

Exergy Analysis of Olkaria IAU & Olkaria II Power Plants

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Keywords: Geothermal, Exergy analysis, Second law, Olkaria, Power Plant

ABSTRACT

The processes of electricity production from geothermal resources at Olkaria IAU and Olkaria II Power Plants in Kenya were analysed using exergy analysis method. The objectives of the analysis were to determine the overall second law (Exergy) efficiency of the power plants, pinpoint the locations and quantities of exergy losses and wastes and suggest ways to address them and improve the overall performance of the power plants. Both Olkaria IAU and Olkaria II power plants share steam supply system and have a combined installed capacity of 341 MWe from 6 generators

In the analysis, the power plants were simplified into sub-systems, each with distinct exergy inflows and outflows and approximated into steady state flow. The theory and mathematical formulations were adapted from the book 'Exergy methods of thermal plant analysis' and several online internet publications. Mathematical models for exergy flows were developed and analysed using the Engineering Equation Solver (EES) software to perform the calculations. The degree of thermodynamic perfection (measure of performance) was based on the rational efficiency concept. Few assumptions and simplifications were made.

The results showed that Olkaria IAU Power Plant has an overall second law efficiency of 45% and an overall 1st law efficiency of 15% while Olkaria II power plant has an overall second law efficiency of 42% and an overall 1st law efficiency of 14%. It was concluded that the lower performance of Olkaria II is likely as a result of the aged equipment and recommended that a redevelopment of the plant may be necessary.

1. INTRODUCTION

The article 'Energy, Status Report' ([World Energy Forum](#)) indicate that the world's energy demands have been increasing rapidly over the past few years as a result of increase in the world's population and economic growth. The article reports that the world energy consumption quadrupled between 1950 and 1992. Despite the high growth in energy demands, traditional world energy resources such as fossil fuels and hydro resources have been declining ([World Energy Council](#)). In addition, the links between the use of energy resources and impacts on the environment have become clearer over the recent years. The increase in energy demands, decline in energy resources and the link between energy utilization and environmental impacts has resulted in calls for sustainable approach to the development and management of the earth's energy resources (Rosen & Dincer, 2001). With finite energy resources and large (and increasing) energy demands, it becomes increasingly important to understand the mechanisms which degrade the quality of energy and energy resources and to develop systematic approaches to improving the systems (Gong & Wall, 1997). Systems and processes that degrade the quality of energy resources can only be identified through a detailed analysis of the whole system.

Exergy analysis has been cited by many researchers and practicing engineers to be a powerful tool to identify and quantify energy degrading processes since it enables the types, locations and quantities of energy losses to be evaluated. Exergy analysis method has been used as an analytical method in many optimization studies of energy systems. The method uses the principles of the First Law of Thermodynamics (conservation of energy) together with the Second Law of Thermodynamics, for the analysis, design and improvement of energy systems. Exergy is a concept that clearly shows the usefulness of energy and shows what is consumed in the course of energy transfer and conversions. In this report, the exergy analysis study of Olkaria IAU and Olkaria II geothermal power plants in Kenya is presented. The study was carried out to determine the overall second law efficiency for the power plants, identify the locations and processes where exergy is wasted, lost or destroyed and suggest steps that can be taken to reduce the exergy losses and wastes.

Olkaria IAU & Olkaria II power plants are located in the Olkaria geothermal area of Kenya, about 120 km North-West of the capital city, Nairobi (Figure 1). The plants have a total of six condensing steam turbine generating units with a total installed capacity of 341 MWe. Olkaria II power plant has three units installed between 2003 and 2010 with each unit having a capacity of 35MWe. Olkaria IAU has 3 units installed between 2014 and 2022, with the first two units having installed capacity of 140MW and the third unit with installed capacity of 86MW. The plants receive steam from two sectors of Olkaria field – Olkaria east and Olkaria Northeast sectors. The Steamfields are interconnected to share the steam gathering system. Whereas Olkaria II Steamfield operate at about 6bar separation pressures, that of Olkaria IAU operate at above 10 bar a separation pressures.

Performance audit of geothermal power plants is commonly based on evaluating the specific steam consumption (SSC) index for each turbine, plant availability, load factors and utilization factors which give indication on the plant status but fail to quantify or locate where energy losses have been incurred. An *exergy analysis* will overcome these shortcomings in that it will enable the locations, types and true magnitudes of wastes and losses to be determined and can give a guide to areas of potential improvement.



Figure 1 Geothermal map of Kenya showing location of Olkaria and other geothermal prospects along the rift valley

2. THEORETICAL BACKGROUND

2.1 The concept of exergy

In the real world, states of complete equilibrium are hardly attainable. Any system that is at a temperature, pressure or chemical composition above or below that of its surrounding is not in equilibrium with its surroundings and has a potential to do work. This work potential is referred to as *the exergy of the system*. When the properties of a system are equal to those of its environment, the exergy of the system is zero. The state at which a system and its surroundings are in equilibrium is known as the dead state. Exergy is a measure of how a system deviates from a state of equilibrium with its environment and is therefore a property of the system and its surroundings.

Exergy is another word used to describe available energy or the measure of energy available to do work above a heat sink (Rosen & Dincer, 2001). Exergy presents the most natural and convenient universal standard of energy quality by using environmental parameters as the reference states and is a common standard for examining exploitability of a reservoir. The exergy of a resource gives an indication of how much work can be done by the resource within a given environment. The exergy concept explicitly shows the usefulness (quality) of energy and matter in addition to what is consumed in the course of energy transfer or conversion steps. When exergy loses its quality, it results in exergy destroyed. Other terms commonly used to refer to exergy include: *available energy, availability and essergy*.

Kotas (1995) states that 'the exergy of a steady stream of matter is equal to the maximum amount of work obtainable when the stream is brought from its initial state to the dead state by processes during which the stream may interact only with the environment'. Thus, the exergy of a stream is a property of the state of the stream and the state of the environment. Once a system is in equilibrium with its surroundings, it is not possible to use the energy within the system to produce work. At this point, the exergy of the system has been completely destroyed.

Exergy like energy exists in kinetic, potential, chemical and physical exergy forms. The kinetic and potential exergies are high grade exergy forms associated with ordered forms of matter and fully convertible to useful work. Chemical and physical exergies on the other hand are low grade forms associated with disordered forms of matter and cannot be easily converted to work.

In this analysis, the whole system was simplified into subsystems, each with distinct exergy inflows and outflows. The system and subsystems were simplified to control volumes, and the flow processes approximated to steady or quasi-steady state flow processes. The primary exergy input was selected to be the exergy of the two-phase fluid from the wells while the desired exergy output was the net electrical energy delivered to the transmission grid. The performance criteria adopted was to compare the desired output exergy to the necessary input exergy or rational efficiency. The difference between the total input exergy and the desired exergy constitute the exergy wasted or destroyed.

The study started with a literature review to get in-depth understanding of the theory and concept of exergy and the methods of analysis and what other researchers have done in the same field. Relevant data were obtained from the plant operation logs, operation and maintenance manuals, plant reports and design values. Schematic flow diagrams were constructed for the systems and the subsystems using Microsoft Visio and state points were assigned some reference numbers. Mathematical equations were developed for each process and modelled in simple excel spreadsheets. By inputting the actual operation and/or design parameters, the exergy balance and exergy performance evaluation was performed. The reference environment was defined as being the ambient conditions at Olkaria geothermal area with mean ambient temperature T_0 of 20°C and Pressure P_0 of 0.86 bar-a. The limitations and simplifying assumptions were stated and finally suggestions for improvement were made.

Many studies applying exergy methods in the analysis of geothermal power plants and other systems have been conducted and published in recent years. All the studies illustrate the importance of exergy analysis in evaluating performances of geothermal plants and identifying exergy wastes. In majority of the studies, the biggest exergy losses are located in the turbines, condensers, gas extraction systems and pipelines/accessories.

2.2 Exergy and energy

Energy is defined as motion or the ability to cause motion and is always conserved in a process (obeys the 1st law of thermodynamics). On the other hand, exergy is defined as work or the ability to cause work and is always *conserved in a reversible process*, but is *always consumed in an irreversible process* (obeys the 2nd law of thermodynamics). While energy is a measure of *quantity*, exergy is a measure of *quantity and quality*. Exergy like energy can be transported across the boundary of a system. For each energy transfer, there is a corresponding exergy transfer.

The First Law of Thermodynamics states that *energy can neither be created nor destroyed*. Energy is available in many different forms and may be converted between these forms. The Second Law of Thermodynamics states that *conversions of energy are possible only if the total entropy increases*. By introducing exergy, energy and entropy may be treated simultaneously. The quality of energy is described by the concept of entropy. High entropy is equal to low quality of energy. Different energy forms have different qualities, indicating to what extent they are theoretically convertible to mechanical work. This limitation, a law of nature, implies that the total energy quality always decreases in each conversion (the Second Law of Thermodynamics).

2.3 Exergy analysis (exergy balance)

Figure 2 illustrates exergy flow in through a system or process. One of the main uses of the concept of exergy is an exergy balance in the analysis of thermal systems. An exergy balance (exergy analysis) can be looked at as a statement of the law of degradation energy (Kotas, 1995). An exergy analysis is a mathematical tool for evaluation of exergy flows through a system and has been cited as a powerful tool for optimization studies and as a primary tool in addressing the impact of energy resource utilisation on environment.

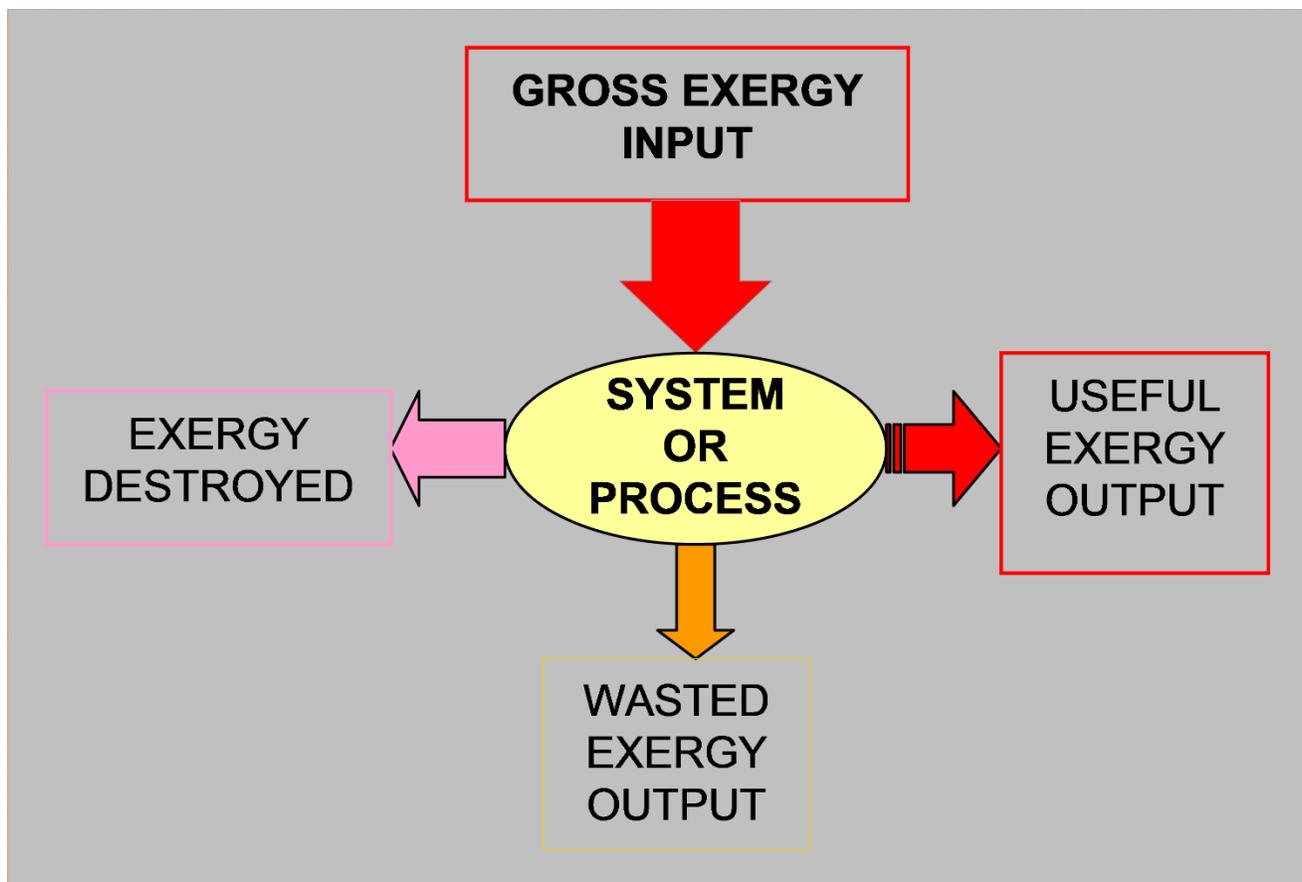


Figure 2 Diagram illustrating exergy flow into and out of a system

A careful evaluation of processes using exergy analysis enables identification of the source of inefficiencies and wastes which leads to improved designs and resultant savings. Exergy analysis is a tool for identifying the types, locations and magnitudes of thermal losses. Identifying and quantifying these losses allows for the evaluation and improvement of the designs of thermodynamic systems. It is an effective method using conservation of mass and conservation of energy principle together with the second law of thermodynamics for design and analysis of energy systems.

Exergy balance methods, commonly known as exergy analysis, can indicate the quantity and quality of heat losses and the locations of energy degradation (quantify and identify causes of energy degradation). Most cases of thermodynamic imperfection cannot be detected

by an energy analysis (Rosen, 2002). Certain processes like throttling, heat transfers, expansion and friction involve no energy losses but they degrade the quality of energy and its ability to do work and therefore involve exergy losses.

2.4 Mathematical expressions of exergy balance

General exergy expressions

For a stream of matter, total exergy flow can be expressed as:

$$E_{total} = E_{KE} + E_{PE} + E_{PH} + E_O \quad (1)$$

Where E_{KE} , E_{PE} , E_{PH} and E_O are respectively the Kinetic exergy, Potential exergy, Physical exergy and Chemical exergy of a system undergoing an exergy flow process.

Both E_{KE} and E_{PE} are associated with high-grade energy and fully convertible to work, while E_{PH} and E_O are low-grade energy where the stream has to undergo physical and chemical processes while interacting with the environment. For this study, only physical exergy shall be considered since the process involves only fixed composition flows (Rosen, 1999). Therefore, exergy will be expressed as equal to the maximum work when the stream of substance is brought from its initial state to the environmental state defined by P_0 and T_0 by physical processes involving only thermal interaction with the environment (Kotas, 1995).

$$E_{total} = E_{PH} = m_i [(h_i - h_0) - T_0 (s_i - s_0)] \quad (2)$$

Where i , 0 , m , h , s and T refer to the state points, the environmental state, the mass flow rates, the fluid enthalpy, the fluid entropy and temperature in °K respectively.

Control volume exergy balance

For a control volume, an exergy balance equation can be expressed as:

$$E_{input} = E_{desired} + E_{waste} + E_{destroyed} \quad (3)$$

Where E_{input} , $E_{desired}$, E_{waste} and $E_{destroyed}$ are respectively the total exergy inflow into the control volume, the total desired exergy output (net work output), the sum of exergy from the system (other than the desired) and the sum of exergy lost in the system as a result of irreversibilities. $E_{destroyed}$ is directly related to entropy generation by the equation:

$$E_{destroyed} = T_0 S \quad (4)$$

Criteria of performance

The performance criteria of exergy systems depend on exergy transfer rates in and out of control volumes. Kotas (1995) categorized exergy transfers as those that represent the *desired output of the process* and those which represent the *necessary input*. Exergy inputs and outputs may be work, exergy associated with heat transfer, exergy associated with the flow of matter in or out of a control region or *change of exergy of a stream of matter passing through a control region such as a throttle valve or a heat exchanger*.

The commonly used measure of performance of a system in terms of exergy is the exergy efficiency which is a measure of the performance of a system relative to the maximum theoretical performance of the system. There are three kinds of exergy efficiency terms often used namely, simple, rational and efficiency with transiting exergy. *Simple efficiency* is defined as a ratio of the sum of exergy outputs to the sum of exergy inputs. *Rational efficiency* is defined as sum of desired exergy outputs to the sum of the necessary exergy inputs. *Efficiency with transiting exergy* is ratio of exergy outputs minus the unused exergy outputs to the total exergy input. *Rational analysis concept* will be used for this study since it is the most appropriate measure of performance.

In equation, the rational exergy efficiency is expressed as:

$$\eta_e = \frac{E_{desired}}{E_{input}} \quad (5)$$

$$E_{input} = E_{output} + E_{destroyed} \quad (6)$$

$$E_{output} = E_{desired} + E_{waste} \quad (7)$$

Where $E_{desired}$, $E_{destroyed}$ and E_{waste} are the sum of desired exergy outputs (net positive work by the system), Exergy lost in the system as a result of irreversibilities and Exergy exiting the system which still has capacity to do work (wasted exergy).

2.6 Conceptual framework of exergy analysis

This study is based on the concept that for a system that undergoes a process under steady or quasi-steady conditions, the exergetic efficiency (second law efficiency, effectiveness or rational efficiency) is a valid measure of the performance of the system from a thermodynamic point of view. Thus, a physical exergy analysis of a geothermal plant used in conjunction with an energy analysis enables the locations, types and true magnitudes of wastes and losses to be determined. More revealing insights can be made if the analysis is conducted using varying reference environments and compared using the same reference environment.

2.7 Reference environment

Exergy is evaluated with respect to a reference-environment model. The state of the reference environment is specified by its temperature, pressure and chemical composition. The results are relative to the specified reference environment, which in most applications is modelled after the actual local environment.

The environment is assumed to be a very large simple compressible system modelled as a thermal reservoir with a uniform and constant temperature T_0 and pressure P_0 . The environment must be a large reservoir so that its intensive properties are not significantly changed by the processes taking place. For practical analysis, the earth's atmosphere, the earth's crust, the ocean or large rivers or lakes are often considered as environments although they are not absolutely uniform and their properties may not be constant.

A global standard environment can be defined in terms of standard atmospheric conditions at sea level and a universal chemical composition. Since temperature conditions and air pressure vary from place to place, it is necessary to introduce local standards. The more a system deviates from its environment, the more exergy it carries. For this analysis, the reference environment will be the local environment at Olkaria geothermal area of Kenya, at an altitude of 1900 meters above sea level. The mean ambient temperature T_0 is 20°C and atmospheric pressure P_0 is 0.86 bar-a. The standard international air composition modelled by Dincer and Cengel (2001) will be assumed.

3 EXERGY ANALYSIS OF OLKARIA IAU & II POWER PLANTS

3.1 Introduction

In all geothermal power plants, a stream of geothermal fluid is brought to the surface with a pressure and temperature which exceeds that of the atmosphere and therefore has the ability to do work (exergy). The fluid is passed through a series of processes from which work is extracted and heat is exchanged between the fluid and its surrounding. Finally, the fluid is discharged into the surrounding which is in a state that is influenced by the prevailing ambient conditions. A geothermal fluid does not experience a cycle in real but rather a series of processes from an initial state to a final state.

For this analysis, the primary exergy input is the total exergy of the two-phase fluid extracted from the connected production wells with the reference environment being the mean ambient conditions at the power plant. The overall desired exergy output is the net electrical energy produced. The fluid from the wells undergoes series of processes from fluid separation to steam cooling (condensation) during which processes some useful work is extracted. With reference to the definitions of exergy, the exergy for Olkaria IAU and II power plants is the maximum possible amount of work that can be extracted from the geothermal fluids leaving the wells with reference to the mean ambient conditions at the plant site.

3.2 Overall exergy flow analysis

Process Description

Figure 4 shows a flow diagram for the exergy flow at Olkaria I power plant. The exergy flow processes have been simplified to consist of a well-separation, steam transmission, steam expansion-energy conversion, steam condensing and cooling water systems. A quantity of exergy is received from the production wells connected to the system. The steam is passed through the processes (subsystems) and from each process; some desired exergy output is obtained which goes to the next subsystem. The overall desired output from the plant is the net electrical energy which is fed to the national grid.

Overall exergy balance (For Normal steady state conditions)

The exergy entering the system consist of the exergy of the two-phase flow from the wells and the exergy of air entering the cooling towers. The exergy leaving the system consist of the net electrical energy sent out (W_{net}), exergy of separated brine disposed (E_3), exergy lost through drains, leakages and vents (E_{3a}) and the sum exergies of cooling tower and NCG exhaust and condensate to reinjection (E_9). Some exergy ($I_{Processes}$) is destroyed due to the internal irreversibilities of the processes.

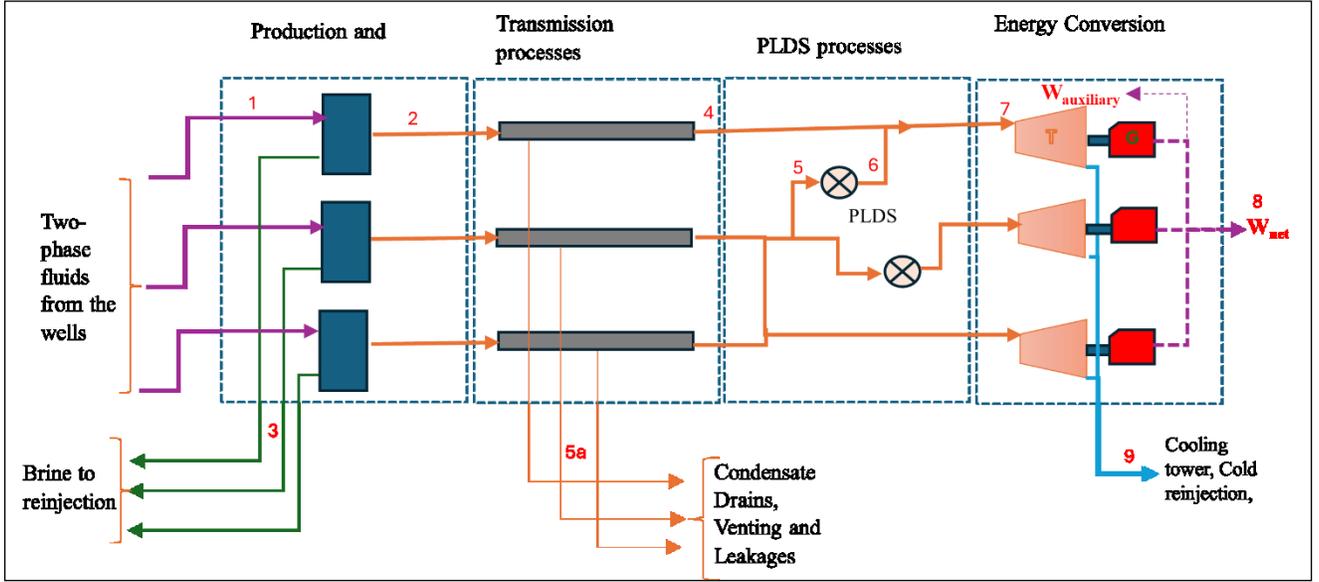


Figure 3 Overall exergy flow diagram for Olkaria IAU & II power plants

With reference to Figure 3 above, the exergy balance can be expressed as below:

$$\sum E_1 = \sum W_{net} + \sum E_3 + \sum E_{5a} + \sum E_9 + \sum I_{destroyed} \quad (8)$$

Where $\sum E_1$ refer to the sum of Exergies entering the system and $\sum W_{net}$, $\sum E_3$, $\sum E_{5a}$ and $\sum E_9$ are the sum of exergies leaving the system and $\sum I_{destroyed}$ is the sum of energy destroyed in the processes.

Performance criteria

The overall objective of this system is to convert the exergy received from the wells into net electrical energy which is the desired output. The rational efficiency will be the ratio of the net electrical energy produced to the total exergy of the geothermal fluids from connected production wells. This is expressed as:

$$\eta_{overall} = \frac{\sum W_{net}}{\sum m_1 \varepsilon_1} \quad (9)$$

3.3 Production and separation processes

System Description

Figure 4 shows a simplified arrangement of the wellhead equipment at Olkaria IAU & Olkaria II power plants. The geothermal wells produce a mixture of steam and brine from a liquid dominated geothermal reservoir ($h_{mean}=2230$ kJ/kg). The fluids reach the wellheads at mean well WHP_{mean} of 7bar a for Olkaria II and 13 bar a for Olkaria IAU.

The two-phase fluids enter and expand through the separators through which the brine is separated from the steam by cyclone action and density difference. The steam leaves the separator and is fed into the steam gathering system while the hot brine is discharged into the wellhead silencer for onward disposal.

Exergy balance equations

The exergy entering the system is the exergy of the two phase fluid discharging from the wells into the separators (1). The exergy leaving the system is the sum of the exergy of the steam (3) and of the separated hot water going to the silencer (2).

The exergy of the steam is the desired output. Some exergy is consumed (destroyed) in the process. These are neglected in this analysis. The exergy balance equation is stated as follows:

$$\sum E_{total} = \sum E_{steam} + \sum E_{water} + \sum I_{separation} \quad (10)$$

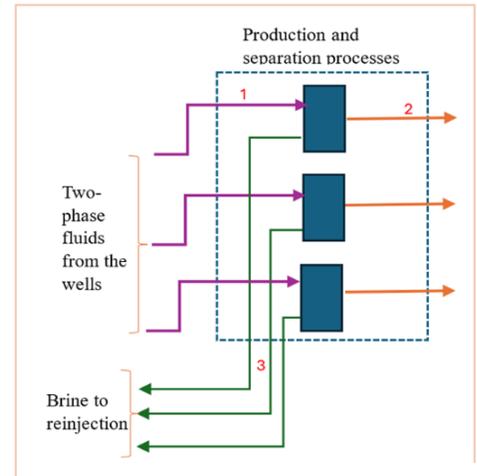


Figure 4 Exergy flow diagram for production and separation process at Olkaria IAU & II power plants

Where; E_{total} , E_{steam} , E_{water} and $I_{separation}$ are the total exergy rates in the two phase flow from the wells, the exergy rate in the separated steam, the exergy rate in the separated brine and the exergy destroyed in the separation processes.

The exergy rate, E is expressed as:

$$E = m\varepsilon = m[(h - h_0) - T_0(s - s_0)] \quad (11)$$

Where m , h and ε are the mass flow rate, fluid enthalpy and specific exergy respectively. T_0 , S_0 and h_0 are the Temperature in Kelvin scale, Entropy and enthalpy at environment conditions.

With reference to Figure 4, the exergy balance equation becomes:

$$\sum m_1 \varepsilon_1 = \sum m_2 \varepsilon_2 + \sum m_3 \varepsilon_3 + \sum I_{separation} \quad (12)$$

Performance criteria

The role of the production and separation system is to receive and separate the two-phase fluids into brine and steam, deliver the steam to the steam gathering and transmission system and direct the brine to reinjection wells. The performance of geothermal separators is a measure of the dryness of the steam leaving the separators which target is 99.99% dryness. In exergy terms for condensing steam plants such as in Olkaria, the desired exergy output from the separation process is the exergy in the steam since the brine is reinjected. In this case, the criteria of performance will be the ratio of the exergy of steam leaving the separators (desired exergy) to the exergy of fluids entering the separators (rational efficiency).

$$\eta_{separation} = \frac{\sum E_3}{\sum E_1} = \frac{\sum m_3 \varepsilon_3}{\sum m_1 \varepsilon_1} \quad (13)$$

3.4 Steam transmission processes

Description

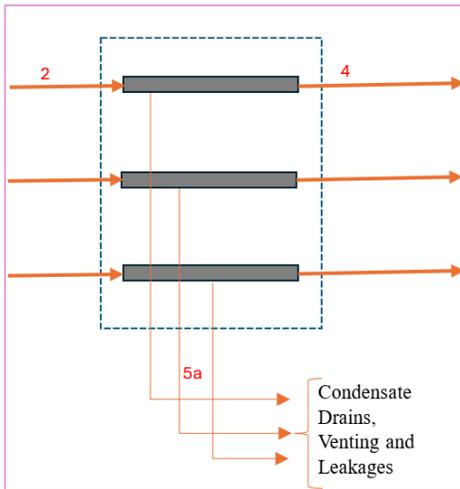


Figure 5 Simplified flow diagram for the steam transmission system

The transmission system arrangement is shown in Figure 5 below. The steam from the connected (3) wells is fed into steam gathering pipes which feed into three steam transmission pipes. Heat and pressure losses in the steam pipelines result in exergy drops which cause condensation of some steam. The condensate is collected in drain pots and disposed via steam traps or orifice plates. Pressure on the main steam pipeline is kept within the desired value by pressure controllers installed on the main steam pipeline. Excess steam is vented out by steam pressure control valves. A moisture separator collects and drains out any residual moisture in the steam before the steam enters the turbines. All the drains and vents discharge to the atmosphere (2d). The steam flow metering devices (one for each unit) is located after the outlets of the moisture separators and is the exit point of this system (4).

Exergy balance equations

The exergy into this system is the sum of the exergy of the steam leaving the separators of the connected wells (3). The exergy leaving the system is the exergy of steam flowing through the flow meters (4). The exergy wasted (leakage and vent out) and exergy exiting by leakages, venting and drains shall be treated as exergy wasted (5a). There is also the exergy destroyed due to irreversibilities in the transmission system ($I_{destroyed}$). The exergy balance for this process can be expressed as follows:

$$\sum E_2 = \sum E_4 + \sum E_{5a} + \sum I_{destroyed} \quad (14)$$

Where E_2 , E_4 , E_{5a} and $I_{destroyed}$ refer to the Exergy of steam entering the process, the exergy of steam leaving to the power plant interface, the exergy of wasted steam and the exergy destroyed due to inherent irreversibilities of the process respectively. With reference to Figure 5, the exergy balance is expressed as:

$$\sum m_2 \varepsilon_2 = \sum m_4 \varepsilon_4 + \sum m_{5a} \varepsilon_{5a} + \sum I_{destroyed} \quad (15)$$

$$\sum I_{destroyed} = + \sum E_{heatloss} + \sum E_{pressuredrop} \quad (16)$$

Performance criteria

The purpose of this system is to transmit the separated steam from the wellhead separators to the turbines as efficiently as possible. The desired exergy output is the exergy of steam entering the flow meters. The criteria of performance will therefore be the ratio of exergy of steam reaching the power plant interface (desired) to the exergy of steam entering the system. For an ideal system, the exergy entering the system will be equal to the exergy leaving the system.

$$\eta_{ts} = \frac{\sum E_4}{\sum E_2} = \frac{\sum m_4 \varepsilon_4}{\sum m_2 \varepsilon_2} \quad (17)$$

5.4 Energy Conversion process

Process Description

The energy conversion system consists of the turbines, the generators, the condensers, the cooling towers, the NCG extraction and auxiliaries and auxiliary power supply system. The exergy input into this system consists of exergy of steam at the power plant entry which include auxiliary steam. The exergy exiting the process includes the net electrical power dispatched to the grid (W_{net}) which is the desired output, the heat rejected into the environment through the cooling towers and the exergy of the condensate injected into the reinjection system. These processes are illustrated in figure 6 below.

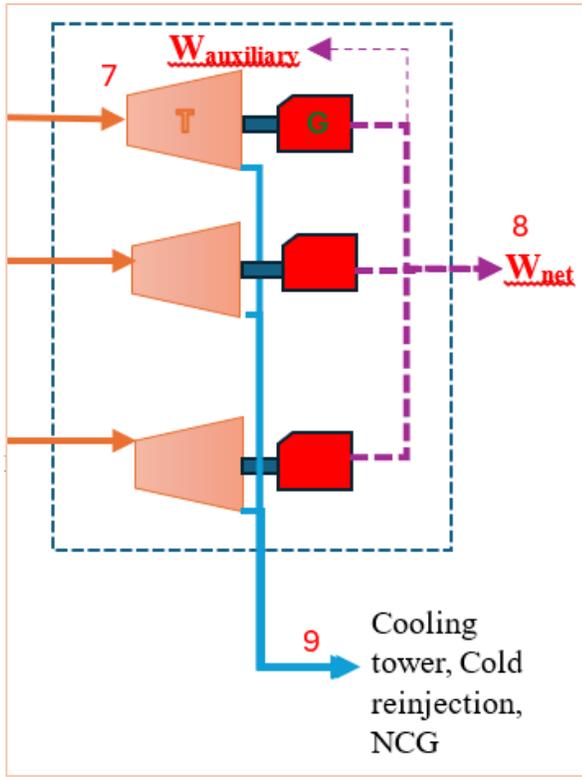


Figure 5 exergy flow diagram of the energy conversion processes

Performance criteria

The objective of this process is to convert as much of the exergy of the steam entering the turbine into electrical energy. The measure of performance will be a ratio of the exergy of the net electricity generated to the exergy of the steam used to produce the work. With reference to Figure 5, the exergy efficiency of the turbine-generator will be given by:

$$\eta_e = \frac{\sum W_{net}}{\sum E_7} \quad (22)$$

4.0 RESULTS AND DISCUSSION OF RESULTS

4.1 Exergy analysis of the production and separation processes

The geothermal wells supplying steam to Olkaria IAU and II power plants produce steam and brine. The wells supplying Olkaria II power plant operate at separation pressures of about 7 bar a while those supplying Olkaria IAU operate at between 12 and 13 bar a. A total of 700 kg/s of steam and 550 kg/s of brine is produced by the wells connected to the power plants. The fluids are separated in the field using

Exergy balance equations

The exergy input is the exergy of steam entering the turbines (7). The exergy output consist of the net electrical energy exported (W_{net}), and the exergy of heat rejected to the atmosphere, NCG ejected and condensate send to reinjection (9). Some exergy is destroyed due to the irreversibilities of the processes involved.

With reference to Figure 7, the exergy balance is written as:

$$\sum E_7 = \sum W_{net} + \sum E_9 + \sum I_{process} \quad (18)$$

Where E_7 , W_{net} , E_9 and $I_{process}$ refer to exergy of steam entering the process, exergy of net electrical energy to the grid, exergy of heat rejected to the environment and exergy destroyed in the conversion processes due to inherent irreversibilities of the processes.

Below are the applicable exergy equations:

$$E_7 = m_7[(h_7 - h_0) - T_0(s_7 - s_0)] \quad (19)$$

$$m_7 = m_9 \quad (20)$$

$$W_{net} = MW_e \quad (21)$$

Where m_s , h_s , s_s , T_0 and h_0 , s_0 are the mass flow of steam entering the turbine, enthalpy and entropy of steam at entry into turbine, reference environment temperature ($^{\circ}\text{K}$) and enthalpy and entropy of the steam at environment condition respectively.

cyclone separators and the steam is fed to the steam gathering system while the brine is channeled to reinjection wells. The total exergy contained in the fluids from the wells is about 670 MW_t out of which 600MW_t is contained in the steam and 70MW_t is contained in the brine. A summary of the exergy flows for the production and separation processes are summarized in Table 1 below. The overall exergy efficiency of the production, separation and transmission processes is 90% which shows that most of the exergy is contained in the steam.

Table 1 Summary results for the exergy analysis of the production and separation processes

Description	Units	Olkaria II	Olkaria IAU 4&5	Olkaria IAU 6	Total
Exergy of brine from production wells	MWt	35	22	12	69
Exergy of steam from production wells	MWt	135	347	116	598
Sum of exergy received from production wells	MWt	170	368	129	667
Overall Efficiency of production and separation processes	%	80	94	90	89

4.2 Exergy analysis of the steam transmission processes

The separators connected to the wells that directly supply steam to Olkaria II power plant operate at separation pressures of 7 bar-a and deliver a total of 174kg/s of steam into the steam gathering system. The separators connected to the wells that supply Olkaria IAU units 4&5 operate at about 13 bar a and deliver about 392 kg/s of steam. The separators connected to Olkaria IAU unit 6 operate at 12 bar a and deliver 116 kg/s. As the steam is transmitted, some is lost to the steam traps, leakages and venting. Ultimately, the steam delivered at the power plants interface is lower than what was received from the wells. The results of the exergy analysis for the steam transmission processes are summarized in Table 2 below. A total of 46 MW_t is lost in the steam transmission processes.

Table 2 Summary results for the exergy analysis of the steam transmission system

Description	Units	Olkaria II	Olkaria IAU 4&5	Olkaria IAU 6	Total
Total exergy of steam received from the separators	MWt	135	347	116	598
Total exergy of steam received at the power plant interface	MWt	125	319	108	552
Total exergy lost in the transmission system	MWt	10	28	9	46
Overall efficiency of the transmission processes	%	93	92	93	92

4.3 Exergy analysis of the pressure let-down processes

The turbines installed at Olkaria II and IAU Units 4&5 plants operate with turbine inlet pressures of 5 bar a. Olkaria II power plant require about 220 kg/s of steam at 5 bar a at interface but the low-pressure wells supply only 165 kg/s. On the other hand, Olkaria IAU Unit 6 receive about 372kg/s at the plant interface at a pressure of 10 bar a. The plant requires 336 kg/s leaving an extra 36 kg/s which is shared with Olkaria II and Olkaria IAU Unit 6 plants. Olkaria II receive 30 kg/s of steam while Unit 6 receive 6 kg/s at pressure of 10 bar a. For Olkaria II and Olkaria IAU Units 4&5 plants to receive steam at 5 bar a, pressure let down station (PLDS) valves have been installed to drop the steam pressure. Results of the exergy analysis for these processes are summarized in Table 3 below. The exergy analysis show that the PLDS result in a loss of 36MW_t of exergy which is dissipated to the environment.

Table 3 Summary results for the exergy analysis of the pressure let-down (PLDS) processes

Description	Units	Olkaria II	Olkaria IAU 4&5	Total
Total exergy of steam at entry of the PLDS	MWt	25	285	310
Total exergy of steam at exit of the PLDS	MWt	22	252	274
Exergy lost through the PLDS valves	MWt	3	33	36
Overall Efficiency of PLDS processes	%	88	88	88

4.3 Exergy analysis of the energy conversion processes at the power plants

The energy conversion processes has been summarized in this analysis to include the turbine - generators, condensers, cooling systems and gas extraction processes. The overall energy conversion efficiency is a comparison of the exergy of steam received at the inlet to the turbines and the net electrical energy dispatched to the grid. The difference between the exergy entering the energy conversion and the net electrical output represent the exergy lost or destroyed in the conversion processes. The results of the exergy analysis for these processes are summarized in Table 4 below.

Table 4 Summary results for the exergy analysis of the energy conversion processes

Description	Units	Olkaria II	Olkaria IAU 4&5	Olkaria IAU 6	Total/mean
Exergy of steam at the entry of the power plants	MWt	146	252	112	510
Exergy of the net electrical energy generated and send out	MWe	93	135	77	305
Exergy lost in the processes	MWt	53	117	35	205
Efficiency of the conversion processes	%	64	54	69	62
Overall efficiency of the power plant	%	55	37	60	50

4.6 Results for overall plant exergy analysis

The summarized results of the exergy analysis for the whole plant are presented in Table 5 below. The results show that the total available exergy from the wells connected to Olkaria IAU & II power plants is 670 MWt. Of this exergy, 70 MWt exergy exist in the brine which is reinjected while 600 MWt is contained in the steam. This demonstrate that most of the exergy from geothermal fluids is carried in the steam phase.

The analysis showed that a total of 46 MWt of the steam exergy is lost in the transmission and 36 MWt exergy is destroyed through the PLDS system. The total exergy received at the turbine inlets is 510 MWt from which 305MWe net is generated and dispatched and 205MW exergy is lost in the process. The lost exergy include the auxiliary power used to run the auxiliary equipment, the exergy of heat rejected through the cooling system and the exergy destroyed by the intrinsic irreversibilities of the system.

The analysis shows that the overall conversion efficiency of the power plants was 62% and an overall utilization efficiency of 50%. Olkaria IAU Unit 6 had the best conversion efficiency while Olkaria IAU Unit 4&5 had the lowest conversion efficiency. The overall performance evaluation is shown in Table 5 below.

Table 5 Summary results for the overall exergy analysis of the plants

Process/System		Total exergy in (MWt)	Desired exergy output (MWt)	Exergy Wasted/Lost (MWt)	Exergy efficiency %
Production and Separation	Olkaria II	170	135	35	80
	Olkaria IAU Units 4&5	368	347	22	94
	Olkaria IA U Units 6	129	116	12	90
Transmission	Olkaria II	135	125	10	93
	Olkaria IAU Units 4&5	347	319	28	92
	Olkaria IA U Units 6	116	108	9	93
PLDS	Olkaria II	25	22	3	88
	Olkaria IAU Units 4&5	285	252	33	88
Conversion	Olkaria II	146	93	53	55
	Olkaria IAU Units 4&5	252	135	117	37
	Olkaria IA U Units 6	112	77	35	60
Overall		55	37	60	50

4.7 Pictorial presentation of overall plant exergy flows at Olkaria IAU & II Power plants

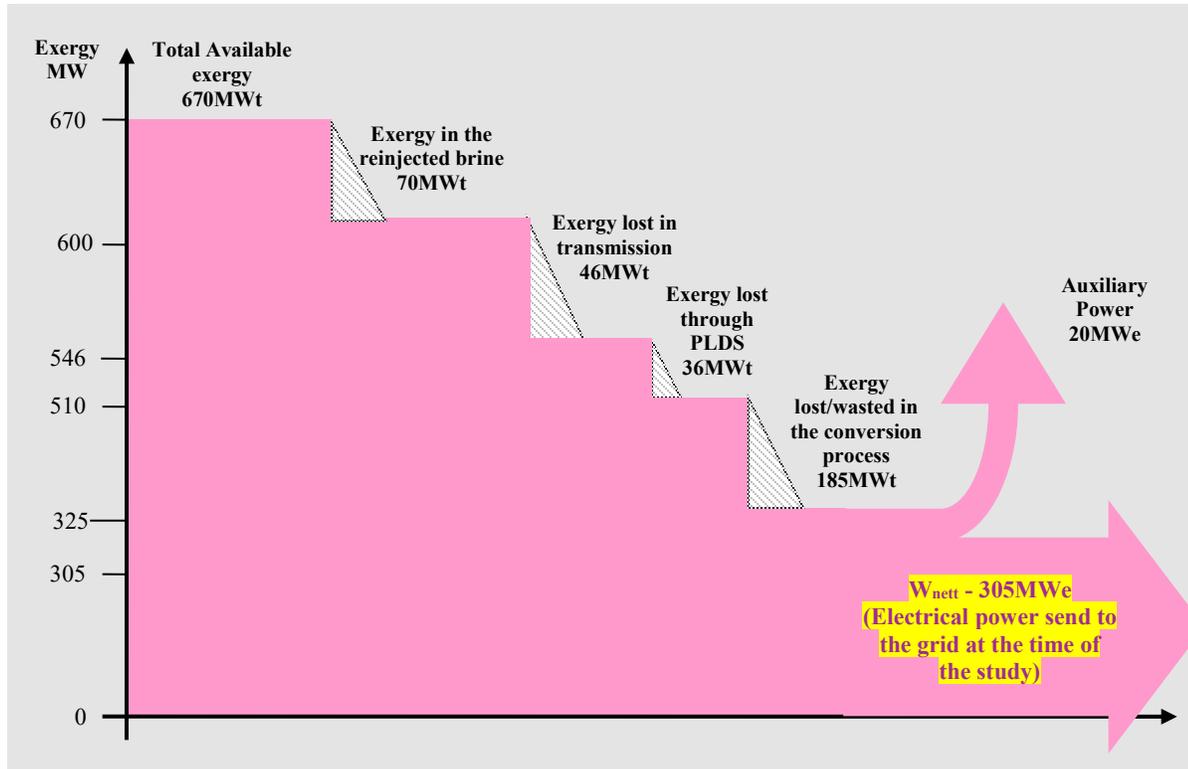


Figure 6 Grassman diagram illustrating exergy flows for Olkaria IAU & II power plants

5 CONCLUSIONS AND SUGGESTIONS

The importance of exergy analysis in evaluation of performance of power plants has been proven. The exergy analysis of Olkaria IAU & Olkaria II power plants has been carried out and the locations and quantities of exergy losses, wastes and destructions in the different processes of the plant have been identified. The analysis has shown that the major exergy losses occur in the energy conversion processes and the separation through the brine that is reinjected hot.

From the results, the following conclusions have been drawn:

1. The total exergy available from production wells at Olkaria IAU & II power plants has been calculated to be 670 MWt with most of the exergy (90%) contained in the steam.
2. The PLDS valves contribute to some wasted exergy of about 36MWt.
3. The analysis has shown that Olkaria IAU units 4&5 to have the lowest conversion efficiency which needs further analysis.

To further refine this analysis and achieve more insights of the processes, the following additional works are suggested.

1. The accuracy of flow metering devices need to be ascertained through calibration and replacement of defective flow meters.
2. The possibilities of utilizing the exergy of separated brine for additional generation or direct uses need to be investigated.
3. The exergy lost in the steam transmission system needs to be investigated. Heat losses due to damaged insulation, steam losses due to defective condensate drains and leakages and avoidable venting are some of the systems that should be given attention.
4. The low conversion efficiency of Olkaria IAU units 4&5 need to be investigated further to establish and address the possible causes

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