Performance Investigation of Geothermal Power Plant Based on Exergy and Exergoeconomic Analyses (Case Study: Sarulla Geothermal Power Plant)

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Abstract. The analyses of exergy and exergoeconomic calculations have been carried out at the Sarulla Geothermal Power Plant (SGPP) unit 1 which has a capacity of 110 MW. The evaluation and modelling process uses Engineering Equation Solver (EES) software commercial version v9.430. This research was conducted to identify exergy lost in certain components to provide suggestions for further development. Both energy efficiency and exergy are calculated based on the thermal fluid flow process on the SGPP. The calculations showed that energy efficiency for Ormat Energy Converter (OEC) Brine, OEC Bottoming, and overall SGPP are obtained in the amount of 13.4%, 7.67% and 10.57%, respectively. Meanwhile, efficiency exergy of OEC Brine, OEC Bottoming, and overall SGPP were obtained respectively at 38.94%, 33.51% and 39.97% with each exergy destruction flow rate at 32,935 kW, 34,726 kW, and 1,644,686 kW, respectively. The highest exergy destruction was obtained at reinjection wells of 58,263 kW, around 21.25% of the production wells exergy. Exergoeconomic analysis was also carried out through consideration of capital costs. The ratio of exergy and energy lost to capital costs is 6.14 Watt/US $ and 0.29 Watt/US $.

1. Introduction

The energy analysis method is applied to calculate the energy losses that occur in a system, but the energy analysis is incapable and precise in determining the location and the amount of energy loss that occurs in the system. Therefore, currently the exergy analysis method is better and more accurate in determining the location of energy losses and providing appropriate steps in an effort to save energy sources efficiently [1], [2]. Low exergy of destruction means low energy loss as well as an indication that shows a good thermal system in a geothermal power plant. The design and operational conditions of the power plant greatly affect the value of exergy destruction [3]. The value of exergy destruction is needed to provide information in improving thermal efficiency by considering the economic side [4].

Sarulla Geothermal Power Plant (SGPP) is in the area of North Tapanuli Regency, North Sumatra, Indonesia. Its position is in the South from Medan with a distance of about 312 km. SGPP consists of 3 units with a capacity of 110 MW each. Each unit utilizes steam and brine extracted from the reservoir. In this study, unit 1 is an analysed study. The conversion technology used in SGPP is classified as: a) steam turbines (back pressure steam turbine), b) steam condensing turbines (condensing steam turbine), and (c) binary cycles [5]. The scheme of the generator system process in Sarulla is shown in Figure 1.
Figure 1 shows the three types of technology used in SGPP. First, the Steam Turbine Generator (STG) that utilizes geothermal fluids to be expanded inside the turbine. Second, Ormat Energy Convertor (OEC) Brine that utilizes separator brine to vaporize organic fluid. Third, OEC Bottoming by utilizing steam turbine output to vaporize organic fluid organic fluid. Both OEC uses n-pentane as working fluid. The selection of this technology configuration results in the most likely project risks associated with chemical brine and reservoir sustainability [5].

Previous researches had performed calculations and analysis of exergy in binary geothermal power plants [6], [7]. The thermal efficiency of the two studies is less than 10%. Meanwhile, each exergy efficiency is obtained in the range of 28-30% of the geothermal fluid in the production well.

Exergy analysis had been conducted on several types of geothermal power plants, like single-flash, double-flash, and flash-binary, Organic Rankine Cycle (ORC) with working fluid R123, ORC using Internal Heat Exchanger (IHE), regenerative ORC, and regenerative ORC using IHE. The performance of each cycle is analyzed based on the efficiency thermodynamics second law, the rate of exergy destruction, and the efficiency of law I thermodynamics [8]. The study shows that the regenerative ORC cycle with IHE is a more promising choice and should be studied in more detail. In the ORC cycle using isobutane as a working fluid. It is obtained that the highest exergy destruction rate is at the evaporator and condenser. The value is around 75% of the total exergy destruction of the whole system [9].

The performance of the single and double flash geothermal power plant system have been reviewed by [10]. Optimization is carried out through the concept of exergy and exergo-economic analysis to obtain maximum flashing pressure with the objective function of the maximum power potential. The study showed that the double flash generating system was able to increase energy efficiency and exergy by 17.73% and 50.89% respectively. The optimization results also show that the optimum cycle of a thermodynamic generating system does not directly show the best conditions economically.

This study aims to identify exergy losses and losses. Identification of thermal efficiency of geothermal power plants is carried out through energy, exergy and exergoeconomic analysis.

2. Basic Theory

2.1. Energy and Exergy Concept

System modelling starts with developing a simulator using the Engineering Equation Solver (EES) commercial version 9,430. The following are some of the assumptions used: (1) The plant operates in steady state conditions, (2) pressure drop through a heat exchanger and pipe is ignored, and (3) changes in kinetic energy and potential energy are ignored.

Mass and energy balance of a control volume, respectively expressed in form [11]:

\[ \sum m_{i} = \sum m_{e} \]  
\[ 0 = \dot{Q}_{cv} - \dot{W}_{cv} + \sum \dot{m}_{i} h_{i} - \sum \dot{m}_{e} h_{e} \]  

Where \( \dot{Q}_{cv} \) and \( \dot{W}_{cv} \) represents heat transfer into/out from system (kW) and work produced/consumed by system (kW), respectively.

Energy efficiency \( (\eta) \) is formulated below. Variable \( \dot{W}_{net} \) represents net power.

\[ \eta = \frac{\sum E_{out}}{\sum E_{in}} = \frac{\dot{W}_{net}}{\sum E_{in}} \]  

The work of turbine, pump, and fan is formulated in equation (4), (5), and (6), respectively.

\[ \dot{W}_{turbine} = \dot{m} \cdot (h_{i} - h_{o}) \cdot \eta_{turbine} \]
\[ W_{\text{pump}} = \frac{\dot{m} \cdot (h_{\text{in}} - h_{\text{out}})}{\eta_{\text{pump}}} \]  
\[ \dot{W}_{\text{fan}} = \frac{\dot{m} \cdot (h_{\text{in}} - h_{\text{out}})}{\eta_{\text{fan}}} \text{ or } \dot{W}_{\text{fan}} = \frac{\text{vol} \cdot \Delta p}{\eta_{\text{fan}}} \]  

Where \( \text{vol} \) and \( \Delta p \) each indicates volume flow rate and pressure drop.

Control volume exergy \( (\dot{E}_x) \) balance in steady state regardless of both kinetic and potential energy changes and is shown as follows:

\[ \dot{E}_{x,\text{heat}} - \dot{E}_{x,W} = \sum \dot{E}_{x,\text{out}} - \sum \dot{E}_{x,\text{in}} + \dot{E}_{x,D} \]  

\( \dot{E}_{x,D} \) represents exergy destruction rate (kW). Meanwhile, \( \dot{E}_{x,\text{heat}} \) defines exergy transferred by heat at temperature \( T \) to reference temperature \( (T_0) \) and \( \dot{E}_{x,W} \) is exergy transfer due to work.

\[ \dot{E}_{x,\text{heat}} = \sum \left( 1 - \frac{T}{T_0} \right) \cdot \dot{Q} \]  
\[ \dot{E}_{x,W} = \dot{W} \]  

Specific exergy \( (e_x) \) and exergy rate \( (\dot{E}_x) \) is formulated each as

\[ e_x = h_x - h_0 - T_0(s_x - s_0) \text{ and } \dot{E}_x = \dot{m} \cdot e_x \]  

The specific exergy of air in the air-cooled condenser is calculated using the following equation [1]:

\[ e_{x,\text{air}} = C_{p,\text{air}} \left( T - T_0 - T_0 \ln \left( \frac{T}{T_0} \right) \right) \]  

Exergy efficiency is formulated below:

\[ \varepsilon = \frac{\dot{E}_{x,\text{product}}}{\sum \dot{E}_{x,\text{in}}} \]  

Based on all equations above, both exergy efficiency and exergy destruction of each vessel are written in table 1.

2.2. Exergoeconomic Concept

Economic system analysis is assessed by the cost of purchasing components and equipment, operations and maintenance, and energy input costs. Meanwhile, exergoeconomic analysis is a study related to economic principles through consideration of exergy analysis. Thermoecenomic analysis is evaluated based on the cost balance equation on the system component where steam passes through the component boundary.

The development of the thermo-economic model has also been done by [12]. The model is used in exergoeconomic analysis studies by introducing energy rate ratios \( (R) \) and exergy lost \( (L) \) to capital costs \( (K) \). The relationship is shown through the equation as follows:

\[ R_{en} = \frac{\dot{L}_{en}}{K} \text{ and } R_{ex} = \frac{\dot{L}_{ex}}{K} \]  

where each \( \dot{L}_{en} \) and \( \dot{L}_{ex} \) is formulated below.
\[ L_{\text{en}} = \sum_{\text{input}} \text{Energy flow} - \sum_{\text{output}} \text{Energy flow} \]
\[ L_{\text{ex}} = \sum_{\text{input}} \text{Exergy flow} - \sum_{\text{output}} \text{Exergy flow} \]  

(14)

**Table 1. Vessels Exergy Efficiency and Destruction**

| Vessel                  | Exergy Efficiency | Exergy Destruction |
|-------------------------|-------------------|--------------------|
| Turbine                 | \( \varepsilon = \frac{\dot{W}_{\text{turbine}}}{\dot{E}_{\text{s,in}} - \dot{E}_{\text{s,out}}} \) | \( \dot{E}_{\text{s,D}} = (\dot{E}_{\text{s,in}} - \dot{E}_{\text{s,out}}) - \dot{W}_{\text{turbine}} \) |
| Heat Exchanger          | \( \varepsilon = \frac{\dot{E}_{\text{s, out, n- pentane}} - \dot{E}_{\text{s, in, n- pentane}}}{\dot{E}_{\text{s,in,thermalwater}} - \dot{E}_{\text{s,out,thermalwater}}} \) | \( \dot{E}_{\text{s,D}} = (\dot{E}_{\text{s,in,thermalwater}} - \dot{E}_{\text{s,out,thermalwater}}) - (\dot{E}_{\text{s, out, n- pentane}} - \dot{E}_{\text{s, in, n- pentane}}) \) |
| Pump                    | \( \varepsilon = \frac{\dot{E}_{\text{s, out}} - \dot{E}_{\text{s, in}}}{\dot{W}_{\text{pump}}} \) | \( \dot{E}_{\text{s,D}} = \dot{W}_{\text{pump}} - (\dot{E}_{\text{s, out}} - \dot{E}_{\text{s, in}}) \) |
| Air-cooled Condenser    | \( \varepsilon = \frac{\sum \dot{E}_{\text{s, out}}}{\sum \dot{E}_{\text{s, in}}} \) | \( \dot{E}_{\text{s,D}} = \sum \dot{E}_{\text{s, in}} - (\sum \dot{E}_{\text{s, out}} - \dot{W}_{\text{fan}}) \) |
| Plant                   | \( \varepsilon = \frac{\dot{W}_{\text{net}}}{\sum \dot{E}_{\text{s, in}}} \) | \( \dot{E}_{\text{s,D}} = \sum \dot{E}_{\text{s, in}} - \dot{W}_{\text{net}} \) |

3. Result and Discussions

3.1. Energy and Exergy Analysis
SGPP Process Flow Diagram is shown in Figure 1. Using equation (10) and (11), exergy rate and other properties are shown in table 2 and table 3. The reference temperature and pressure are selected respectively at 23.5°C and 0.95 Bar, respectively. Exergy losses, both exergy and energy efficiency are calculated based on data of each stream line table 2 and table 3. The calculation results are shown in the following table 4.

Because of the limited data, the efficiency of several vessels in table 2 and table 3 is assumed by adjusting the data in the PFD. The efficiency of each OEC Brine Plant and OEC Bottoming Plant is obtained from the ratio of the net power produced by the OEC Plant to the energy of geothermal fluid entering the OEC. Meanwhile, overall plant efficiency is obtained from the ratio of the total net power to the energy of production well. Thus, the efficiency of OEC Brine, OEC Bottoming, and overall plant is 13.4%, 7.67% and 10.57%, respectively.

Figure 2 shows the energy flow rate of the SGPP unit 1 through Sankey Diagram. It is shown that the electricity that can be produced is 11.33% of geothermal fluid. It is obtained that parasitic power and net are 0.72% and 10.61% of geothermal energy fluid input, respectively.

The results of the exergy flow is shown in Figure 3. It shows that the exergy losses is 57.15%. The remaining 42.85% is converted to electricity and 2.74% of the electricity is used for parasitic loads. These parasitic loads include pumps and fans for air-cooled condensers. The exergy efficiency of SGPP is 39.97%, based on production wells exergy input. The highest exergy loss is in the reinjection well at 58,263 kW (19.03% of geothermal fluid), followed by condensation process, about 17.37% of geothermal fluid energy in the production well.
Figure 1. SGPP Unit I Process Flow Diagram
| No. | Fluid    | T (°C) | P (Bar) | h (kJ/kg) | s (kJ/kg·K) | m (kg/s) | e_s (kJ/kg) | E_s (kW) |
|-----|----------|--------|---------|-----------|-------------|----------|-------------|----------|
| 0   | Thermal water | 23.5   | 0.95    | 98.64     | 0.3461      | -        | 0           | 0        |
| 0'  | n-Pentane    | 23.5   | 0.95    | -5.557    | -0.0178     | -        | 0           | 0        |
| 0'' | Air        | 23.5   | 0.95    | 297.1     | 5.709       | -        | 0           | 0        |
| 1   | Thermal water | 223    | 24.4    | 1379      | 3.396       | 201      | 375.7       | 75508    |
| 2   | Thermal water | 223    | 24.4    | 1352      | 3.341       | 201      | 364.9       | 73328    |
| 3   | Thermal water | 234    | 29.8    | 1418      | 3.454       | 201      | 397.3       | 79856    |
| 4   | Thermal water | 223    | 24.5    | 1375      | 3.387       | 201      | 374.2       | 75208    |
| 5   | Thermal water | 214    | 20.7    | 1366      | 3.384       | 401.9    | 365.5       | 146920   |
| 6   | Thermal water | 214    | 20.7    | 1397      | 3.448       | 401.9    | 377.7       | 151794   |
| 7   | Thermal water | 213    | 20.4    | 910.9     | 2.452       | 305.2    | 187.7       | 57271    |
| 8   | Thermal water | 213    | 20.4    | 913.1     | 2.456       | 298.9    | 188.5       | 56345    |
| 9   | Thermal water | 213    | 28.4    | 911.2     | 2.45       | 605.7    | 188.3       | 114069   |
| 10  | Thermal water | 213    | 20.4    | 2799      | 6.332       | 96.79    | 924.4       | 89476    |
| 11  | Thermal water | 213    | 20.4    | 2799      | 6.332       | 103      | 924.4       | 95261    |
| 12  | Thermal water | 213    | 20.4    | 3452      | 7.404       | 199.8    | 1260        | 251801   |
| 13  | Thermal water | 80     | 26      | 337       | 1.074       | 1.611    | 22.5        | 36.26    |
| 14  | Thermal water | 80     | 26      | 337       | 1.074       | 0.1389   | 22.5        | 3.126    |
| 15  | Thermal water | 80     | 26      | 337       | 1.074       | 0.6944   | 22.5        | 15.63    |
| 16  | Thermal water | 211    | 19.6    | 2786      | 7.401       | 162.8    | 1245        | 202708   |
| 17  | Thermal water | 211    | 19.5    | 2724      | 6.195       | 162      | 890.2       | 144216   |
| 18  | Thermal water | 126    | 2.4     | 529.6     | 1.593       | 0.8333   | 41.81       | 51.93    |
| 19  | Thermal water | 107    | 1.3     | 449.1     | 1.387       | 1.056    | 44.13       |         |
| 20  | Thermal water | 107    | 1.3     | 2327      | 6.348       | 159.6    | 448.4       | 71537    |
| 21  | Thermal water | 107    | 1.3     | 449.2     | 1.387       | 0.2778   | 41.82       | 11.62    |
| 22  | Thermal water | 107    | 1.3     | 449.2     | 1.387       | 0.8056   | 41.82       | 33.69    |
| 23  | Thermal water | 107    | 1.3     | 449.2     | 1.387       | 0.0278   | 41.82       | 1.162    |
| 24  | Thermal water | 100    | 1       | 417.5     | 1.303       | 1.833    | 35.07       | 64.3     |
| 25  | Thermal water |        |         |           |            |          | 1.392       | -        |
| 26  | Thermal water |        |         |           |            |          | 0.4472      | -        |
| 27  | Thermal water | 211    | 22      | 902.3     | 2.433       | 302.8    | 184.4       | 55851    |
| 28  | Thermal water | 148    | 20      | 625       | 1.821       | 322.3    | 88.86       | 28643    |
| 29  | Thermal water | 211    | 22      | 902.3     | 2.433       | 302.8    | 184.4       | 55851    |
| 30  | Thermal water | 148    | 20      | 625       | 1.821       | 322.3    | 88.86       | 28643    |
| 31  | Thermal water | 148    | 20      | 625       | 1.821       | 644.7    | 88.86       | 57285    |
| 32  | Thermal water | 80     | 27      | 337.1     | 1.074       | 2.444    | 22.6        | 55.25    |
| 33  | Thermal water | 90     | 21      | 338.9     | 1.081       | 2.778    | 22.37       | 62.13    |
| 34  | Thermal water | 105    | 1.23    | 2390      | 6.513       | 159.6    | 462.1       | 73730    |
| 35  | Thermal water | 105    | 1.23    | 2422      | 6.596       | 39.89    | 468.9       | 18705    |
| 36  | Thermal water | 80     | 20      | 336.6     | 1.074       | 37.97    | 21.91       | 831.9    |
| 37  | Thermal water | 91.6   | -       | 330.8     | 1.064       | 0.388    | 19.31       | 7.49     |
| 38  | Thermal water | 105    | 1.23    | 2390      | 6.513       | 39.89    | 462.1       | 18433    |
| 39  | Thermal water | 80     | 20      | 336.6     | 1.074       | 37.97    | 21.91       | 827.2    |
| 40  | Thermal water | 91.6   | -       | 330.8     | 1.064       | 0.388    | 19.31       | 7.49     |
| 41  | Thermal water | 105    | 1.23    | 2390      | 6.513       | 39.89    | 462.1       | 18433    |
| 42  | Thermal water | 80     | 20      | 336.6     | 1.074       | 37.97    | 21.91       | 827.2    |
Table 3. Thermophysical Properties and Exergy Rate for Stream Line 43 to 71

| No. | Fluid         | $T$ (°C) | $P$ (Bar) | $h$ (kJ/kg) | $s$ (kJ/kg-K) | $m$ (kg/s) | $e_x$ (kJ/kg) | $E_x$(kW) |
|-----|---------------|----------|-----------|-------------|---------------|------------|--------------|------------|
| 43  | Thermal water | 91.6     | -         | 330.8       | 1.064         | 0.388      | 19.31        | 7.49       |
| 44  | Thermal water | 105      | 1.23      | 2390        | 6.513         | 39.89      | 462.1        | 18433      |
| 45  | Thermal water | 80       | 20        | 336.6       | 1.074         | 37.76      | 21.91        | 827.2      |
| 46  | Thermal water | 91.6     | -         | 330.8       | 1.064         | 0.388      | 19.31        | 7.49       |
| 47  | Thermal water | 80       | 20        | 336.6       | 1.074         | 75.51      | 21.91        | 1654       |
| 48  | Thermal water | 80       | 20        | 336.6       | 1.074         | 75.73      | 21.91        | 1659       |
| 49  | Thermal water | 80       | 20        | 336.6       | 1.074         | 151.2      | 21.91        | 3314       |
| 50  | Thermal water | 80       | 20        | 336.6       | 1.074         | 154        | 21.95        | 3381       |
| 51  | Thermal water | 80       | 20        | 336.6       | 1.074         | 151.6      | 21.91        | 3322       |
| 52  | Thermal water | 135      | 19        | 569.3       | 1.687         | 798.7      | 72.95        | 58264      |
| 53  | Thermal water | 135      | 14.8      | 568.9       | 1.687         | 477.6      | 72.51        | 34633      |
| 54  | Thermal water | 135      | 18.3      | 569.2       | 1.687         | 318.4      | 72.85        | 23196      |
| 55  | n-Pentane     | 71.3     | 23.5      | 111.8       | 0.3369        | 184.5      | 12.15        | 2243       |
| 56  | n-Pentane     | 172      | -         | 409.4       | 1.089         | 184.5      | 86.61        | 15979      |
| 57  | n-Pentane     | 173      | 23.5      | 582.1       | 1.476         | 184.5      | 144.6        | 26674      |
| 58  | n-Pentane     | 102      | -         | 506.9       | 1.657         | 92.25      | 69.33        | 6396       |
| 59  | n-Pentane     | 102      | -         | 506.9       | 1.476         | 92.25      | 69.33        | 6396       |
| 60  | n-Pentane     | 73.3     | 1.72      | 446.8       | 1.377         | 92.25      | 38.57        | 3558       |
| 61  | n-Pentane     | 73.3     | 1.72      | 446.8       | 1.377         | 92.25      | 38.57        | 3558       |
| 62  | n-Pentane     | 73.3     | 1.72      | 446.8       | 1.377         | 184.5      | 38.57        | 7117       |
| 63  | n-Pentane     | 47       | 1.67      | 50.07       | 0.1623        | 184.5      | 2.223        | 410.2      |
| 64  | Air           | 23.5     | 0.95      | 297.1       | 5.709         | 0          | 0            | 0          |
| 65  | n-Pentane     | 71.3     | 23.5      | 111.8       | 0.3369        | 92.25      | 12.15        | 1121       |
| 66  | n-Pentane     | 71.3     | 23.5      | 111.8       | 0.3369        | 92.25      | 12.15        | 1121       |
| 67  | n-Pentane     | 95.5     | 5.4       | 476.2       | 1.341         | 88.46      | 78.8         | 6971       |
| 68  | n-Pentane     | 67.1     | -         | 438.1       | 1.411         | 88.46      | 19.69        | 1741       |
| 69  | n-Pentane     | 42       | 1.42      | 38         | 0.1244        | 88.46      | 1.387        | 122.7      |
| 70  | n-Pentane     | -        | 5.4       | 47.07      | 0.1509        | 88.46      | 2.586        | 228.8      |
| 71  | Air           | 23.5     | 0.95      | 297.1       | 5.709         | 0          | 0            | 0          |

Brine Energy Input 1,037,160 kW
Brine Reinjection 1,037,160 kW (30.20%)
Condenser Losses 606,487.14 kW (58.48%)
Parasitic Power 7,500 kW (0.72%)
Net Power 110,000 kW (10.61%)

Figure 2. Energy Flow Diagram SGPP unit I
Table 4. Exergy and Energy Efficiency

| No | Equipment                          | Exergy Efficiency, ε (%) | Exergy Destruction (kW) | Heat transfer (Q) / Power Rate (W) (kW) | Energy Efficiency (%) |
|----|------------------------------------|--------------------------|-------------------------|----------------------------------------|-----------------------|
| 1  | Brine Booster Pump 1               | 39.35                    | 326.30                  | 538.00                                 | 75                    |
| 2  | Brine Booster Pump 2               | 39.32                    | 326.70                  | 538.40                                 | 75                    |
| 3  | Scrubbing Pump                     | 50.96                    | 1.53                    | 3.13                                   | 75                    |
| 4  | Purifier Flash Drum                |                          | 5.62                    | -                                      | -                     |
| 5  | Separator A                        | 55.25                    | 144.10                  | -                                      | -                     |
| 6  | Separator B                        | 55.25                    | 144.10                  | -                                      | -                     |
| 7  | Steam Purifier                     |                          | 4,655                   | -                                      | -                     |
| 8  | Steam Turbine Generator (STG)      | 86.71                    | 9,629                   | 62,848                                 | 85.65                 |
| 9  | Vaporizer - OEC Brine 5           | 91.14                    | 1,106                   | 33,891                                 | -                     |
| 10 | Pre Heater - OEC Brine 5          | 79.95                    | 3,663                   | 58,383                                 | -                     |
|    | Pre Heater - Vaporizer - OEC Brine 5 | 84.49                  | 4,769                   | -                                      | -                     |
| 11 | Pre Heater - Vaporizer - OEC Brine 5 | 84.49                  | 9,538                   | -                                      | -                     |
| 12 | Turbine - OEC Brine 5             | 75.09                    | 4,608                   | 13,891                                 | 86.12                 |
| 13 | Turbine - OEC Brine               |                          | 9,216                   | 27,782                                 | -                     |
|    | Recuperator - OEC Brine 5         | 41.43                    | 673                     | 6,325                                  | -                     |
|    | Recuperator - OEC Brine           |                          | 1,347                   | 12,650                                 | -                     |
| 14 | Cycle Pump - OEC Brine 5          | 77.16                    | 294.90                  | 1,291                                  | 80                    |
|    | Cycle Pump - OEC Brine            |                          | 590                     | 2,582                                  | -                     |
|    | Air-Cooled Condenser - OEC Brine 5| 15.73                    | 6,378                   | 76,030                                 | -                     |
|    | Air-Cooled Condenser - OEC Brine  |                          | 12,756                  | 152,060                                | -                     |
| 16 | Vaporizer - OEC Bottoming 31      | 82.2                     | 2,946                   | 39,951                                 | -                     |
|    | Vaporizer - OEC Bottoming         |                          | 11,784                  | 79,902                                 | -                     |
| 17 | Turbine - OEC Bottoming 31        | 64.47                    | 3,702                   | 6,717.50                               | 92.09                 |
|    | Turbine - OEC Bottoming           |                          | 14,808                  | 26,870                                 | -                     |
| 18 | Cycle Pump - OEC Bottoming 31     | 96.4                     | 7.88                    | 219.98                                 | 71.02                 |
|    | Cycle Pump - OEC Bottoming        |                          | 31.53                   | 879.90                                 | -                     |
|    | Condensate Pump - OEC Bottoming 31| 96.7                    | 3.61                    | 110                                    | 85.02                 |
|    | Condensate Pump - OEC Bottoming   |                          | 14.46                   | 438                                    | -                     |
| 19 | Air-Cooled Condenser - OEC Bottoming 31 | 12.19                | 3,047                   | 35,440                                 | -                     |
|    | Air-Cooled Condenser - OEC Bottoming |                      | 12,188                  | 141,760                                | -                     |
| 20 | OEC Brine Plant                   | 38.94                    | 32,935                  | 23,951                                 | 13.4                  |
| 21 | OEC Bottoming Plant               | 33.51                    | 34,726                  | 23,871                                 | 7.668                 |
| 22 | Plant (overall)                   | 39.97                    | 1,644,686               | 109,590                                | 10.57                 |
3.2. Exergoeconomic

Table 5 shows the value of the exergoeconomic Sarulla Unit I.

| Item                                      | Cost                        |
|-------------------------------------------|-----------------------------|
| Capital Cost (K)                          |                             |
| Drilling                                  | $68,000,000                 |
| Steam Field and Power Plant               | Rp997,764,000,000           |
| Total                                     | $268,000,000                |
| Exergy Destruction, $L_{ex}$ (W)          | 1,664,686,000               |
| Energy Loss, $L_{en}$ (W)                 | 919,660,000                 |
| $R_{ex} = \frac{L_{ex}}{K}$ (Watt/Rp)     | $4.23 \cdot 10^{-4}$       |
| $R_{ex} = \frac{L_{en}}{K}$ (Watt/$)     | $6.14$                      |
|                                           | (Watt/$)                   |
|                                           | $2.73 \cdot 10^{-4}$       |
|                                           | $0.291$                    |

The capital cost consists of drilling, steam fields and power plants. Therefore, the ratio of exergy loss and energy loss to capital investment is $4.23 \cdot 10^{-4}$ Watt/Rp and $2.73 \cdot 10^{-4}$ Watt/Rp, respectively.

4. Conclusions

Having developed the calculation, the energy efficiency for Ormat Energy Converter (OEC) brine, bottoming, and overall PLTP are respectively 13.4%, 7.67% and 10.57%. Meanwhile, exergy efficiency of OEC brine, bottoming, and overall plant respectively at 38.94%, 33.51% and 39.97% with each exergy extermination flow rate of 32,935 kW, 34,726 kW, and 1,644,686 kW each. Exergoeconomic analysis shows that the exergy and energy loss ratios for each capital cost were obtained respectively by $6.14$ Watt/$ and $0.291$ Watt/$.

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