GRC Transactions, Vol. 44, 2020

Energy and Exergy Analysis of Olkaria Domes Field: Well Head and Single Flash Power Plants Comparison

Alvin Kiprono Bett [1*], Saeid Jalilinasrabady[2] , Leonard K Langat[3]

[1] Department of Earth Resources Engineering, Kyushu University, 744 Motooka, Nishiku, Fukuoka 819-0395, Japan

[2] Faculty of Engineering, Kyushu University, 744 Motooka, Nishiku, Fukuoka 819-0395, Japan

[3] Kenya Electricity Generating Company (KenGen)

[*]corresponding. Author: iklaeb@gmail.com

Keywords

exergy, well head, non-condensable gases, exergy destroyed, Olkaria.

ABSTRACT

Kenya is ranked 5th globally in geothermal development. Geothermal exploration started around 1950's in Olkaria and Bogoria. In power plant development, the main parameters applied are power generated and exergy, among others. Well head installation in Olkaria was adopted in 2012 has a total installed capacity of 81 MWe. The well head units in Olkaria are all single flash type. Single flash are the main power plants globally.

In this study exergy analysis and parametric comparison of conventional single flash generating 142 MWe and well head of 7 MWe is presented. The plants are optimized based on maximum power generated, highest efficiencies and lower parasitic loads with the focus on the non-condensable gas removal. The obtained results show that well head and single flash operates in the same trend with different optimization objectives. Well head has the best exergy efficiency at 64% and least exergy destroyed in the separator.

1. Introduction

Geothermal energy is one of the renewable sources of energy emissions (Herbst et al., 2010). Geothermal exploration and forecasting are reported to have started around the 1950's in Olkaria and Bogoria regions which led to the drilling of six exploration wells in Olkaria in 1976 (Omenda, Mangi, Ofwona, & Mwangi, 2020). Total installed geothermal capacity in Kenya in

2019 was 865 MWe contributing to about 29% of total installed electricity capacity and about 47% of electricity consumption (Omenda et al., 2020). Kenya's geothermal capacity growth during the period 2015 to 2019 has been one of the fastest in the world (Huttrer, Rica, & Salvador, 2020).

In power plant development, the main parameters that have been applied are power generated and efficiency exergy.

Well head installation in Olkaria was adopted in 2012 (Saitet & Kwambai, 2015). Well head technology is a temporary plant that generates reliable and climate-friendly energy and takes a shorter time to construct unlike conventional power plants (Rojas, 2015). Well head units are suitable for remote and un-developed areas or for production wells awaiting to be connected to the main power plant. Exergy analysis is the tool that is yet to be fully adopted in power plant design and economics. In Olkaria the exergy part that have been carried out is on Olkaria I SF and Olkaria II (Kwambai, 2005, 2010).

The paper presents energy and exergy analysis of well head unit and convectional single flash power plants in the biggest geothermal field in Kenya. The results are to compare the latest technology for small power plants that have been presented as fast revenue returns using the energy and exergy concept (Saitet & Kwambai, 2015). The states and components that tend to predict highest destruction are suggested for improvement in the next phases of power plant development with objective functions of improved utilization efficiency (Saeid, Jalilinasrabady Ryuichi, Itoi Hiroki, Gotoh Hiroyuki, 2010). In geothermal power plants (GPP) there is a composition of non-condensable gases (NCG) that affect the thermodynamic efficacy of the system. To optimize the efficiency the NCG should be removed using sizeable removal systems and is part of the parasitic loads and occupies part of plant cost (Özcan & Gökçen, 2010). NCGs (they include CO_2, H_2S, NH_3, N_2, CH_4) percentages vary from plant to plant between 0.2% and 25% by weight of steam (Özcan & Gökçen, 2010). As the NCG content increases in the geothermal steam, its removal should be part of the plant system and contributes to the parasitic loads. In (Özcan & Gökçen, 2010). NCG should be part of the analysis since it decreases the network of the power plant and come with extra investment, and operation and plant maintenance cost.

2. System Description, Energy and Exergy Analysis

Typical SF GPP consists of reservoir, production well, separator, turbine, condenser, NCG removal system, cooling tower and reinjection well. The simple layout for the analysis is shown in *Figure 1*. The plants are modelled in EES software and energy and exergy analysis performed for conventional SF and well head in Olkaria geothermal field in Kenya, both operated by KenGen.

Olkaria IV power plant has two condensing steam turbines generating 140 MWe of electricity and started commercial operations in September 2014 (Langat, 2015; Rop, 2017) and located in Domes field which is one of the seven fields in Olkaria complex (Langat, 2015). Each turbine has a steam inlet pressure of 5.2 bar gauge, which is arrived at from the high-pressure separation at 11.8 bar (Langat, 2015). This pressure let down is consideration for the optimization part of SF Olkaria IV units by varying the turbine inlet pressure.

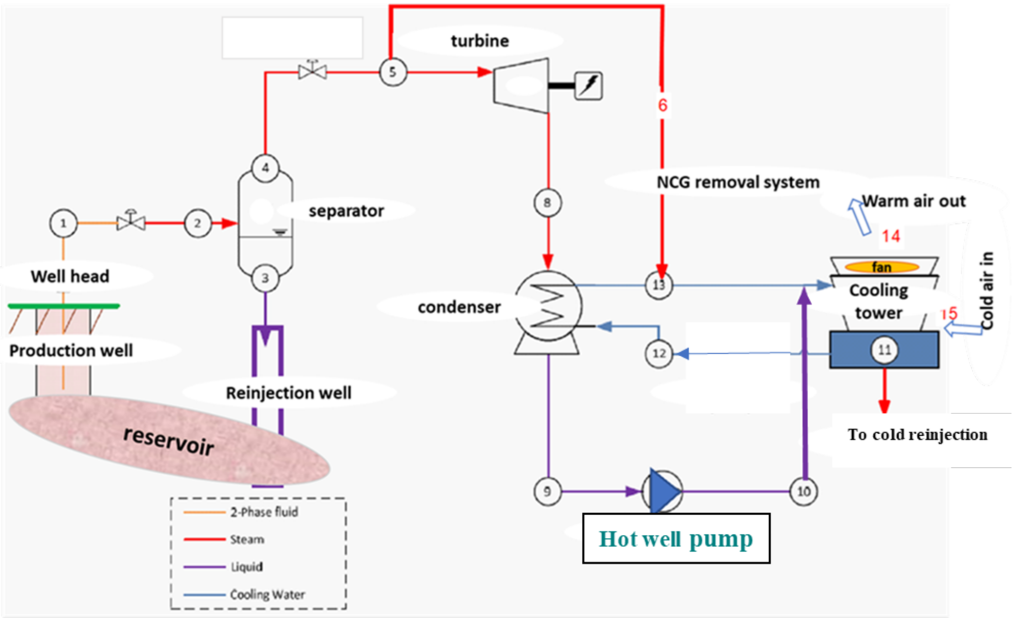

Figure 1: Schematic diagram of the SF GPP to be considered for both the well head 914 and Olkaria IV power plants in Olkaria (modified from *(Langat, 2015)*).

Olkaria Domes is one of the high enthalpy reservoir fields to have been reported in Olkaria and borders on another geothermal prospect (Longonot) in Kenya geothermal fields (Rop, 2017). The down-hole temperature profiles indicate a high temperature field between 200°C and 360°C as shown in *Figure 2.*

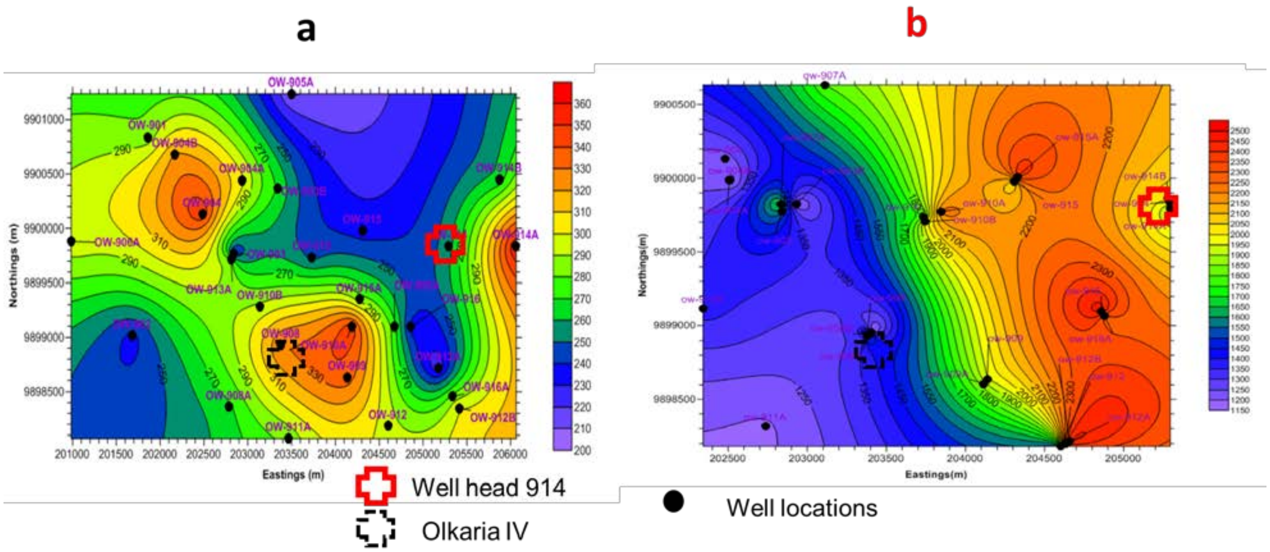

Figure 2: Olkaria domes field (a) enthalpy contour maps in Olkaria Domes field and (b) Temperature contour maps in Olkaria Domes wells at -500 m.a.s with the wells and the power plants locations (modified from *(Rop, 2017)*).

2.1 Energy and Exergy Analysis

The general steady state energy balance equation for any components are as shown in equations 1 and 2 (Bombarda et al., 2018; El-Emam & Dincer, 2013; Jalilinasrabady, Palsson, Saevarsdottir, Itoi, & Valdimarsson, 2013).

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

$$\dot{Q} - \dot{W} + \sum \dot{m}_{in} h_{in} - \sum \dot{m}_{out} h_{out} = 0 \tag{2}$$

Equation 3 shows the general expression for specific exergy involving environmental thermal interaction (Caliskan, 2015; DiPippo, 2015; Jalilinasrabady, Saeid Ryuichi, Itoi Hiroki, Gotoh Rie, 2011; Koroneos, Polyzakis, Xydis, Stylos, & Nanaki, 2017).

$$e = h - h_0 - T_0(s - s_0) \tag{3}$$

The energy efficiency of the system is calculated as follows:

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} \tag{4}$$

$$\Delta \dot{E}x = \dot{E}x_{in} - \dot{E}x_{out} = \dot{E}_Q + \sum_{i=1}^{k} \dot{m}_i e_i - \dot{E}_W - \sum_{j=1}^{k} \dot{m}_j e_j \tag{5}$$

Exergetic power input and output equations are given by equations 6 and 7 respectively for each component (DiPippo, 2015):

$$\dot{E}x_{in} = \dot{E}_Q + \sum_{i=1}^{k} \dot{m}_i e_i \tag{6}$$

$$\dot{E}x_{out} = \dot{E}_W + \sum_{j=1}^{k} \dot{m}_j e_j \tag{7}$$

where i is for all incoming streams and j for all outgoing streams with the exergy loss, $\Delta \dot{E}$ is always positive (DiPippo, 2015). Exergy losses are mainly subdivided into each component in the thermodynamic process. For a control volume the general exergy balance is as seen in Figure 5 where the total exergy output is always less than the total exergy input into the system (Jalilinasrabady, Itoi, Valdimarsson, Saevarsdottir, & Fujii, 2012). Exergy destruction for each component is calculated using equation 5 (El-Emam & Dincer, 2013).

Exergy losses/destruction represent actual losses of the potential that exists to generate the desired product from the given driving input and exergetic efficiencies measure how nearly the system approaches the ideal or theoretical upper limit (Dincer & Rosen, 2012).

Each component has exergy destruction rate expressed as exergy destruction ratio to the total exergy destruction of the whole system as shown in equation 8 (Saeid, Jalilinasrabady Ryuichi, Itoi Hiroki, Gotoh Hiroyuki, 2010):

$$\dot{Ex}_{ratio} = \frac{\Delta\dot{E}}{\sum\Delta\dot{E}} \tag{8}$$

Utilization/exergetic (η_u) and second utilization (η_{u2}) efficiencies are calculated as:

$$\eta_u = \frac{\dot{W}_{net}}{\dot{Ex}_{in}} \tag{9}$$

$$\eta_{u2} = \frac{\dot{W}_{net}}{\dot{Ex}_{available}} \tag{10}$$

2.2 Main Assumptions

In the analysis the following assumptions were applied in this paper:

- ✓ Same component types.
- ✓ Cooling tower height 30m.
- ✓ Pressure and thermal losses considered not considered.
- ✓ Constant well head pressures and flow rates.
- ✓ Efficiencies:
    - o turbine of 85%,
    - o pump 75%,
    - o generator 98%,
    - o mechanical 99%.
- ✓ Geothermal brine is considered to have thermophysical properties of IAPWS (Mohammadzadeh, Jalilinasrabady, & Fujii, 2017).

3. Results and Discussion

The results of the optimized power plants are presented for parametric analysis. *Table 1* shows summary of the energy and exergy analysis comparison of the power plants. The exergy destroyed in the separator is low for SF and approximately nil for the well head. The well head power plant utilizes higher pressure of 1300 kPa unlike SF at 600 kPa. The enthalpy of the steam exiting the turbine increases with pressure.

Table 1: Summary of the exergy analysis

Component	**Exergey destroyed (%)**	
	Olkaria IV SF	Well head 914
Separator	6.8	0
Turbine and generator	35.6	43.9
Gas removal system	3.02	2.8
Condenser	19.6	19.8
Cooling Tower	34.8	33.4
Summation of exergy destroyed (kW)	**69,033**	**5,229**

Network (kWe)	**142,783**	**7,122**
	Efficiencies (%)	
Thermal	15.9	13.7
Second utilization	54.9	48.5
Exergetic	59.6	64.5

In plant analysis the key parameters that are usually of interest are the power generated, how efficient the system is and the economic translation of the investment. The two types of power plants are presented in order to compare the important power plant indicators.

Power generated in geothermal and binary power plants are in most cases a function of turbine pressure. *Figure 3* shows the relationship between the turbine pressure and gross and net turbine work generated. The power generated increases gradually as pressure increases. Higher pressures improve the quality of the steam at turbine outlet reducing the effects of turbine blades corrosion.

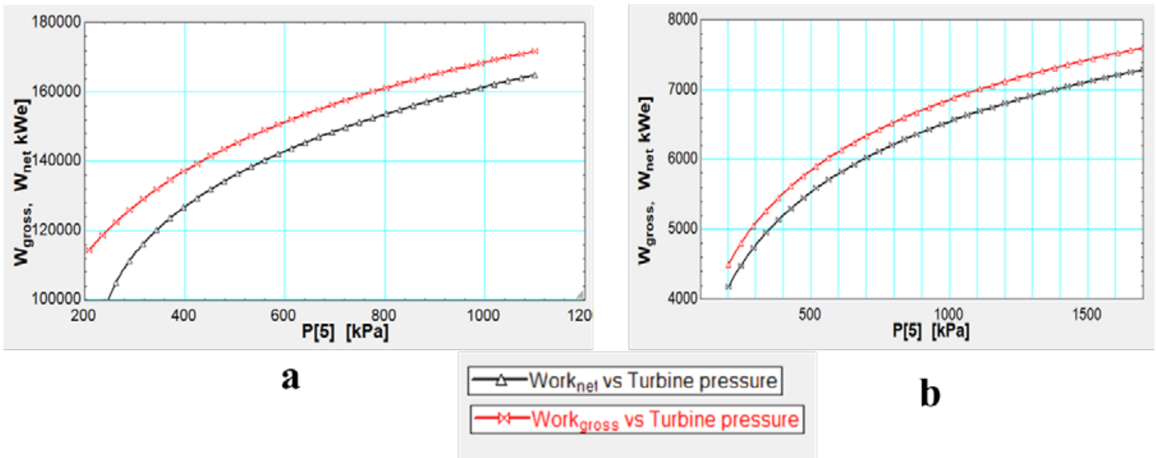

Figure 3: Effect of the turbine pressure on the power generated for the (a) SF and (b) well head power plants.

The optimized power plants were arrived after considering the highest efficiencies (thermal, second efficiency and exergetic efficiencies) as in *Figure 4.*

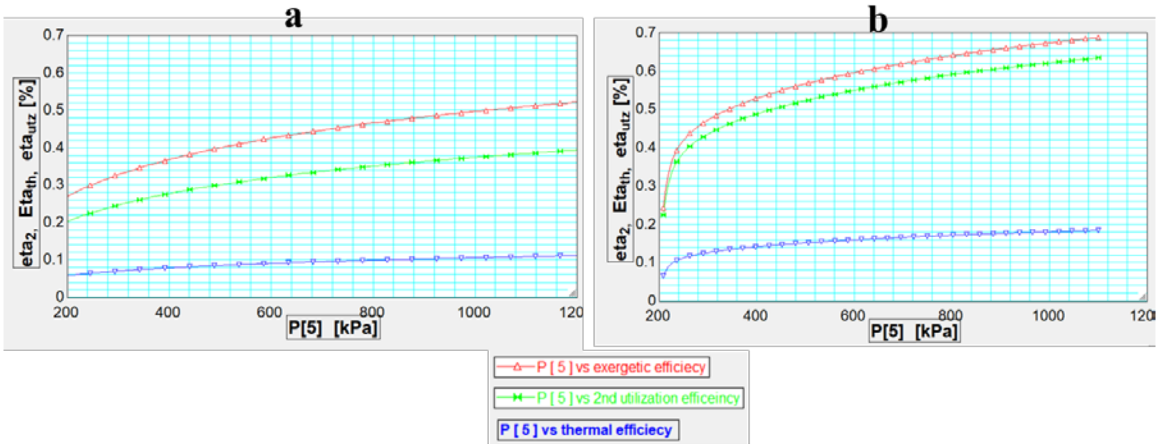

Figure 4: Efficiency optimization objective function (a) SF and (b) well head power plants, respectively.

Minimizing the parasitic loads is key and should be included in exergy and design geothermal power plants especially when the NCG content is high. In the case of Olkaria field NCG is approximately 0.6 to 1.8%, but for the analysis in this paper 0.25% (as per Olkaria I (Kwambai, 2005)) of NCG was considered and the NCG removal unit takes 1620 kWe for SF and 54.86 kWe for well head power plants, respectively. From *Figure 5* the best turbine pressure with the lowest work done on NCG unit is between 500-600 kPa for SF.

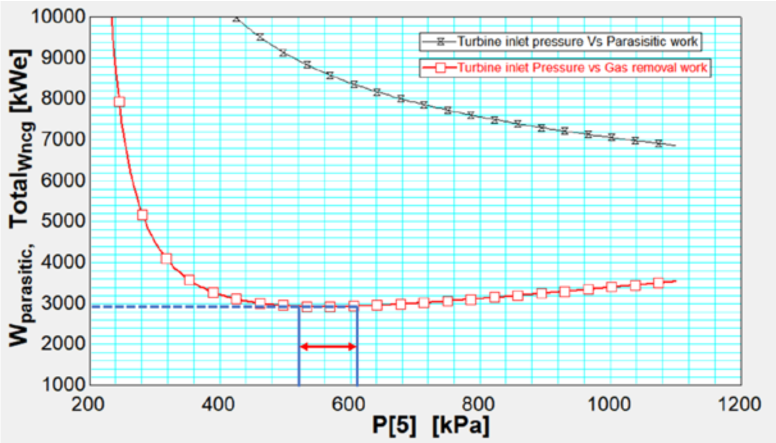

Figure 5: Optimization of SF power plant showing the range of turbine pressure that consume the least power for gas extraction that will also reduce the parasitic loads.

In the gas extraction facility, the optimum intercooler and condenser pressures were considered for the least work for NCG and maximum power generated. In both the plants (a and b) the condenser pressure was suggested to be 8.5 kPa as in *Figure 6.*

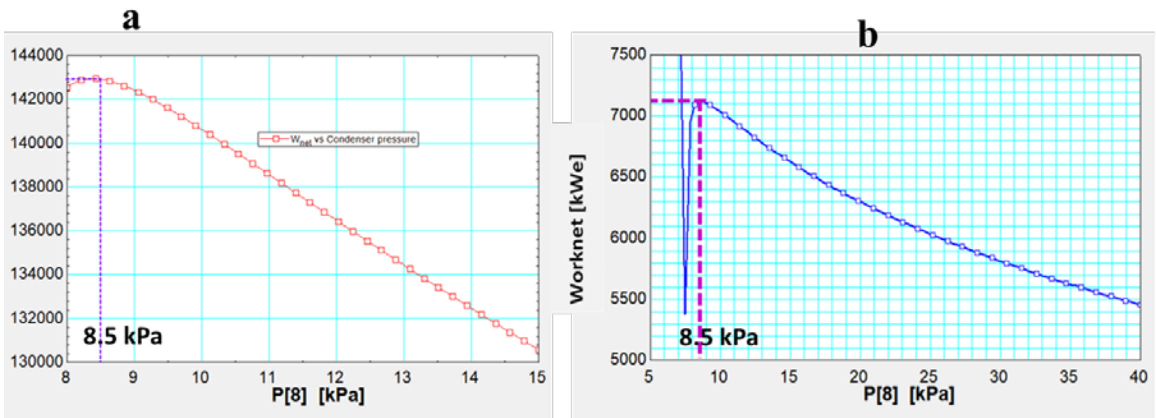

Figure 6: Optimum condenser pressure of 8.5 kPa for maximum work net.

The NCG removal system is an integral part of geothermal power plants. As much as the geothermal is renewable, NCG is treated as the only part to produce CO_2 for flashing power plants.

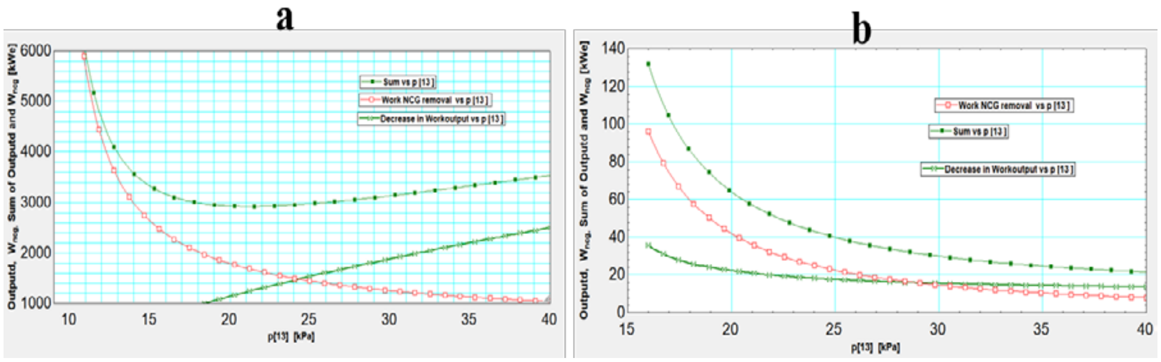

Figure 7: Effect of NCG removal on motive steam power reduction by varying the intercooler condenser P_{13}.

The power reduction is a result of diverting steam/ motive steam to the gas ejection system for NCG removal. *Figure 7* shows the optimum intercooler pressure is higher than the condenser pressure for both scenarios considered.

4. Conclusions

Exergy analysis of the convectional SF power plant and well head power plants is presented. The exergy and optimization are similar. The advantage of well head is early revenue generation and maximum power output at well head.

The main conclusions from the analysis of the two single flash units are:

- Exergy is important tool in power plant design and analysis.
- Well head optimization is possible for the highest possible pressures since the plant relies only on one well. Independent well will not be affected by other well head pressures within the field, unlike for the conventional SF plant whose steam pipeline is interconnected to several wells.
- The highest exergy destruction is on the turbine for the two geothermal power plants.
- NCG removal system contributes to the parasitic loads with exergy analysis applied. From the results, the least exergy destroyed is in the gas removal system with the likelihood to increase depending on the amount of NCG in the geothermal steam.

Acknowledgement

The authors wish to express sincere gratitude to KenGen for the data from Olkaria geothermal field which has been used for this paper.

REFERENCES

Bombarda, P., Bowen, R., Bowen, R., P, B. T., S, H., S, T., … Jonshagen, K. (2018). Thermoeconomic comparison between pure and mixture working fluids of organic Rankine cycles (ORCs) for low temperature waste heat recovery. *Energy Conversion and Management*, *8*(April), 25–29. https://doi.org/10.1016/j.joei.2014.03.010

Caliskan, H. (2015). Novel approaches to exergy and economy based enhanced environmental analyses for energy systems. *Energy Conversion and Management*, *89*, 156–161. https://doi.org/10.1016/j.enconman.2014.09.067

Dincer, I., & Rosen, M. A. (2012). *Exergy: Energy, Environment and Sustainable Development*. Elsevier.

DiPippo, R. (2015). Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact: Fourth Edition. In *Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact: Fourth Edition*. https://doi.org/10.1016/C2014-0-02885-7

El-Emam, R. S., & Dincer, I. (2013). Exergy and exergoeconomic analyses and optimization of geothermal organic Rankine cycle. *Applied Thermal Engineering*, *59*(1–2), 435–444. https://doi.org/10.1016/j.applthermaleng.2013.06.005

Herbst, G., Bartenstein, B., Weiner, H. J., Kuhn, D., Wiemer, H., & Kuhn, D. (2010). Thermodynamic Evaluations for Efficient Energy Conversion of Geothermal Heat. *Power*, (April), 25–29.

Huttrer, G. W., Rica, C., & Salvador, E. (2020). Geothermal Power Generation in the World 2015-2020 Update Report. *World Geothermal Congress 2020*, 1–17.

Jalilinasrabady, Saeid Ryuichi, Itoi Hiroki, Gotoh Rie, Y. (2011). Exergetic Optimization of Proposed, Takigami Binary Geothermal Power Plant, Oita, Japan. *GRC Transactions*.

Jalilinasrabady, S., Itoi, R., Valdimarsson, P., Saevarsdottir, G., & Fujii, H. (2012). Flash cycle optimization of Sabalan geothermal power plant employing exergy concept. *Geothermics*, *43*, 75–82. https://doi.org/10.1016/j.geothermics.2012.02.003

Jalilinasrabady, S., Palsson, H., Saevarsdottir, G., Itoi, R., & Valdimarsson, P. (2013). Experimental and CFD simulation of heat efficiency improvement ingeothermal spas. *Energy*, *56*, 124–134. https://doi.org/10.1016/j.energy.2013.04.057

Koroneos, C., Polyzakis, A., Xydis, G., Stylos, N., & Nanaki, E. (2017). Exergy analysis for a proposed binary geothermal power plant in Nisyros Island, Greece. *Geothermics*, *70*(June), 38–46. https://doi.org/10.1016/j.geothermics.2017.06.004

Kwambai, C. B. (2005). Exergy Analysis of Olkaria I Power Plant , Kenya. *UNU Geothermal Training Programme.*, *Reports 5.*(5), 1–37.

Kwambai, C. B. (2010). *Exergy Analysis for Olkaria I Geothermal Power Plant, Kenya*. (5), 25–29.

Langat, R. K. (2015). *TOPPING UNIT AT OLKARIA IV GEOTHERMAL POWER PLANT ,*. (18).

Mohammadzadeh, S., Jalilinasrabady, S., & Fujii, H. (2017). Geothermics Thermo-economic evaluation of various bottoming ORCs for geothermal power plant , determination of optimum cycle for Sabalan power plant exhaust. *Geothermics*, *70*(June), 181–191. https://doi.org/10.1016/j.geothermics.2017.06.007

Omenda, P., Mangi, P., Ofwona, C., & Mwangi, M. (2020). *Country Update Report for Kenya 2015-2019*. (4).

Özcan, N. Y., & Gökçen, G. (2010). Performance Analysis of Single-Flash Geothermal Power Plants : Gas Removal Systems. *Proceedings World Geothermal Congress 2010*, (April), 25–29.

Rojas, F. (2015). Geothermal wellhead power plants are proving to be a faster way to develop new energy projects in Kenya. Retrieved from https://www.thinkgeoenergy.com/wellhead-geothermal-plants-are-a-key-pillar-of-kenyas-renewable-success/

Rop, E. (2017). *Results of Well Production Test for Olkaria Domes Field , Olkaria Kenya*. 21–23.

Saeid, Jalilinasrabady Ryuichi, Itoi Hiroki, Gotoh Hiroyuki, K. (2010). Energy and Exergy Analysis of Takigami Geothermal Power Plant, Oita, Japan. *GRC Transactions*, *34*.

Saitet, D., & Kwambai, C. (2015). Wellhead Generating Plants : KenGen Experience. *World Geothermal Congress 2015*, (April), 1–6.