

# LCOE and Exergoeconomic analysis of Air-cooled Binary Power Plant

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## Keywords

*cost of products; exergoeconomics; exergy; levelized cost of electricity*

## ABSTRACT

Geothermal binary power plants can be utilized using low-grade resources. As power plants being thermal conversion units, there is a need to combine economics and exergy optimization from the available energy resource. This study analyzed isobutane air-cooled binary power plants at different geothermal brine temperatures at 187°C, 156°C, and 120°C, accordingly. The geothermal binary power plant was designed and analyzed using Engineering Equation Solver (EES) code and System Advisor Model (SAM). Further, it was optimized by different turbine inlet pressure, and EES results which are the basis to Levelized Cost of Electricity (LCOE) calculations. The exergy efficiencies were obtained between 20-35%. Thermal efficiencies were between 6 - 9.5%, and LCOE varied between 0.079 and 0.099 \$/kWh. It is important to combine thermo-economic, exergy, and LCOE in power plant design for optimum utilization of available resource.

## 1. Introduction

Geothermal power development has been increasing over the years (Huttrer et al., 2020; Magnus and Victor, 2012; Omenda et al., 2020). Geothermal resources have varying temperatures and pressure depending on location and reservoir characteristics. For optimum utilization of the available geothermal energy, exergy and economic analysis were considered in an air-cooled binary power plant for three temperature ranges of 187°C, 156°C, and 120°C, accordingly. In Kenya, most of the geothermal power plants are single flash (SF) which are namely, Olkaria I, Olkaria II, Olkaria III, Olkaria IV, and Olkaria V. There is also a new upcoming Olkaria AU I, and other numerous well-head technologies under way. (Bett et al., 2020; Kwambai, 2005; Langat, 2015; Mendive et al., 2012; Saitet and Kwambai, 2015). The brine temperatures considered in this study are based from Olkaria I, (Kiprono et al., 2019; Kwambai, 2010) and Olkaria IV (Langat, 2015). Further, 120°C was assumed for modeling optimization, and analysis of air-cooled binary plant (Kiprono et al., 2019).

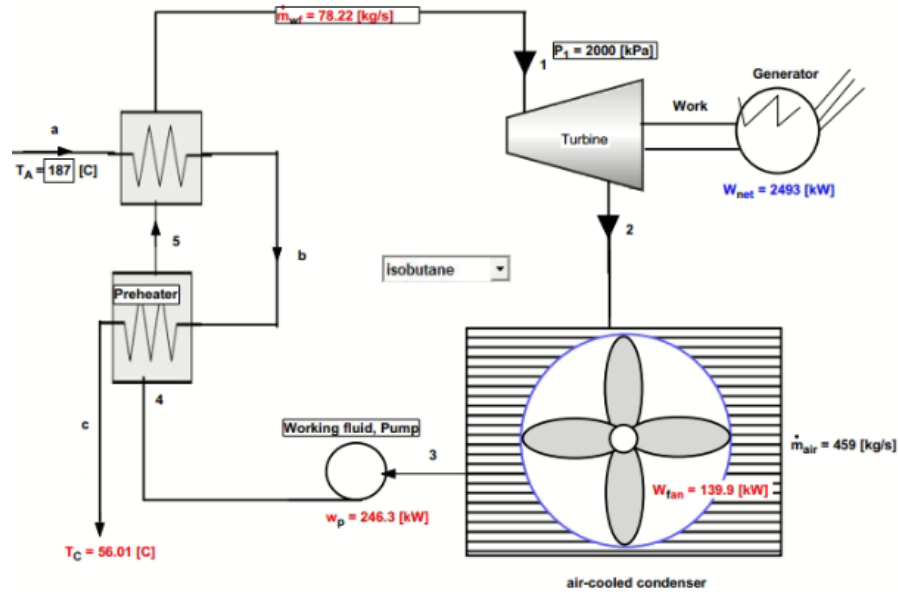
Developing a geothermal power plant from exploration to operations is expensive mainly because the capital costs are high (IRENA, 2017). Levelized Cost of Electricity (LCOE) is one of the tool in estimating the cost of electricity generation technologies (Comello et al., 2017; Timilsina, 2020). Renewable energy technologies have been reported to have smaller LCOE than fossil fuel technologies (Timilsina, 2020). LCOE also shows the cost of resources utilized/consumed to generate 1 kWh of electricity (Comello et al., 2017). As environmental factors increase and fossil fuel reserves are depleting, it urges the need for renewable and sustainable energy options (El Haj Assad et al., 2017). In Kenya, LCOE for geothermal power plants is between US\$ 0.043-0.064 per kWh (Magnus and Victor, 2012). An isobutane binary plant using brine temperature at 154.5°C and 457 kg/s and reinjection of 62.8°C has LCOE between \$0.182-0.1191/kWh (Li et al., 2020). Another example is the comparison between Organic Rankine Cycle (ORC) and Kalina cycle using LCOE calculations. The results are \$0.22/kWh and \$0.18/kWh, respectively (Campos Rodriguez et al., 2013).

Exergy analysis shows a future usage in entropy generation for power plant design (Kowalczyk et al., 2015). Exergy analysis of ORC optimization with an optimum reinjection temperature that ranges from 79 °C to 116 °C presented the energy and exergy efficiencies of 16.37% and 48.8%, respectively (El-Emam and Dincer, 2013). The butane group of hydrocarbons has been identified in most applications as dry-type, thus, isobutane has been selected for the study. (Agahi and Valdimarsson, 2015; Aghahosseini and Dincer, 2013; Ahangar, 2012; Edrisi and Michaelides, 2013; Han et al., 2020; Jalilinasrabady et al., 2011; Li et al., 2019; Pratama et al., 2020; Quoilin et al., 2011; Saito et al., 2016; Tunc et al., 2013).

In this paper, isobutane was used as the working fluid for air-cooled binary power plant. Economic and thermodynamic analysis are performed for different heat sources in Olkaria geothermal field, Kenya with the objective of the optimization of available energy source.

## 2. Methodology

This paper considers Organic Rankine Cycles (ORC) for power generation that uses isobutane as working fluid. The air-cooled binary power plant was modelled and analyzed exergoeconomic using Engineering Equation Solver (EES) code (Beckman and Klein, 2008). From the thermodynamic approach, enthalpy drop in turbine generates work. Results from EES code are part of the primary data input of the System Advisor Model (SAM) (“System Advisor Model (SAM) 2020,” 2020) which will eventually used for LCOE calculations. Figure 1 shows the power plant layout of the proposed unit. The geothermal brine (State A) from the separator heats the ORC binary evaporator while the working fluid enters the preheater and evaporator (States 4 and 5 respectively). The working fluid will expand in the turbine (State 1) and will become a saturated vapour, in which it will generate power. The vapour air-cooled from State 2 to State 3. At State 3 the working fluid is pumped to the preheater as liquid. Note that in each heat exchangers pinch point of 8°C was applied (Jalilinasrabady et al., 2011a).



**Figure 1: Basic air-cooled binary power plant layout modelled and optimized using EES code.**

SAM is applied for the analysis of same plant layout, utilizing isobutane working fluid for three temperatures (187°C, 156°C and 120°C). LCOE calculates electricity generation cost during the plant's lifetime (Sun et al., 2018). The LCOE is calculated using the equation:

$$LCOE = \frac{\sum_{t=1}^n \frac{C_t + FXD + VOM_t - I_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \quad (1)$$

with  $C_t$ - capital investment,  $FXD$  - fixed operation, and maintenance cost,  $VOM_t$  - operation and maintenance,  $I_t$  - income from the sale of electricity,  $E_t$  - electricity generated in year  $t$ ,  $r$  - discount rate,  $n$  the lifetime of the plant (Arinaldo and Pujantoro, 2019; Lazard, 2018; Zhou et al., 2013). Capital costs are well drilling, power plant costs, reservoir stimulation costs, steam gathering system costs, and exploration costs. Values applied in the study are capital costs of US\$ 4,640/kW,  $VOM_t$  of US\$ 1.16/Mwh and a capacity factor of 90% (EIA, 2013). The size of the reservoir is approximately 5,000 m by 8,000 m (Munyiri, 2016; Rop, 2017).

The sizes that were assumed in LCOE calculations were 5,000 m and depth of 3,000 m. Distance between reinjection and production wells is approximated to be 1,500 m in the study. For LCOE calculations, default parameters in the SAM adopted are:

1. Permeability - 0.05 Darcy.
2. Fracture aperture - 0.0004 m.
3. Fracture width - 175 m
4. Fracture angle 15 degrees from horizontal
5. Subsurface water loss – 2% of reinjected

Isentropic steam expansion turbines result in enthalpy drop ( $\Delta h$ ) (equation 2) generating as  $\dot{W}_{\text{gross}}$ .

$$\dot{W}_{\text{gross}} = \dot{m}_{wf} \Delta h \quad (2)$$

**Table 1: Operating parameters for the ORC LCOE and exergoeconomic analysis.**

Parameter		Value	Unit
Brine flow rate	$\dot{m}_{\text{brine}}$	50	kg/s
Reinjection temperature	$T_c$	> 56	°C
Pinch point	$T_{\text{pp}}$	8	°C
Turbine isentropic efficiency ( $\eta_{\text{tur}}$ )	$\eta_{\text{tur}}$	85	%
Pump isentropic efficiency	$\eta_{\text{pump}}$	75	%
Ambient Pressure	$P_0$	86	kPa
Ambient temperature	$T_0$	20	°C
Number of years	n	25	years
Annual plant operation hours	t	8,760	hrs
Interest rate	r	10	%
Plant capacity	[-]	90	%
Capital cost	$C_t$	4,640	\$/kWh
Variable operating cost	$VOM_t$	1.16	\$/MWh
Fixed operation and maintenance	$FXD$	128	\$/kWh-year

For a thermodynamic steady state energy balance equations are as shown in equations 3 and 4 (El-Emam and Dincer, 2013).

$$\sum \dot{m}_{\text{in}} = \sum \dot{m}_{\text{out}} \quad (1)$$

$$\dot{Q} - \dot{W} + \sum \dot{m}_{\text{in}} h_{\text{in}} - \sum \dot{m}_{\text{out}} h_{\text{out}} = 0 \quad (2)$$

The net power generated by the power plant is calculated as

$$\dot{W}_{\text{net}} = \dot{W}_{\text{gross}} - \dot{W}_{\text{parasitic}} \quad (3)$$

where the parasitic are work done by cooling tower fans, and pumping power consumed pump and specific exergy equation is given by (Jalilinasrabad and Itoi, 2012).

$$e = h - h_0 - T_0(s - s_0) \quad (4)$$

The thermal energy efficiency of the system is given by:

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} \quad (5)$$

$$\Delta \dot{E}x = \dot{E}x_{in} - \dot{E}x_{out} = \dot{E}Q + \sum_{i=1}^k \dot{m}_i e_i - \dot{E}W - \sum_{j=1}^k \dot{m}_j e_j \quad (6)$$

$$\dot{E}x_{out} = \dot{E}W + \sum_{j=1}^k \dot{m}_j e_j \quad (7)$$

Exergy efficiencies (utilization/exergy ( $\eta_u$ ) and second utilization ( $\eta_{u2}$ )) show how power plant approaches the theoretical operating condition and are calculated as (Zahata et al., 2020):

$$\eta_u = \frac{\dot{W}_{net}}{\dot{E}x_{in}} \quad (8)$$

### 3. Results

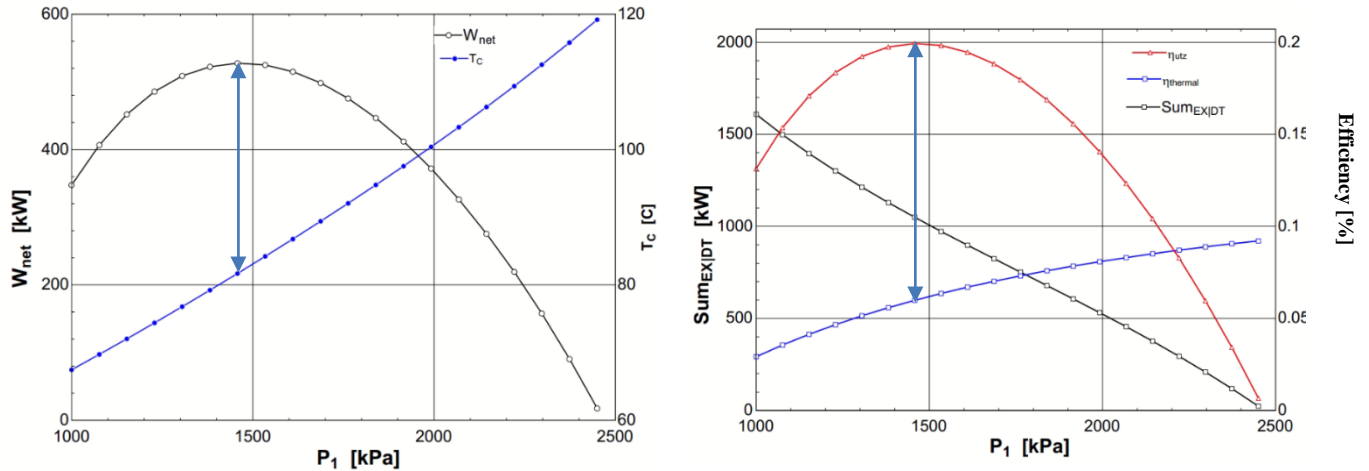
The optimal parameters of the power plant were maximizing the net power output for three brine temperatures and pinch point of 8 °C with the reinjection temperature of 56 °C. Optimization for each unit was performed by varying turbine inlet pressure,  $P_1$  between 100 and higher value less than critical pressures. The optimum turbine pressures were 2,000 kPa, 2,600 kPa and 1,458 kPa for 187 °C, 156 °C and 120 °C, respectively. Table 2 shows the outputs of the optimized power plant. Figure 1 shows the optimum output of the power plant for brine source at 187 °C modelled in EES code.

**Table 2: Results of the optimum operating parameters (net work generated) of the air-cooled binary power plant.**

Parameter	Geothermal brine temperature (Heat source)		
	187 °C	156 °C	120 °C
$P_1$ (kPa)	2,000	2,600	1,458
Gross power generated (kW)	2,633	1,675	568.3
Working fluid flow rate (kg/s)	78.22	40.94	23.86
Energy efficiency (%)	8.0	9.5	6.0
Exergy efficiency (%)	35.42	33.5	20
Sum of exergy destruction (kW)	4,081	1,987	1,049
LCOE (cents/kWh)	7.96	8.12	9.94
$T_c$ (°C)	56.0	86	81

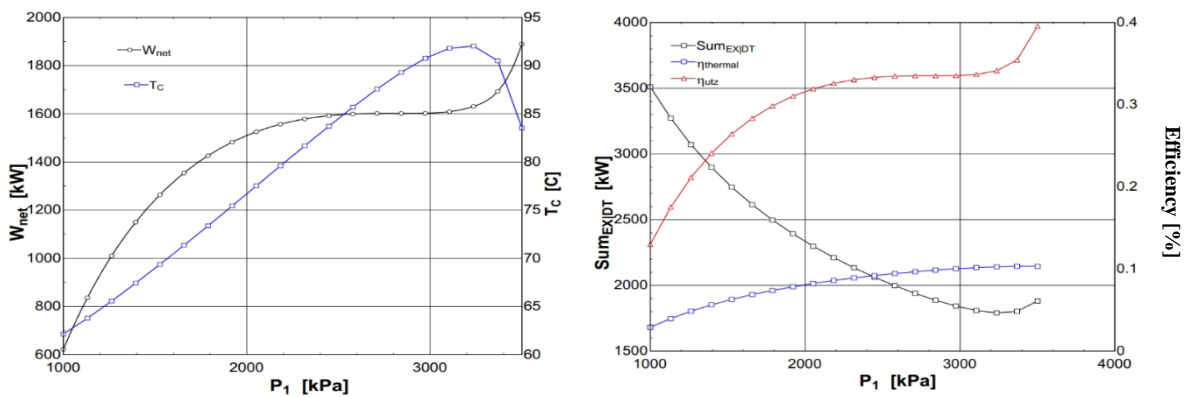
Calculation of LCOE using SAM shows that when LCOE increases, the temperature decreases. Binary plant using 187 °C brine has the lowest LCOE at 7.96 cents/kWh because of the higher value of annual electricity generated due to higher net power output.

Utilization of the geothermal brine can generate at least 565.3 kW at 120 °C and at most of 2,633 kW by the use of hotter brine at 187 °C.



**Figure 2: Effect of turbine inlet pressure on the net work generated, exergy destruction and efficiencies 120 °C geothermal brine.**

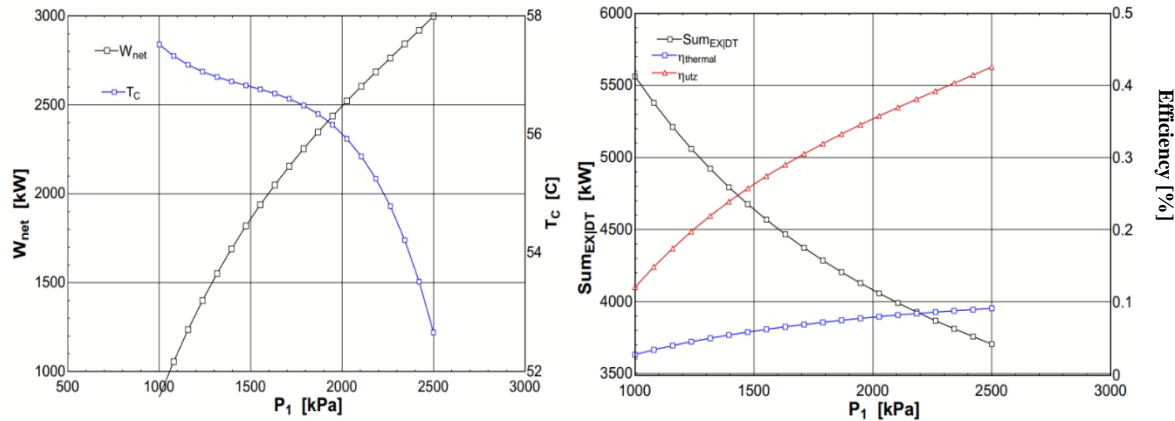
Figure 2 shows the maximum network generated, thermal and exergy efficiencies, and summation of total exergy destruction for the heat source at 120 °C. Net power output generated is at maximum in 1,458 kPa turbine inlet pressure. From Figure 2, the total exergy destruction of the power plant is seen to be decreases when the turbine inlet pressure increases. There was a reduction in exergy destroyed because of the increasing values of reinjection temperature as shown in Figure 3.



**Figure 3: The performance indicators of binary power plant showing effects of turbine inlet pressure for 156 °C geothermal brine.**

Figure 3 shows the effect of turbine inlet pressure in net power output, reinjection temperature and efficiencies of the geothermal brine from Olkaria I power plant. The optimum turbine inlet pressure is 1,675 kPa and for the thermal and exergy efficiencies are 9.3 and 33.5, respectively.

In this study, performance of the high temperature brine from Olkaria IV power plant is not efficient for the proposed power plant that uses isobutane as working fluid. Figure 4 shows the effect of turbine pressure in some of the key parameters for power plant analysis. The reinjection temperature is low at 56 °C. The high temperature in geothermal fluid calls for selection of another working fluid and modification of the energy and mass balance equations in the heat exchangers is recommended.



**Figure 4: Effects of turbine inlet pressure on net work generated, reinjection temperature, efficiencies, and exergy destruction for heat source of 187 °C.**

Table 2 shows the total exergy destruction is directly proportional to the brine temperatures. As high temperature enters into the system, the exergy is high and thus, it requires efficient utilization.

#### 4. Conclusion

The exergoeconomic analysis of air-cooled binary unit was done and the following conclusions were made:

- the lower the heat source, the less the power is generated.
- turbine inlet pressure affects the work generated, efficiencies, and reinjection temperatures above 56°C.
- isobutane working fluid is suitable for the 156°C geothermal brine with a higher thermal efficiency of 9.5% and reinjection temperature at 86°C.
- geothermal brine at 187°C could be suitable for consideration for a different types of working fluid with critical temperature close to the brine temperature for optimum utilization.
- the highest heat source temperature is least effective with very low reinjection temperatures at 56°C.

LCOE at higher brine temperature is lower than the brine with lower temperature because of high net power output.

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