separated brine and hot water unutilized. These unutilized fluids have substantial energy that can be used efficiently to generate electricity using other forms of methods such as wellheads, binary technology or as low-pressure steam. The same energy can be cascaded to direct applications.

To ensure the efficiency of utilisation, a thorough analysis of the well behaviour, chemistry, and planned development need to be considered. In Menengai, for example, the field is a high enthalpy field, with phase one development considered only wells with high WHP. This was to maximize the output from these wells. The SGS was designed to separate steam at 8 bara, leaving a number of wells with high enthalpy unconnected. The high separation pressure also meant a resultant high temperature brine, 180oC to be reinjected. The chemistry of the Menengai fluids can allow cooling of the wells to about 110oc which is above the silica saturation temperature. It is, however, important to note that Menengai wells exhibit different characterizes and when details analysis and key decision are required, individual wells behaviour and characteristics need to be evaluated critically.

This paper has analysed the average behaviour of four categories of wells and the energy that can be mined from the available energy. Fluids for conventional generation using flash condensing unit has not been evaluated. Evaluations have been done on separated brine and the low enthalpy wells. Energy from such fluids can be used for electricity generation using binary power technology or using direct uses or both. It has been established that about 90 MW is available from the unutilized fluids and much more can be obtained through cascading. Using a conversion efficiency of 21%, about 20 MWe can be obtained from the available fluid. Assuming that 60 percent of this energy is utilised, to allow for plants, wells and steam gathering maintenance, 11 MWe would be availed for utilisation. Moreso, process heating which requires lower energy should utilise reject energy from the power plants. The direct use applications utilise hot water to temperatures as low as 100^{o}C.

5. CONCLUSION

Menengai geothermal field is a high enthalpy field producing high pressure fluids. But there are also medium and low enthalpy fluids which can be used to generate power using wellhead technology, binary plants and also for direct uses.

The amount of fluids and its characteristics, wellhead pressure and chemistry determine the amount of energy that can be obtained from geothermal fluids. Cascading available energy from high end uses to those that require the lowest energy can substantially increase the profitability of the geothermal power investment. Flash-binary power system would increase the production compared with single flash power system. The more energy conversion stages, the more power output. However, the power output is finite and the invest cost increases when the power energy conversion stage is added. It is therefore critical to undertake the cost benefit analysis of such an investment. About 90 is available in the unutilized fluids in Menengai but conversion efficiency of about 22% would result in 20 MWe. More low-grade thermal energy is available for direct applications which have a greater impact in the local community especially in addressing food security in areas such as greenhouse heating, food storage such a s drying, preservation and value addition and energy

REFERENCES

Chao LUO, Yulie GONG Geothermal Energy Conversion between Flash-Binary and Double Flash Power System luochao@ma.giec.ac.cn, Proceedings World Geothermal Congress, 2015, Melbourne, Australia; 19-25 April 2015.

Cukup Mulyana, Reza Adiprana, Aswad H. Saad, M. Ridwan H., and Fajar Muhammad, 2016. The thermodynamic cycle models for geothermal power plants by considering the working fluid characteristic Cite as: AIP Conference Proceedings 1712, 020002 (2016); https://doi.org/10.1063/1.4941863 Published Online: 24 February 2016

DiPippo R. Geothermal energy as a source of electricity: a worldwide survey of the design and operation of geothermal power plants, U.S. Dept. of Energy, DOE/RA/28320-1. Washington, DC: Gov. Printing Office; 1980.

Gong YL, Luo C, MA WB, WU ZJ. Thermodynamic analysis of geothermal power generation combined flash system with binary cycle, Proceedings World Geothermal Congress, 2010, Bali, Indonesia; 25–29 April; 2010.

Lund JW, and Boyd TL, Direct utilization of geothermal energy 2015 worldwide review. Proceedings World Geothermal Congress, 2015, Melbourne, Australia; 19-25 April 2015