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Feasibility of Wellhead Technology Power Plants for Electricity Generation

Moses Jeremiah Barasa Kabeyi *

[*1] *Lecturer, Department of Mechanical and Manufacturing Engineering, University of Nairobi*

mkabeyi@uonbi.ac.ke, moseskabeyi@gmail.com

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Abstract: The overall objective of this research was to determine the feasibility of wellhead power plants for a sustainable supply of geothermal electricity. Technical, financial and environmental sustainability and feasibility were investigated. A profitability assessment model showed that the payback period based on profit after Tax is 4.4 and 3.4 years without corporate tax which demonstrates financial feasibility. Environmental challenges encountered include corrosive geothermal fluid contamination and emissions of no condensable gases. Technically, it was found out that wellhead plants have lower power plant availability and capacity factor but still acceptable since it is over 70% compared to over 95% for central power plants. Lack of reinjection wells, however, raise concerns over sustainability of resource use in the long term. The study concluded that the Eburru and Olkaria wellhead power plants in Kenya are technically, financially and environmentally sustainable and feasible. Financial viability can be enhanced by tax rebates and holidays while re-injection of geothermal fluid can enhance resource sustainability. The research showed that wellhead power plants make an investment in geothermal less risky and ensure quick returns though technically the central power plants are superior.

Key Words*:* Geothermal resources; types of geothermal power plants; feasibility of wellhead power plants; geothermal power plant performance; geothermal electricity generation; Generation capacity.

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1. Introduction

As the global economy and population grow, so is the energy demand which causes increased consumption of fossil fuels and hence increased pollution. These have led to increased demand for renewable and less polluting energy sources for heat and electricity applications (Liu et al. 2017). The word geothermal is derived from two Greek words "geo" which means earth and 'thermos' which means heat (Quick, Michael, Huber & Arslan, 2010). Geothermal energy and electricity is has got higher reliability, is more sustainable, gives higher power plant capacity factor and less environmental impact (European Union, 1999; Liu et al. 2017; Kabeyi, 2019; Lundin, Lundin & Leijon, 2014; Ugochukwu, 2013). The energy content of the earth's crust is huge and is equivalent to 10,500 times the confirmed fossil fuel reserves. At the same time, volcanic/magmatic resources are equivalent to 400 times the known fossil fuel reserves. On the other hand, and geo-pressured resources are about 70 times the fossil fuel reserves (Bp, 2013; Karytsas & Mendrinos, 2013). Geothermal electricity is renewable with ability to supply baseload at high load factor and can act as a backstop for fluctuating supply from solar and wind whose supply is unsteady (Micale, Trabacchi, & Boni, 2015)..

2. Geothermal Energy Potential in Kenya and Challenges

2.1 Geothermal Potential

Geothermal potential in Kenya is estimated to be between 7,000 – 10,000 MWe, and is located along the East African Rift. Geothermal development in Kenya started with an exploration of the Olkaria Geothermal Field, which started in 1956. Deep drilling began in 1973 (KenGen, 2020). In 2019, Kenya became the eighth largest producer of geothermal electricity globally after commissioning of Olkaria V unit 1, bringing total geothermal generating capacity to 612 MW (Gitogo, 2019; Tubei, 2019). It follows the completion of the first unit of Olkaria V project. While preparing for this rapid increase in production, there is a need for accurate reservoir modeling to ensure that the development of the reservoir is sustainable. To ensure this is realized, numerous outside consultants and agencies have been involved in building and improving the reservoir model for the various steam fields (KenGen, 2020).

2.2. Current Capacity

Kenya was the first African country to build a geothermal power plant and in 2019, had generation installed capacity of 699 MW. Most of these electricity plants are owned by The Kenya Electricity Generating Company (KenGen) which is 74% government-owned Examples of geothermal plants are in the Olkaria geothermal resource field namely, Olkaria I with (185 MW), Olkaria II with (105 MW) and Olkaria IV with (140 MW), and 81 MW Wellhead generation plants. Olkaria III, with the capacity of 139 MW is privately owned by Orpower Ltd which used organic Rankine cycle while the KenGen plants use flash generation technology. A pilot wellhead plant of 2.5 MW was installed on well W-37A in olkaria in February 1982. Other plants are Eburru wellhead plant with 2.55 capacity and two wellhead plants of 2 MW capacity each built by the Oserian Development Company Ltd to power their rose farm facilities with a total of 4 MW (KenGen, 2020; Saitet& Kwambai, 2017).

2.3 Challenges of Geothermal Development

Exploration for geothermal energy in Kenya started in the 1960s with surface exploration that led to drilling two geothermal wells at Olkaria in Naivasha. In 1970s more geological and geophysical work was carried out between Lake Bogoria and Olkaria followed by drilling of more wells, and in June 1981, the first 15 MWe generating unit was commissioned at Olkaria (Simiyu, 2010). That means that it took 21 years to develop the g first geothermal power plant in Kenya. The second 15 MWe unit was commissioned in November 1982 and the third unit in March 1985, which increased the total generation to 45 MWe. This was the first geothermal power station in Africa and is owned and operated by KenGen. In 2003, KenGen commissioned a 2 x 35 MWe Olkaria II power plant in the Northeast field (Simiyu, 2010). This means that it took 18 more years to develop the second 70 MW geothermal power plant. This demonstrates the challenge of developing geothermal electricity, as it takes very many years.

The Kenyan Government has been working hard to accelerate geothermal electricity generation to meet its own ambitious growth targets. The country has made a huge investment in research, drilling and generation plants with the objective of having 15% to 27% of electricity mix from geothermal. The challenge is that the sector does not attract sufficient funding and challenges of huge upfront costs and risks (ESMAP, 2012; GDC, 2015; Micale, Trabacchi, & Boni, 2015). Financing from the carbon fund has faced challenges with respect to project boundary with regard to steam supply, inadequate monitoring, poor data analysis, reduced funding and increasing carbon credit projects hence competition for funds, delay in project registration, delay in project execution, and stringent government procurement regulations (Ogola, 2015).

2.3.1 Other barriers facing geothermal

There are several barriers to geothermal electricity development. They can be classified as;

(I) Financial barriers

A conventional geothermal power plant has high upfront costs and risks, long gestation periods and significantly high payback periods (Kabeyi; Kombe & Muguthu, 2019). The resource state, and resource risks, are main factors that influence investment decisions and hence the rate of development (ESMAP, 2018).

(II) Institutional and policy barriers

Governments should put in place policy frameworks and institutions to facilitate coordinated and faster geothermal resource development and exploitation. Such arrangements are missing in many countries (Kombe & Muguthu, 2019). There Is a need to put in place enabling legal measures, political will and institutionalization of geothermal energy development (Mwagombo,2015).

(III) Technical barriers

Geothermal development requires several technical inputs which include professionals from different related fields like geologists, surveyors, reservoir engineers, mechanical engineers, drilling engineers and others. Not many countries are blessed with all these expertise, hence limiting progress in geothermal development (Kabeyi, 2019; Kombe & Muguthu, 2019).

(IV) Environmental and social barriers

Whereas geothermal energy is classified as clean and renewable, its development and operations have socio-economic impacts leading to conflicts with other stakeholders and pollution. This includes Sulphur dioxide and other non-condensable gas emissions, brine pollution and seepage, the visual impact of steam and pipelines (Kabeyi; Kombe & Muguthu, 2019).

3. Types of Geothermal Resources

Geothermal resource exists in different forms depending on many factors like geology.

3.1 Convective hydrothermal resources or convective fracture-controlled systems

In this resource, the heat is conveyed upwards by the convective circulation of hot water and steam with cases where water circulates along with fractures (Lund 2007). This resource exists in all possible ranges of fluid temperature and pressure (Kabeyi, 2019). The resource of heat is the hot crust at depth in tectonically active areas. Earth's heat is carried upwards through the convective circulation of naturally occurring hot water or steam. The high-temperature hydrothermal resources result from deep circulation of water along with vertical fractures (Lund, 2007)

3.2 Hot dry rock (HDR) or enhanced Engineered Geothermal Systems (EGS)

This resource exists as heat stored in dry rocks within 10 km from the surface. The resource has a challenge in exploitation due to lack of a heat carrier or geothermal fluid to deliver heat from these hot rocks (Lund, 2007; Kabeyi, 2019). These are volumes of rock that have been heated by abnormally high heat flow or by volcanism, with low permeability or are fully impermeable. Experiments have been done to create artificial reservoirs in these systems using hydro-fracturing.

3.3 Magma/Molten Rock Resources

The geothermal resource is found in molten rocks, also called magma. To exploit these resources, the rock is drilled and a heat exchanger installed on the surface of the magma. An example is Heimaey in Iceland after the 1973 volcanic eruption. This heat was experimentally used for space heating (Kabeyi, 2019; Lund, 2007).

3.4 Radiogenic Resources

Radiogenic resources are located in areas with granitic intrusions close to earth's surface, thus causing heating of local groundwater by heat from radioactive decay of potassium, uranium and thorium. It is heating that increases the geothermal gradient which creates energy potential of the area for low-temperature geothermal exploitation (Kabeyi, 2019; Lund, 2007)

3.5 Geo-pressured Resources

These geothermal resources exist in the form of deeply buried fluids contained in permeable sedimentary rocks normally heated in a normal or enhanced geothermal gradient under confined conditions of impermeable rock and acquire pressure that is greater than hydrostatic. The fluid contains dissolved methane, heat energy and mechanical energy which can be exploited (Kabeyi, 2019; Lund, 2007).

3.6 Sedimentary Basins

These geothermal resources have thermal gradient greater than 30OC/km due to lower thermal conductivity than the surrounding of the basins or high heat flows or both and cover wide areas, e.g. the Madison Formation of North Dakota, Montana, South Dakota and Wyoming of the northern USA and Pannonia Basin of central Europe (Lund, 2007).

3.7 Vapor Dominated Geothermal Systems

These geothermal resources exist inform of steam from deep, water in permeable rocks and are ideal for electricity generation. Examples of these resources are the Geysers in the USA, Larderello in Italy and Matsukawa in Japan. Such resources are, however, quite scarce (Lund, 2007).

3.8 Water Dominated Systems

These geothermal resources exist in the form of hot water produced by ground circulation to some depth in the reservoir and ascending by buoyancy in permeable rocks. These geothermal resources often have surface manifestations like hot springs, geysers, chemically altered rocks, fumaroles, and travertine deposits. Blind water dominated resources do not have surface manifestations (Lund, 2007; Kabeyi, 2019).

3.9 Shallow resources

Shallow geothermal resources constitute thermal energy stored close the earth's surface. The heat partially originates from solar radiations and partially from geothermal. The application of these resources can be harnessed as ground source heat pumps for heating and cooling buildings (Axelsson, 2016; Quick, Michael, Huber, & Arsalan, 2010).

3.10 Co-Produced Resources

Co-produced geothermal resources are typically found at temperatures of 300F (150oC) or less. Electricity can be generated from coproduced low-temperature sources to using binary cycle technology. Co-produced hot water is a by-product of oil and gas production. This hot water is being examined for its potential to produce electricity, helping to lower greenhouse gas emissions and extend the life of oil and gas fields (National Renewable Energy Laboratory, n.d.; Kabeyi, 2019). According to Matek (2016) fluids resulting from oil and gas field development are utilized for the production of geothermal power/energy for electricity or heat applications.

3.11 Supercritical Geothermal Resources

Supercritical geothermal resources have extremely high temperature and pressure and pose a lot of challenges during drilling for resource development. These resources located close to the transition between the brittle-ductile zones. Supercritical resources have significant energy potential but provide challenges during drilling in terms of handling the high temperature and pressure. This is because available tools allow recording temperatures with a maximum of 350 °C and 4 hours of the operation time, but supercritical resources have a higher temperature (Kruszewski and Wittig, 2018).

Therefore geothermal energy resources exist in various forms and potential, and this influences the technology selection and overall potential. Not all resources are suitable for electricity generation.

4. Types of Geothermal Power Plants

4.1 Geothermal Electricity Generation Technology for Central Power plants

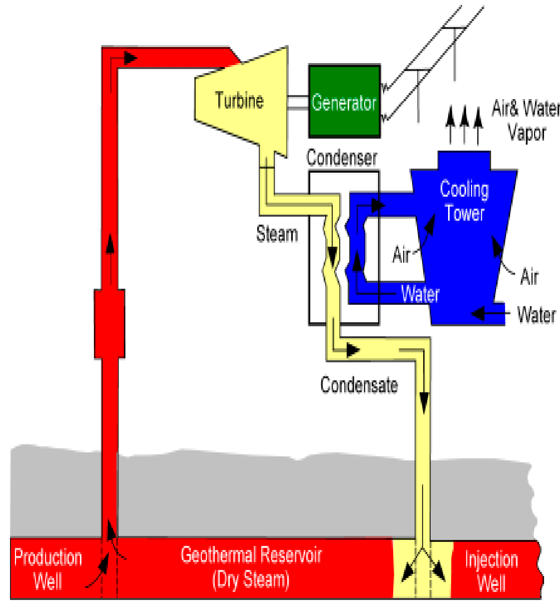
There are three conventional technologies, and a combination of one or more of the conventional technologies (IRENA, 2017; Hillesheim & Mosey, 2013; Kabeyi, 2019) used to exploit geothermal resources:

i). Dry steam plants

Dry steam power plants directly use steam, from production wells which are dry and piped to towards steam turbine. The first, ever exploited, geothermal field, at Larderello in Italy, is among the very few dry steam fields recorded worldwide in addition to Geysers' of USA)Kabeyi, 20019).

Dry steam turbines require fluids of at least 150°C and can be backpressure or condensing type turbines. For backpressure turbines, steam is passed through the turbine and vented to atmosphere leading to consumption of almost twice more steam per produced kilowatt-hour (kWh), than a similar condensing cycle turbine working with same steam. However, backpressure turbines may prove rewarding as a pilot or/and stand by plants in case of small supplies from remote, isolated wells and for generating electricity in the early stages of field development s in wellhead power plants. Backpressure is ideal where geothermal fluid has high non-condensable gas contents, in excess of 12% in weight, in the vapour phase (Geothermal Energy Council, 2009).

Figure 1. Illustrates a dry steam power plant.

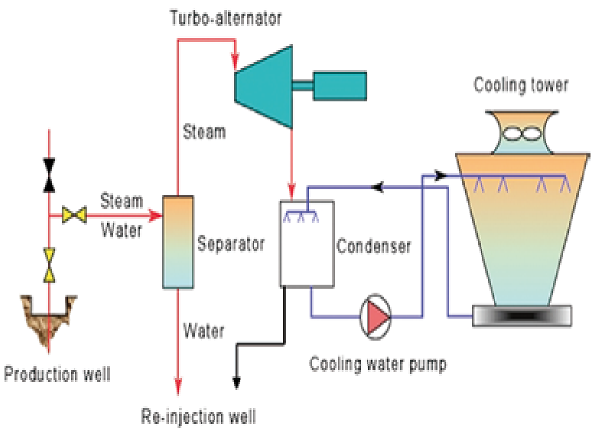


Source: Dry steam plant (Kabeyi, 2019)

Figure 1 shows the main elements of a dry steam plant as production and reinjection wells,

ii). Flash steam plants (single, double, and triple)

Flash steam plants are commonly used for water dominated reservoirs with temperatures above 150°C. The hot pressurized water flows up the well until its pressure decreases to the stage it vaporizes, leading to a two-phase water-steam mixture and a vapour. Steam, separated from the water, is piped to the turbine while separated left over brine, together with the condensed steam, is piped back into the source reservoir, through reinjection wells (European Geothermal Energy Council, 2009)

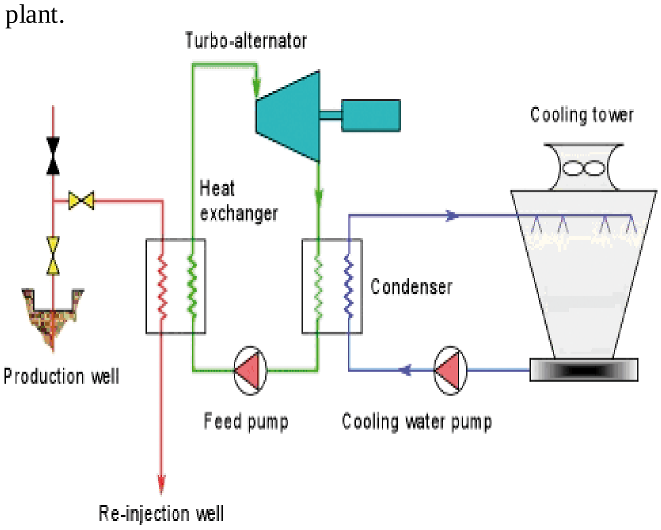


Source: Flash steam plant European (Geothermal Energy Council, 2009).

Figure 2 shows the main features of a flash steam plant as the separator, production and reinjection wells, steam turbine and generator, cooling tower and condenser.

iii). Binary plants

The conversion process in binary power plants involves vaporizing a low boiling point working fluid, either a hydrocarbon -Organic Rankine Cycle (ORC) - or an ammonia/water mixture called Kalina cycle. Binary plants can generate electricity from low temperature geothermal sources typically within 100-120°C range and even exceptionally down to 70-75°C depending upon the availability fluid. (Geothermal Energy Council, 2009; Kabeyi, 2019). Figure 5 bellow illustrates a binary cycle plant.



Source: Binary plant (European Geothermal Energy Council, 2009)

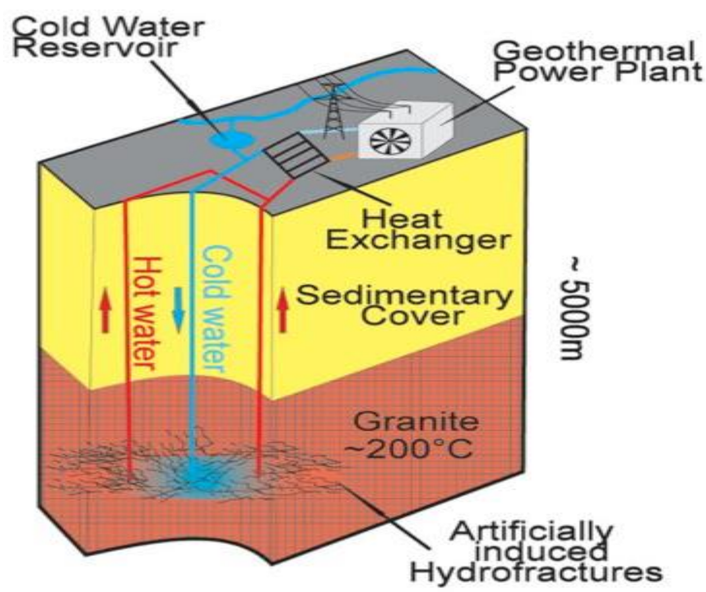
From figure 3, main features include production and reinjection wells, heat exchanger and secondary fluid normally organic fluid.

iv). Combination of the conventional technologies

The heat content of a geothermal field typically determines the technology used. Dry steam plants use steam of 150oC or higher, and the steam entering the turbine needs to be at least 99.9% dry to avoid scaling and/or erosion of the turbine or piping components (IRENA, 2017). Flash steam plants typically require resource temperatures in the range of 177oC to 260oC, whereas binary plants which include Kalina plants are designed to utilize geothermal fluids in the range of 85oC to 170oC with the working fluid being an organic gas like Isobutane or NH3/H2O mixture (Murugan & Subbarao, 2008; Shehata , 2019).. Single flash has limited ability to provide flexible power, while binary systems are flexible (Kahlen, Kurdziel, Day & Schiefer, 2019; Irena 2017).

v). Enhanced geothermal Systems plants

Used places where the geothermal resources have no geothermal fluid in the form of steam or hot water exist, In this case, the heat of the rock is extracted by creating artificial permeability for fluids extracting that heat.it is also called "Hot Dry Rock" technology (Kabeyi, 2019). In some cases, the ground is not "dry" as such hence the objective is to open pre-existing fractures and fissures for permeability. The Enhanced Geothermal Systems (EGS), comprises everything from stimulation of already existing sites with insufficient permeability, to the classical HDR development (Geothermal Energy Council, 2009). Figure 6 below illustrates Enhanced Geothermal System plants



Source: Enhanced geothermal systems (European Geothermal Energy Council, 2009; Golstein, etl, 2010)

Figure 4 shows that an EGS system involves underground modification of the reservoir and installation of a water pumping system

4.2 Direct Use of Geothermal

Direct use of geothermal energy includes centralized heating, or district hating, space heating, greenhouse heating, thermal SPA, industrial process heating (Schellschmidt, Sanner, Pester, & Schulz, 2010). Other applications are medical or therapeutic, recreation, agricultural applications, industrial applications and others (Georgsson, 2010). Geothermal fluid can be utilized directly, or the heat can be transferred to a secondary fluid for better distribution and use. The longest geothermal fluid distribution pipeline is 62 Km long and runs from Deildartunga hot spring to Akrale in Iceland. The fluid temperature drops by about 19oC in the process (Georgsson, 2010). The challenge is that if water or steam is conveyed outside of the geothermal field for direct utilization, it is unlikely that the fluid will be reinjected into the reservoir (Georgsson, & Haraldsson, 2016). Therefore it is possible to transmit and use geothermal heat over long distances although with difficulty in reinjection for sustainable resource use.

4.3 Combined Geothermal Electricity and Power (CHP)

Most of the heat in geothermal fluid is wasted after electricity generation and hence need to use the excess heat in the fluid to increase efficiency. Low temperature geothermal resource has been exploited, since 1960's, by combining power generation and direct uses of waste and excess heat/steam. The heat in CHP may be regarded as a byproduct of geothermal power production in terms of either waste heat released by the generating units or excess heat from the geothermal source (European Geothermal Energy Council, 2009).

The technology to use is dictated by resource temperature, pressure and quantity, capital availability and the application since some technologies are more expensive than others and they offer different efficiencies.

5. Wellhead Geothermal Power plants

In wellhead generation, steam from a geothermal well is converted to electricity in a wellhead power plant units installed above or close to the well. The plant has no steam field development except for brine and cooling tower blowdown disposal systems. Wellheads have little or fewer permanent civil works and are preferably containerized or skid mounted for easy transfer from one well site to another (Saitel & Kwambai, 2015). According to Imaidi (2017) a wellhead geothermal plant is a modular or containerized electricity generating plant that is installed within the confines of a geothermal steam well pad. Electricity generated from wellheads can be fed to the grid Wellheads are small geothermal power plants with an installed capacity of between 1MW and 10MW, installed at the well pad of a geothermal well. They can be installed in as short as 6 months to commissioning. They are used to optimize production characterized of a given well pad. Which are used to overcome the short comings of traditional methods of exploiting geothermal resources such long gestation periods of up to 10 years.

5.1 Design and Construction of Wellhead Plant

Elements of the wellhead power plant has all the features of a conventional geothermal power plant in a smaller scale. According to Imaidi (2017), the layout of a wellhead power plant is comprised of the following components:

i.) Steam gathering system like pipes , valves, steam e separator or flash tank, brine disposal system or reinjection well , pressure control system, brine level control system, a silencer or rock muffler and saturated steam delivery piping to the turbine.

ii.) A steam turbine whose design depends on generation technology. The turbine is coupled to a generator unit with several auxiliary units. The turbine can be back pressure, condensing extraction type.

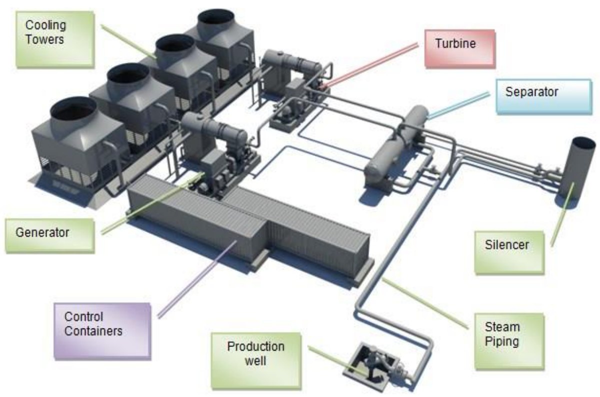
iii.) A compact cold end, comprising of surface, direct contact or air-cooled condensers, hot well pump, cooling towers, cooling water circulation pump, a collector sump and associated control systems.

iv.) An extraction system for non-condensable gases which may be a pure ejector, vacuum pump or combination of both ejector and vacuum pump.

v.) A switchgear and control room often in a container although a permanent structure can be used.

vi.) A standard centralized or compact switchyard on a portable skid and transmission line.

Figure 5. Below illustrates a wellhead power plant



Source: A wellhead plant (Saitel & Kwambai, 2015).

Figure 5 illustrates a wellhead geothermal power plant and the basic elements which include the generator, steam pipes, production well, control containers, cooling towers, silencer, steam turbine and silencers.

5.2 Wellheads Vs. Conventional Plants

Table one bellow summarizes the differences between wellhead power plants and centralized power plants.

Table 1: Comparison between geothermal central power plants and the wellhead generators.

PARAMETERS	CENTRAL POWER PLANT	WELLHEAD GENERATOR
Set up period	Takes more than 2 years to set up	Takes between 3-6 months
Flexibility/Portability	Not flexible and can't be moved from one site to another.	Are modular containerized plants that can easily be relocated and customized to alternative viable geothermal sites
Customization	Are not site specific and doesn't have to fit a specific requirement.	Are customized to fit the requirements of the specific wells they are fitted on.
Number of wells	Fed by multiple wells.	Operate on a single well.
Start per MW ratio	Healthy due to the economics of scale they enjoy.	Poor due to the low capacities.
Operating Efficiency	High	Low because the technology is in its developmental stages; thus much is known it.

5.3 Wellhead Power plants in Kenya

In Kenya, a pilot wellhead power plant was installed and commissioned by Kenya Electricity Generating Company in 2012 on well OW-37A located in Olkaria geothermal steam field in 2012 (KenGen, 2020). Wellhead power plants accounted for 10% of total installed geothermal generation capacity in Kenya by July 2016 from 12 wellhead power plants at Eburru and Olkaria generating 65 MW electricity with plans for 120 MW more (Kiptanui & kipyego, 2016). As in 2020, KenGen has installed fourteen (14) wellhead power plants in Olkaria geothermal steam field generating 81 MW (KenGen, 2020).

5.4 Geothermal wellhead power plant in Naivasha, Kenya

This plant was delivered by the Geothermal Development Associates (GDA) in June 2007. It is a non-condensing flash system with the advantage of simplicity, affordability and maximum portability of wellheads.

5.5 Eburru Wellhead plant

Eburru wellhead plant has generating capacity of 2.44 MW and is set to be expanded to 25 MW. The Eburru geothermal field has estimated electricity capacity of 50 MW (KenGen, 2020). The Eburru wellhead plant is located approximately 60 km to the northwest of Olkaria. Geothermal exploration activities in the Eburru field began in 1972 leading to the drilling of six exploratory wells between 1989 and 1991. In 2015, KenGen engaged Mannvit to undertake an optimization study of the wellhead plants with the purpose of analyzing the technical design, operation, maintenance and resource utilization (KenGen, 2020).

5.6 Advantages of Wellheads

According to Saitet and Kwambai (2015), wellhead generators have the following advantages;

i.) Require minimum civil engineering works hence low capital cost.

ii.) Wellheads being quick and mall, they are easy to attract financing.

iii.) They are flexible and can be moved from one well to another and easily modified to suit changes in steam or well characteristics.

iv.) It is easier to take advantage of unique characteristics of each well and select optimum points on the load curve for use by the well head hence optimum output can be realized for individual well characteristics.

v.) Wellheads have attractive feed in tariffs hence offer better and quick returns to consumers.

vi.) Wellheads are less complex and hence easy to operate and maintain thus guarantee high profit margins.

6. Materials and Methods

This study was a survey and used both qualitative and quantitative approaches to collect data. The researchers collected data through observation, document review and analysis, interview and questionnaires. These techniques include:

6.1 Data Collection Techniques.

This technique involved systematic selection, watching and recording of the wellhead power plant processes and activities being investigated. A non-participant observation approach was applied where we watched the installation operation and maintenance of the wellhead generator(s).

6.2 Document review / Document studies

Document review involved examining existing documents with the aim of gathering information on a particular subject. Documents under review were hard copies and electronic copies which included; performance ratings, manufacturers manuals, maintenance schedules, textbooks, publications, meeting minutes, newsletter and environmental assessment reports.

6.3 Interview

This technique of data collection involved oral face to face question and answered session with targets being engineers and technicians in the operations and maintenance functions of wellhead power plants. Answers provided were put in writing during the interviews. In-depth interviews were conducted not limiting the respondent's scope provided the information was within geothermal energy exploitation. Questions asked were prepared in advance and then asked during a predetermined interview, and the respondent(s). Answers provided were recorded during the interviews. The targeted respondents were engineers at Eburru and Olkaria. Information on the installation, operation, output, challenges, costs and maintenance is expected to be obtained using this method.

6.4 Questionnaires

A written questionnaire is a data collection tool which uses written questions which are presented to the respondent for answered. In our case, open-ended questions were written and send to the correspondent, mainly engineers at Olkaria, via e-mail and responses sent via the same channel. Information gathered include installation, operation and maintenance, costs involved and other pertinent information.

7. Research Data Analysis

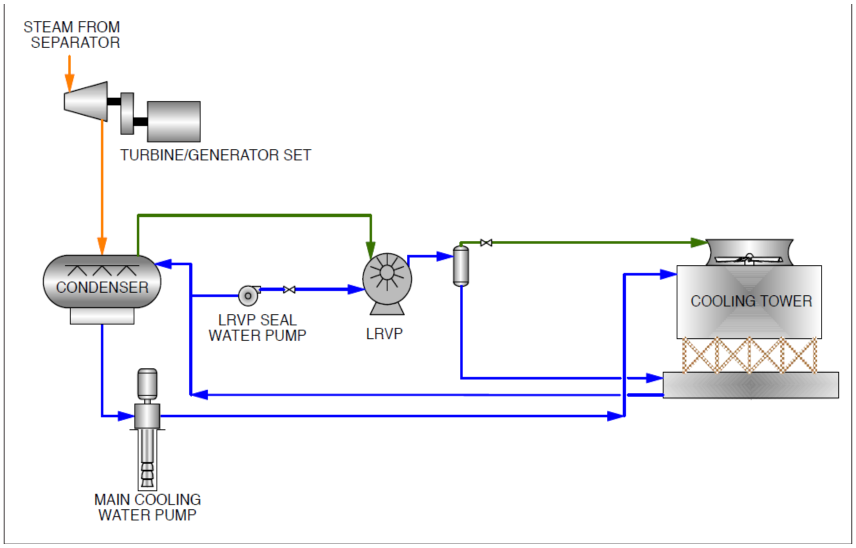
Data collected was analysed and presented using descriptive statistics. One on one interviews were conducted with the engineers working on wellhead OW 43 and the findings noted down. We also conducted a site visit on the 12th of April 2017 where we observed the wellhead OW 43 in operation. Questionnaires (2 sets) were admitted the first to a senior engineer at Olkaria via email, and the second to the 3 engineers on the ground at wellhead OW 43. The researchers were also supporting technical data and reports with respect to the plants and operations.

7.1 Technical specifications of Eburru wellhead plants

The Eburru geothermal wellhead generator has the following design conditions;

Turbine steam flow	-	21,100 kg/hour
non-condensable gas	-	15% by weight
Turbine inlet pressure	-	58.5 kPa (absolute)
Condenser pressure	-	10 kPa (absolute)
Gross generator output	-	2,400 kW

This plant is a single flash condensing steam cycle plant that has a separator pressure of absolute 6 bar. The separated steam is then routed to the turbine where it is used to produce 2.4 MW of power. Exhaust steam is then cooled and condensed with the heat being rejected into a counter flow fibreglass cooling tower



Technical feasibility involved analysis of capacity, availability, breakdowns and maintenance. Other technical issues on the application of the wellhead technology include; Heavy deposits of silt and algae forming at the bottom and walls of the cooling tower sump. Such deposits were thoroughly cleaned as was the case during the inspection of OW 014 held on 27th January 2016. Observations noted include;

i.) Evacuation line frequent trips,
ii.) Brine valves seizure,
iii.) Turbine rotor failure,
iv.) Cooling tower fan breakdown and
v.) Air compressor breakdowns.
vi.) The load factor of OW043 was at an average of 72.585% between 2014 – 2015 and 2015 2016 while that of the central plants are used mostly for the baseload with the wellhead generators are sometimes used to address changes in demand.
vii.) Malfunction of turbine inlet valve positioners, thus the valves allowing steam into the turbine prematurely.
viii.) OW043s utilization factor averaged 81.095% for the financial years 2014/2015 and 2015/2016 in comparison to that of the central plant, which ranges from 92.81% to 96.24%. This is due to the technical issues mentioned above and also due to numerous teething problems experienced with this technology due to its infancy.
ix.) Presence of heavy silica deposits on the perforated tube was also observed and can be managed by scrubbing off the solid deposits. Also chocking of the condenser cooling water inlet strainer was a problem.
x.) Electricity evacuation line frequent trips.
xi.) Availability factor OW043 was 87.77% in 2014 /2015 and 92% in 2015/2016 which is high though relatively lower than a. This was occasioned by the evacuation line frequent trips, brine valve seizures, the cooling tower fan and compressor breakdowns.

The technical parameters which include availability factors, capacity utilization and load factors exhibited at the wellhead power plants are less than values for conventional geothermal power plants under study. Maintenance-related problems like equipment breakdown are not unique to wellhead power plants but may be influenced by other factors.

7.2 Economic/Financial feasibility

Revenues and costs from wellhead electricity sales are analysed in this section to determine the financial/economic feasibility of the investments in wellhead power plants—however, lack of total access to data considered confidential limited complete financial analysis.

7.3 Data and analysis

This data concerns the financial records of wellhead generator OW 43 since inception in 2013 to the financial year ending June 2016. The graph in the next page shows the cumulative revenues.

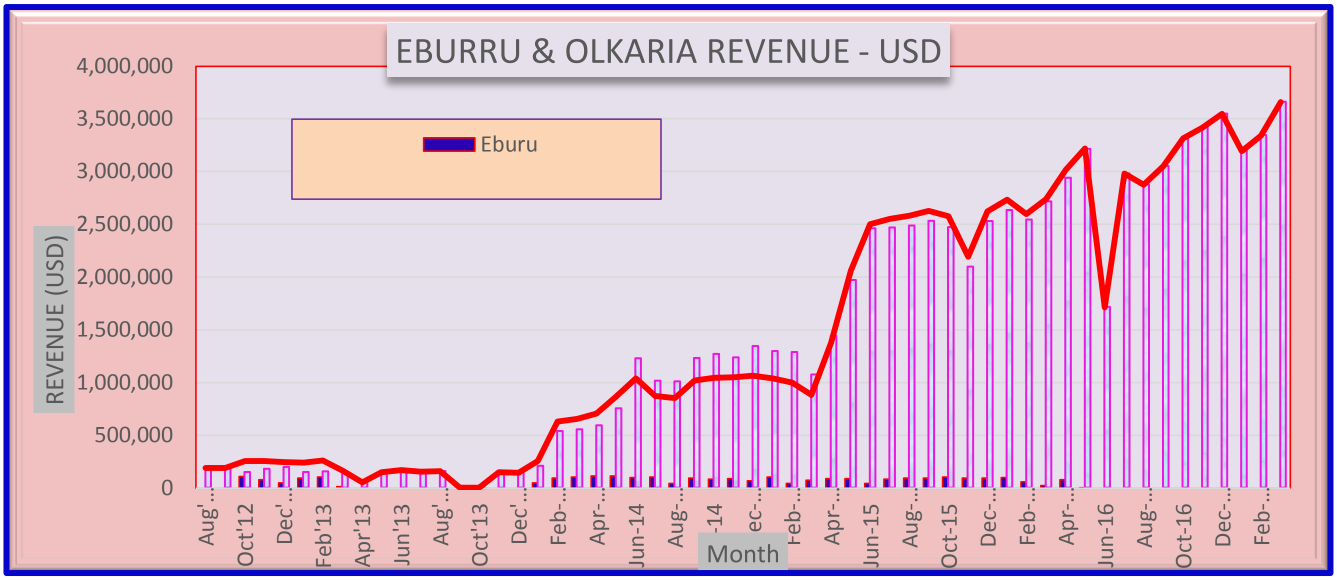


Figure 2: Cumulative revenue for Olkaria and Eburru wellhead power plants

Figure 2 shows cumulative revenues of both Olkaria and Eburru wellheads for the period between August 2012 to Feb 2017

7.4 Wellhead Power plant Operating Profits

Table 2 bellow shows revenue and operating profits for Eburru and Olkaria wellhead power plants.

Table 2: profits for wellhead power plant

	YEAR (USD)		
	2013/2014	**2014/2015**	**2015/2016**
Revenue (USD)	2,488,395.29	6,592,900.73	6,397,391.31
Annual budget expenditure	(201,312.52)	(134,655.18)	(429,085.93)
Gross Revenue	2,287,082.77	6,458,245.55	5,968,305.38
Tax at 30%	(686,124.83)	(1,937,473.67)	(1,790,491.61)
Net profit	1,600,957.94	4,520,771.88	4,349,292.83
Rate of return $= \frac{\text{NetProfit}}{\text{Revenue}} * 100$	= 64.3	= 68.6	= 65.3

7.5 Payback Period

The payback periods is a measure of the duration it takes for wellhead investors to recoup their investment.

Table 3: Payback Period for wellhead plants with 30% corporate tax

	CASH FLOWS (USD)	CUMULATIVE (USD)
Initial investment	16,518,580.00	
2013/2014 Cash flows	1,600,957.94	(14,917,622.06)
2014/2015 Cash flows	4,520,771.88	(10,396,850.18)
2015/2016 Cash flows	4,177,813.77	(6,219,036.41)
2016/2017 Cash flows	4,349,292.83	(1,869,743.59)
2017/2018 (projected)	4,349,292.83	2,479,549.25

From the table 2, payback period is as follows

Therefore: Payback Period $= \frac{1,869,743.59}{4,349,292.83} + 4 = 4.4$ Years

This shows that based on net profit, the payback period for wellhead plants is on average 4.4 years. This is financially/economically quite attractive for any investor in energy projects.

Table 4: Payback Period for wellhead plants with no corporate tax

	CASH FLOWS (USD)	CUMULATIVE (USD)
Initial investment	(16,518,580.00)	
2013/2014 Cash flows	2,287,082.77	(14,231,497.23)
2014/2015 Cash flows	6,458,245.55	(7,773,251.68)
2015/2016 Cash flows	5,968,305.38	(1,804,946.3)
2016/2017 Cash flows	6,213,275.47	4,408,329.17
2017/2018 (projected)	6,213,275.47	10,621,604.64

$$\text{Payback period} = 3 \text{ years} + \frac{1,804,946.3}{6,213,275.47}$$

$$= 3.4 \text{ years}$$

Therefore computed payback with corporate tax is 4.4 years but with no corporate tax, it reduces to 3.4 years. Therefore tax incentives can significantly improve the financial feasibility of wellhead power plants.

7.6 Environmental Feasibility

This section analysis of environmental audit reports was done to get a picture of the environmental status of wellhead plants. These audit reports numbered 104G5K-IEA-H-005, 104G5K-IEA-H-003, 104G5K-IEA-H-002 and 104G5K-IEA-H-001 were conducted by Howard Humphreys (East Africa) limited for Kenya Electricity Generating Company Limited and submitted in December 2015. These audits were conducted in accordance to the Environmental Management and Coordination Act (EMCA) of 1999, which requires that an environmental audit in Kenya is conducted to: Facilitate the management and control of environmental practices, assess the level of compliance with relevant statutory and regulatory requirements on development and environment, raise awareness of and commitment to environmental policy by development practitioners, the community and other concerned parties and finally maintain environmental health and safety standards, while continuously exploring opportunities for improvement.

7.7 Environmental and Social Impact.

Analysis of the environmental, safety and health and social-economic impacts associated with existence and operations of the Eburru WHGs, OW 043, OW 914 and OW 915 within their localities showed the following;

i.) Increased revenues to the government and the Kenya wildlife service thus enhancing conservation efforts,

ii.) Promotion of geothermal tourist and in the process highlighting Eburru forest reserve and the Hell's gate tourist destinations with many local and international visitors to the,

iii.) Additional electricity between of 1.9-2.4 MW for Eburru, 12.8 MW, 26MW, 10 MW respectively from Olkaria wellheads

iv.) Increased revenue and financial performance of Kenya Electricity Generating Company PLC.

v.) Increased grid electricity stability and mitigation of carbon emissions for diesel power plants through generation substitution, this also reduces the cost of grid electricity through the reduction inexpensive, emergency and polluting diesel power plants

vi.) Pollution and increased human activity in National Parks and protected areas leading to increased human and animal conflict.

vii.) Habitat loss due to the massive geothermal infrastructural installations. Invasion species, creation of noise, air and water pollution from such project have also led to ground instability resulting from project equipment vibrations.

7.8 DISCUSSION OF RESULTS

According to Howard Humphreys (East Africa) Limited, December 2015, major issues arose in regard to the environmental management practices by KenGen at both Eburru and Olkaria. Firstly, was the issue of waste disposal? Here it was observed that KenGen did not segregate its waste leading to uncontrolled disposal of wastes. Corrective measures were suggested during the audits, which included; segregation of wastes at the source and the provision of clearly marked bins to facilitate segregation of the wastes into categories, e.g. ordinary vs hazardous waste. This step has already been implemented as we witnessed during our visit on 12/04/2017.

The general trend of technical parameters which include availability factors, capacity utilization and load factors exhibited at the Olkaria and Eburru wellhead power plants are marginally lower in comparison to the conventional geothermal power plants under study. The central geothermal power plants enjoy economies of scale, and this makes them more efficient and reliable. Maintenance-related problems like equipment breakdown are not unique to wellhead power plants but may be influenced by design, operations and geothermal water characteristics. Ultimately this makes geothermal wellhead power plants technically feasible.

From the generalized graph showing the revenues of the Eburru and Olkaria from August 2012 through to March 2017, we can observe a trend of increased revenues from the lows of 188,959.25 USD in August 2012 to highs of 3,668,845.32 USD in March 2017. This represents an increase of about 1836% in revenue over a period of 4 years 7 months. This growth has been attributed to;

i.) In February 2012, OW 37 and Eburru were commissioned then the breakdown for early 1 year in 2014(January - June) and 3.2 MW plants were installed. They are considering the financial data specific to OW043. The results show that the plant had average profitability of above 65% for the financial years between 2013/ 2014 to 2015/2016. These values are after charging a corporate tax of 30% and a payback period of 4.4 years compared to that of central power plant that is 10 years.

ii.) Technically availability of staff, their qualification, continuous training, increased infrastructural problems and maintenance of the wellheads contributed to the learning curve and hence improved performance over time after commissioning for earlier plants. It was also observed that all wellhead power generation sites had qualified, trained and experienced engineers. Continuous or regular trainings by Green Energy Geothermal of Iceland, who are the suppliers of the wellhead generators used by KenGen. They also provide installation services.

7.9 FINDINGS AND RESULTS OF THE STUDY

The following findings came up from the research;

i.) According to Howard Humphreys (East Africa) limited, December 2015, major issues that arose in regard to the environmental management practices by KenGen at both Eburru was waste disposal where it was observed that KenGen did not segregate its waste leading to uncontrolled disposal of wastes. Corrective measures were suggested during the audits which included; segregation of wastes at the source and the provision of clearly marked bins to facilitate segregation of the wastes into categories e.g. ordinary vs hazardous waste. This step has already been implemented as we witnessed during our visit on 12/04/2017.

ii.) From the generalized graph showing the revenues of the Eburru and Olkaria from August 2012 through to March 2017, we can observe a trend of increased revenues from the lows of 188,959.25 USD in August 2012 to highs of 3,668,845.32 USD in March 2017. This represents an 1836% increase in revenue over a period of 4 years 7 months. This growth has been attributed to; In February 2012, OW 37 and Eburru were commissioned failed between January and June 2014, and 3.2 MW plants were installed. Considering the financial data specific to OW043 we can see that the plant has had an average estimation profitability of above 65% for the financial years of between 2013/2014 to 2015/2016. These values are after charging a corporate tax of 30% and a payback period of 4.4 years compared to that of central power plant that is 10 years.

iii.) Technically, it was observed that even wellhead power generation sites most employees were technical and often trained in partnership with Green Energy Geothermal of Iceland, who are the suppliers of the wellhead generators used by KenGen. They also provide installation services. This supplier relationship contributed to the capacity to operate and maintain the power plant.

iv.) Constant power trips were noted mainly because the power plant was connected to the consumer distribution line rather than a high voltage transmission line as in the case of central power plants.

v.) Susceptibility of the brine valve to silica deposit on moving parts, malfunction of turbine inlet valve positioners, thus the valves allowed stream into the turbine prematurely. Turbine rotor failures, brine valve seizures, cooling tower fan breakdowns and compressors breakdowns have also been managed through regular maintenance carried out twice annually.

vi.) Looking at the availability factor OW043 had an availability of 87.77% in 2014 – 2015 and 92% in 2015 – 2016. This was occasioned by the evacuation line frequent trips, brine valve seizures, the cooling tower fan and compressor breakdowns. Regular maintenance practices have been adopted to minimize the downtime of the wellhead, thus improving its availability factor.

vii.) OW043s utilization factor averages at 81.095% for the financial years 2014 – 2015 and 2015 – 2016 in comparison to that of the central plant, which ranges from 92.81% to 96.24%. This is due to the technical issues mentioned above and also due to numerous teething problems experienced with this technology due to its infancy.

viii.) The load factor of OW043 was at an average of 72.585% between 2014 – 2015 and 2015 – 2016, while that of the central plants are used mostly for the baseload with the wellhead generators, are sometimes used to address changes in demand. The variability in peak load can also explain this difference.

ix.) This research revealed that the overall availability of the wellheads was rather low compared to the expected availability factors for central geothermal power plants of at least 94%. In addition, the capacity factor was also variant due to a decline in steam output in several units as.

7.9 Results of the study

The following results were realized from the study with respect to the objective;

	Subject	Results
1	Technical feasibility	Technically feasible with availability and capacity factor less than that of central power plants but above 70% which is acceptable. This makes central power plants more superior
2	Financial/economic feasibility	Financially feasible with payback of 4.4 years based on net profit after tax and 3.4 years with no corporate tax, which is attractive to investors. Additionally, investors start earning a return on investment within a year of drilling hence earlier payback
3	Environmental sustainability	Wellheads are environmentally sustainable, with common issues common to all power plants.

8. Conclusion

Geothermal development is characterized by long gestation periods and high upfront costs and risks which significantly limit the rate of geothermal electricity project execution. The wellhead technology is a technique that involves tapping steam from wells that are undergoing tests or awaiting connection to permanent plants. The technology not only helps to recoup the investment put into drilling the wells, which would otherwise be lying idle but also benefits from early generation as drilling and steam field development progress to have enough steam for a power plant. This technology is fairly new in conventional geothermal development, but this research shows that wellhead power generation can successfully realize early electricity generation from geothermal. Adoption of wellheads significantly reduces the time between completion of drilling and revenue generation from the steam or wells and minimizes wastage of drilled resource and shortens the period for return on investment (ROI) for drilling expenses.

The study also concluded that geothermal wellhead technology is environmentally feasibility. This follows the study of the initial environmental audit reports and also a follow up to confirm that the recommendations made by the audit reports were implemented. The main issues noted are waste management, noise pollution, and flue gas emissions, lack of fencing of the brine ponds, pollution of the Lake Naivasha and water invasion by foreign plant species. This concludes that wellhead technology is environmentally feasible.

Technically, the limitations of wellhead plants is resource sustainability with respect to reinjection. Several wellhead power plants have no reinjection well which compromises the sustainability of resource use. The study also noted declining steam flow in some wellhead plants like Eburru over time. Major technical issues involves evacuation line tripping, breakdown of the compressor, lack of redundancy of the compressor, brine valve seizures due to deposition of silica and turbine rotor failures. The capacity factor and availability of wellhead power plants is lower than that of central geothermal power plants.

Economic and financial feasibility study demonstrated that wellhead plants are profitable and have an attractive payback period of 4.4 years with corporate tax and 3.4 without corporate tax. Which is significantly lower than that of the central power plant of 10 years and more? This makes the geothermal wellhead technology highly attractive to investors. This study shows that geothermal WHG technology is financially feasible.

This study concludes that Eburru and Olkaria geothermal wellhead plants are technically, financially and environmentally feasible and there use as permanent should be encouraged but with enhanced sustainability features.

9. Recommendations

From our findings mechanical failures should be managed and controlled through regular maintenance carried out twice annually and an overhaul done every 2 years. Plans are also underway to install an evacuation line to prevent occurrence of frequent line trips. All these efforts have made this technology technically feasible.

It is recommended that the management of the geothermal wellhead power plants be vigilant in implementing the recommendation of the initial audit reports according to the given deadlines. It should also work closely with NEMA and KWS to ensure that they are always in compliance with the relevant legislations. Regular maintenance should also be done as at when scheduled at all times to avoid breakdowns.

To further enhance feasibility and sustainability of wellhead plants, the following measures are recommended;

i.) The government should give financial incentives like tax holidays and rebates to increase financial feasibility.

ii.) Encourage brine or used geothermal fluid reinjection especially for permanent wellhead plants.

iii.) Develop policy measures to encourage investors to use wellhead plants to avoid steam wastage during field development and reduces use of diesel engines in drilling by using electricity from wellheads.

iv.) Develop preventive and breakdown maintenance schedules specific to unique wellhead conditions to ensure higher availability, reliability and capacity factors.

v.) There is need to install a high voltage evacuation line instead of low voltage line for power evacuation to reduce trips and increase plant availability and load factor. .

9.1 Suggestions for further research

A study is recommended for overall performance and lifecycle costing to investigate possibility of replacing central power plants with wellhead plants.

10. Disclosure

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10.2 Conflict of Interest

The first author is a former employee of Kenya Electricity Generating Company PLC. Where he worked as a mechanical engineer between 2009 and 2012. There is however no conflict of interest from author that influenced the research.

10.3 Funding

The research did not receive any funding from third parties and was financed by the researchers.

Abbreviations

KenGen; Kenya Electricity Generating Company PLC; KWS: Kenya Wildlife Services; NEMA: National Environment management Authority;

References

[1] Alshareef, A.S. (2017).Technology Assessment Model of Developing Geothermal Energy Resources for Supporting Electrical System: the Case for Oregon" (2017). Dissertations and Theses. Paper 3515. Retrieved from . BP (2012): statistical review of world energy, 2012. Retrieved from https://www.laohamutuk.org/DVD/docs/BPWER2012report.pdf.

[2] ESMAP (2012). Geothermal handbook: Planning and financing power generation. *Energy Sector Assistance Management Program.* Retrieved from https://www.esmap.org/sites/esmap.org/files/DocumentLibrary/FINAL_Geothermal%20 Handbook_TR002-2_Reduced.pdf.

[3] ESMAP (2018). Opportunities and challenges for scaling up geothermal development in lac. *Energy sector Assistance Management Program.*Retrieved from http://documents.worldbank.org/curated/en/173681539626591426/pdf/128045-ESMAP- REVISED-PUBLIC.pdf

[4] European Commission (1999). Blue book on geothermal resources. European Commission http://www.geoelec.eu/wp-content/uploads/2012/04/EU-Blue-Book-Geothermal-2000.pdf.

[5] Geothermal Energy Association (2014). Geothermal energy. Retrieved from http://geo-energy.org/basics.aspx.

[6] Gitogo, W. (2019, July). Kenya ranked 8th largest geothermal power producer in the world. *The Kenyan Wall Street.* https://kenyanwallstreet.com/kenya-ranked-8th-largest-geothermal-power-producer-in- the-world/.

[7] Johnson, W.J. & Ogeya, M. (2018). Risky business: developing geothermal power in Kenya *Stockholm Environment Institute* https://www.sei.org/wp-content/uploads/2018/10/181025b-gill-johnson-keny a-geothermal-transrisk-db-1810g-1.pdf.

[8] Kabeyi, M.J.B (2019). Geothermal electricity generation, challenges, opportunities and recommendations. *International Journal of Advances in Scientific Research and Engineering, 5*(8), 53-95. doi: 10.31695/IJASRE.2019.33408 Retrieved from https://ijasre.net/uploads/2/4019_pdf.pdf.

[9] Karytsas, C. & Mendrinos, D. (2013, June). *Global Geothermal Power Market. European Geothermal Congress,* Pisa Italy. Retrieved from https://www.researchgate.net/publication/258926033_Global_Geothermal_Power_Market.

[10] Kenya Electricity Generating Company (2020). *Olkaria Wellhead Generation Plants*. https://www.kengen.co.ke/index.php/business/power-generation/geothermal.html

[11] Kiptanui,S. & Kipyego,E. (2016). Viability of wellhead power plants in accelerating geothermal development in Kenya: case of Menengai. Proceedings, 6th African Rift Geothermal Conference Addis Ababa, Ethiopia, 2nd – 4th November 2016. Retrieved from http://theargeo.org/fullpapers/FEASIBILITY%20OF%20USING%20WELLHEAD%.

[12] Kruszewski, M., Wittig, V.(2018). Review of failure modes in supercritical geothermal drilling projects. *Geothermal Energy* 6, 28. doi: 10.1186/s40517-018-0113-4.

[13] Liu XM, Wei M, Yang LN, Wang X. (2017). Thermo-economic analysis and optimization selection of ORC system configurations for low temperature binary-cycle geothermal plant. Appl Therm Eng. 125,153–64. https://doi.org/10.1016/j.applthermaleng.2017.07.016.

[14] Lund, J.W. (2007, June).Characteristics, development and utilization of geothermal resources. *GHC Bulletin. Retrieved from* https://pdfs.semanticscholar.org/084d/ecf2a958f35fa125251181253401600a5708.pdf

[15] Lundin,J., Lundin,U.& Leijon,M.(2014). EUSUSTEL-WP3 report- Geothermal power production. Retrieved from https://www.academia.edu/30759059/1_EUSUSTEL_WP3_Report_Geothermal_power.

[16] Mwagomba, T. (2015). Opportunities and challenges of developing geothermal in developing countries. Proceedings World Geothermal Congress 2015Melbourne, Australia, 19-25April 2015. Retrieved from https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/03016.pdf.

[17] Saitet, D. & Kwambai, C. (2017). Wellhead Generating Plants: KenGen Experience. *Proceedings World Geothermal Congress 2015, Melbourne, Australia, 19-25 April 2015* https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/08016.pdf.

[18] Stober and K. Bucher(2013). History Of Geothermal Energy Use, Berlin Heldelberg: Springer-Verlag,

[19] Simiyu, S. (2010). Status of Geothermal Exploration in Kenya and Future Plans for Its Development. Retrieved from https://orkustofnun.is/gogn/unu-gtp-30-ann/UNU-GTP-30.

[20] Imaidi, D.L. (2017). Analysis of maintenance methods and developing strategies for optimal maintenance of wellhead power plants at olkaria geothermal field in Kenya. Retrieved from https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-2017-12.pdf.

[21] Kombe, E.Y. & Muguthu, J. (2018). Geothermal energy development in East Africa: Barriers and Strategies. *Journal of Energy Research Reviews*. 2(1), 1-6. Doi: 10.9734/JENRR/2019/45278.

[22] Loksha, M. Gehringer and V. Loksha, (2012). Geothermal handbook; Planning and Financing power generation," ESMAP/ World bank Group, Washington DC, 2012.

[23] Ogola, P.F.A. (2015). KenGen geothermal energy carbon credit projects: status, benefits, challenges, lessons learnt and post-2012 plans. *Proceedings World Geothermal Congress 2015 Melbourne, Australia, 19-25 April 2015* Retrieved from https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/36001.pdf.

[24] Quick, H., Mechael,J., Huber,H. & Arslan,U. (2010). History of international geothermal power plants and geothermal projects in Germany. *Proceedings World Geothermal Congress 2010 Bali, Indonesia, 25-29 April 2010*. Retrieved from https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0605.pdf.

[25] Tubei, G. (2019, July). Kenya beats Iceland to be ranked 8th globally in world's largest geothermal Powerhouses. *Business Insider*. Retrieved from https://www.pulselive.co.ke/bi/finance/kenya-ranked-8th-globally-in-worlds-largest- geothermal-powerhouses/442penz Ugochukwu, A.A. (2013). *Geothermal energy resources*. https://www.academia.edu/5358353/GEOTHERMAL_ENERGY_RESOURCES

[26] Micale, V., Trabacchi, C., & Boni, L.(2015). *Using Public Finance to Attract Private Investment in Geothermal: Olkaria III Case Study, Kenya.* https://climatepolicyinitiative.org/publication/using-public-finance-to-attract- private-investment-in-geothermal-olkaria-iii-case-study-kenya/.

