Comparative analysis of Ormat and Kalina Cycle for the geothermal resource in Mabini, Batangas using thermoeconomic analysis

G E E Dela Cruz III and M C E Manuel, PhD
School of Mechanical and Manufacturing Engineering
Mapua University, Muralla St., Intramuros, Manila, Philippines
geedelacruz@mapua.edu.ph and mcemanuel@mapua.edu.ph

Abstract. The Philippines is amongst the countries located in the ring of fire, thus makes it rich in geothermal energy. The Department of Energy is considering the low-temperature resource for power generation to address the continuous increase in electricity demand. The binary plants designed by Ormat technologies are currently in use for power production for the Philippine low-temperature heat source. Another technology used for the low-temperature heat source is the Kalina power cycle. In this paper, both cycles are evaluated using the parameters from the Mabini, Batangas geothermal resource, and principles of thermoeconomics are applied to determine the performance of the two cycles under Philippine conditions.

1. Introduction
The Philippines is blessed with an abundance of natural resources. One resource in specific is geothermal energy since it is situated in an area called the “Ring of Fire”. It has made use of its geothermal resource mostly for power generation and used to be rank as the world’s second-largest producer of geothermal energy but has been recently overtaken by Indonesia in the global ranking in which the United States is leading [1].

The Department of Energy (DOE) estimated the geothermal resource potential of the country at around 4,000 MWe [2] while the installed capacity of the Philippines is only 1944 MWe [3]. There is still a large number of resources that can be harnessed and help in the increasing energy dependence of the country. The DOE added that the country has already been developed most of the high-enthalpy geothermal sources into commercial operations but there are marginalized low enthalpy resources that can be tapped for exploitation [4]. Optimization of the utilization of the geothermal resource through cascade use and development of the low enthalpy direct use is one of the goals of the DOE [5].

Significant support for the geothermal energy resource development of the country was realized through the passage of Republic Act No. 9513 also known as the Renewable Energy Law of the Philippines which took effect on January 30, 2009, and resulted in a total of 42 contracts for geothermal projects [6]. Geothermal companies also increased from 2 to 11 because of attractive government incentives [7].

The development of low enthalpy geothermal resources in the Philippines has been hindered because of the high cost and high risks involved in the exploration, production drilling, and construction phase. Intermediate to low-enthalpy resources in the Philippines are mostly used for nonelectrical and direct utilization like hot springs, geothermal salt making, and drying [8]. These low enthalpy resources can be used to generate power using a binary power cycle or ORC [9]. One prospect for development is located in Mabini, Batangas which is an intermediate-temperature with a reservoir temperature of at
least 180°C with possible 20MWe [10]. The development of these resources is in line with the government’s energy plan in which a total of 253MW will be available on 2030 based on the outlook of the DOE for a balanced energy mix and reducing dependence on fossil fuels.

At present, binary plants in the Philippines are used together with the traditional flash system to maximize the efficiency of the heat recovery from the geothermal wells that are still producing. The Binary plants operate on an Organic Rankine Cycle (ORC) which is a steam cycle system where refrigerants and hydrocarbons as a replacement to water to utilize the low-temperature heat resource for power production [11]. Ormat Technologies Inc. supplied the technology for the binary plants in the Philippines using heat from the waste brine [12].

Unfortunately, geothermal power plant efficiency is lower than the conventional power plants like coal-fired power plants. Increasing the current plant efficiency of geothermal plants becomes important to maximize the energy conversion from the current resource without an increase in cost due to drilling and exploration that sometimes yield unfavorable results when no productive steam is drilled. Another option is to use emerging technologies for low-temperature resource development. One of these technologies for low-temperature geothermal resources is the Kalina cycle. This technology was conceptualized by Dr. Alexander Kalina using ammonia-water in the cycle and modifying the Rankine cycle to achieve higher efficiency for low heat energy sources [13].

With the government pushing for cleaner energy, the development of the low to medium enthalpy geothermal areas will be a significant part of the future of geothermal energy in the Philippines. Using the appropriate technology for the development and efficient extraction of energy from these resources becomes imperative. The study of the thermodynamic efficiencies and economic viability of the available technologies namely the ORC together with the Kalina cycle system 34 will be the focus of this study. The study of both exergetic and economic analysis is known as thermoeconomics and consists of detailed exergy and economic analyses of the components of the cycle after which an evaluation of each component is conducted.

1.1. Binary Cycle
With the advent of innovative technology, it has become possible to also produce power from low-to-medium enthalpy reservoirs with temperature below 150°C with the use of a binary power plant or an Organic Rankine cycle [14]. The Organic Rankine cycle uses the geothermal water to heat a secondary fluid with lower boiling temperature, also called as the working fluid, such as propane, isobutane, isopentane, pentafluoropropane, and ammonia. Heat exchangers are used for transferring energy from the hot brine to the secondary fluid which turns the turbines to produce electricity. The geothermal water is also re-injected in a closed loop. There is no direct contact of the geothermal fluid and the hydrocarbon in this type of plant unlike the direct and flash system.

One notable binary power plant is the 125 MW Upper Mahiao Power Plant in Leyte which utilized the Ormat air-cooled Geothermal Combined Cycle technology designed for high enthalpy fluid other than pure dry steam. The cycle has a back-pressure steam turbine for the high-pressure steam followed by the Ormat Energy Converter for preheating and recovered in a binary plant or Organic Rankine Cycle [15].

1.2. Kalina Cycle
An efficient novel cycle was developed during the mid-1980s by a Russian engineer named Dr. Alexander Kalina. The cycle named after Dr. Kalina was used on a combined-cycle system as the bottoming cycle that replaced the use of the Rankine cycle. The key feature of this novel cycle is the use of a combination of ammonia and water (70/30 mass percent mixture) as the working substance. An increase of about 20% system efficiency and a 50-52% increase in a conventional gas turbine cycle was achieved [16]. The cycle provides varying temperatures for heating and boiling which matches the cooling curve of the heat source reducing entropy generation and unique heat rejection system that permits the working fluid composition to be less volatile [17]. The flexibility of the Kalina cycle is attributed to the ammonia-water properties but the limitation of the cycle is also seen in the fluid
chemistry of Ammonia which is unstable at higher temperatures greater than 300°C where hardening or nitride corrosion becomes a problem [18].

Mlcak [13] discussed the difference of the ammonia-water mixture used by Kalina as compared to pure water (H2O) or ammonia (NH3). The following are the main differences between the mixture and pure substances.

1. Both pure H2O and NH3 have constant boiling / condensing temperatures which is not the case for the ammonia-water solution [19].
2. The thermophysical properties of the ammonia-water solution can be improved by adjusting the concentration which is not true for pure water and pure ammonia as their properties are fixed.
3. The temperature of pure water and pure ammonia will not change without energy while the mixed fluid temperatures of ammonia-water can change without heat content.
4. Ammonia-water solution freezing temperature is very low compared to water freezes at 0°C and ammonia at -78°C.

There are several proprietary Kalina Cycle Systems that are modifications of the cycle designs that make use of the flexibility of the ammonia-water concentration. The first cycle used as gas turbine bottoming cycle mentioned earlier, this was later named the Kalina Cycle System 1 (KCS 1) and was used for the US DOE-ETEC at Canoga Park, California demonstration [19]. Other notable Kalina cycles are KCS 6 which has the highest efficiency applies to gas turbine and KCS 5 used for direct-fired plants [19].

The United States DOE funded a research and development grant to POWER Engineers, Inc to perform pilot testing of the Kalina cycle to determine if the viability of the cycle for heat recovery of a silica-rich geothermal brine with a temperature of 171°C in Roosevelt hot spring in Utah. It was found that installing a 13 MW Kalina cycle power plant is feasible in the said geothermal area. The plant is estimated to generate power at a high availability greater than 95%.

Low to medium temperature geothermal resources are by far the most commonly available type of geothermal resource in the world. The binary power plant is the technology that is used to exploit this type of source of energy. The Kalina cycle system is suitable for this application. KCS 11 and KCS 34 are the common system designs for geothermal applications. KCS 11 can be used for resources up to 204°C while KCS 34 is utilized for lower temperatures [19]. The Kalina cycle is composed of the separator, recuperators, evaporator, feed pump, condenser, and turbine generator. Geothermal brine heats the ammonia-water which produces a rich ammonia vapor that is extracted in the separator and utilized in the turbine to generate power. After expansion, the ammonia-rich liquid is mixed with the liquid from the separator to the recuperator before going to the condenser for further cooling and then returns to the evaporator to re-start the cycle [20].

According to Mlcak [21], The KCS 34 consists of a vapor turbine-generator, evaporator, separator, condenser, recuperator exchangers, and feed pump. KCS 34 was designed for generating power from low-to-medium-enthalpy geothermal resources which were used for district heating topping cycle and this is the cycle that is being utilized in the Orkuveita Husavikur Geothermal Power Plant system located in the town of Husavik, Iceland which has been in service since July of 2000. The plant performance ranges from 20% to 25% compared to the Organic Rankine Cycle that was considered for the plant. The KCS 34 cycle also proved to have an advantage over the ORC as the plant actual power output of 2,060 kW at 121°C brine inlet temperature during the operation was greater than that of the proposed ORC at 124°C with output ranging from 1,550 to 1,610 kW guaranteed [22].

Arslan [20] conducted a study of the KCS 34 using the Simav geothermal resource conditions in Turkey. The Simav field has temperatures up to 148°C with drilled depths at 169m to 725m. The waste heat is recommended to be used for heating. The electricity generated from the Simav geothermal field was determined to vary from 32.3 to 43.4MW depending on the ammonia concentration used. The net plant electricity output ranged from 243 to 346 GWh per year while the efficiency of the KCS 34 varied from 9.7 to 14.8%. The KCS 34 exergetic efficiencies were found to be at 36.2% for a temperature of 90°C and 34.6% for 100°C.
Mergner and Weimer [23] performed a comparative thermodynamic analysis on a geothermal power plant using KCS 34 and compared it to a Siemens’ patent geothermal cycle Kalina SG-1 similar to the Kalina cycle. The main difference between the KCS 34 and SG-1 cycles being the internal heat recovery location. KCS 34 utilizes bypassed liquid while SG1 uses the expanded steam and the bypassed liquid for the recovery. Calculations suggest that the KC SG1 attains a high flow rate through the turbine compared to the KCS 34 which operates at high turbine enthalpy difference. However, the efficiency increase could not be validated due to challenges with the absorption and resorption processes. They recommended further study focusing on validating the simulation results of the cycles used.

Tiangco [24] recommended the study of the Kalina Cycles, such as KCS34, for industrial waste heat and low-temperature low enthalpy geothermal resources in the Philippines which can be beneficial for power generation.

Nasruddin et al. [25] modeled the KCS 34 using cycle tempo 5.0 and validated the model for the installation in Husavic, Iceland, which resulted in electrical output of 1,959 MW compared to the actual electrical power output of the plant at 1,950 MW. Energy and exergy analysis was performed, and it was concluded that the system power output and performance will increase if the ammonia mass fraction is held constant while decreasing the exit pressure from the turbine or by increasing the fraction with the turbine exhaust pressure is constant. They also studied the Kalina cycle application in Indonesia where the highest electrical power output is reached with a 78% mass fraction and 7.4 bar exit pressure from the turbine.

Salman [26] worked on a computational investigation of the Kalina Cycle System 34 for power generation using low-medium heat source from industrial waste heat. Engineering Equation Solver (EES) was used for the thermodynamic analysis of the KCS 34. The maximum cycle efficiency was found to be about 29.5% at mass-fraction of 0.76 and inlet pressure of 100 bars. 26% efficiency was the lowest recorded at a mass fraction of 0.77 and inlet pressure of 60 bars. The pressure ranges were selected to avoid critical conditions.

2. Methodology
The following steps are undertaken for the analysis, the first step is to conduct a detailed thermodynamic analysis using mass balances, traditional energy balanced and exergy balances for the selected system or plant. This is followed by a detailed economic analysis in which the investment and operating costs for each component of the plant is determined. The next step is to calculate the component’s exergy unit cost and then the cost allocated to exergy loss for the whole system.

2.1. Thermodynamic Analysis
The thermodynamic analyses of the two cycles used the parameters from the Ormat Bulalo power plant Single OEC Unit gathered from Ormat Technologies, Inc. [27]. The turbine and pump efficiencies were based on the recommendation of Karlsdottir, Palsson, and Palsson [28].

| Parameter   | Value | Description                        |
|-------------|-------|------------------------------------|
| P<sub>high</sub> | 19.48 Bar | Pressure (High-side) |
| P<sub>low</sub>  | 1.4 Bar   | Pressure (low-side)           |
| T<sub>high</sub> | 180°C  | Geothermal Water inflow Temperature |
| T<sub>low</sub>  | 140°C   | Geothermal Water outflow Temperature |
| m<sub>W</sub>    | 361 kg/s | Geothermal water flowrate       |
| η<sub>T</sub>   | 85%    | Turbine isentropic efficiency    |
| η<sub>p</sub>   | 50%    | Pump isentropic efficiency       |

The main assumptions for the simulation are as follow:
1. The cycle works under the steady-state
2. The potential energies and kinetic energies are negligible
3. The temperature losses and pressure losses of the geothermal fluid, heat exchangers, and pipes are considered as negligible.
The thermodynamic principles of mass balance, energy balance, and exergy were used to determine
the thermodynamics equations of the components of the plant. The energy and exergy relations of the
subsystems are listed below and were used for the analysis of the binary cycle.

![Figure 1. Ormat Binary Cycle and KCS 34 Configuration (source: [19])](image)

The calculation of the properties, energy, and exergy streams was conducted using the EES program
with the parameters from Ormat and n-pentane is the motive fluid used for the Upper Mahiao geothermal
power plant situated in Leyte [15]. The equation below was used to calculate the exergy streams and
considering the dead state conditions of 27°C and 101.325 kPa.

\[
\dot{E}_E = \dot{m}[(h - h_o) - T_o(s - s_o)]
\]  

(1)

| Subsystem    | Energy Relation | Exergy Relation |
|--------------|-----------------|-----------------|
| Evaporator   | \( \dot{m}_w(h_{1w} - h_{iw}) = \dot{m}_{wf}(h_1 - h_5) \) | \( \dot{E}_{in} - \dot{E}_{int} = \dot{E}_1 - \dot{E}_5 + \dot{E}_{evap,D} \) |
| Pre-heater   | \( \dot{m}_w(h_{iw} - h_{2w}) = \dot{m}_{wf}(h_5 - h_4) \) | \( \dot{E}_{int} - \dot{E}_{out} = \dot{E}_5 - \dot{E}_4 + \dot{E}_{pht,D} \) |
| Turbine      | \( \dot{W}_t = \dot{m}_{wf}(h_1 - h_2); \eta_t = \frac{h_1 - h_2}{h_1 - h_{as}} \) | \( \dot{E}_1 = \dot{W}_t + \dot{E}_2 + \dot{E}_{turb,D} \) |
| Condenser    | \( \dot{m}_{wf}(h_2 - h_3) = \dot{m}_{cw}(h_{cw, out} - h_{cw, in}) \) | \( \dot{E}_2 - \dot{E}_3 = \dot{E}_{cw, out} - \dot{E}_{cw, in} + \dot{E}_{cond,D} \) |
| Pump         | \( \dot{w}_p = \nu_3(P_4 - P_3); \eta_p = \frac{h_3 - h_{as}}{h_3 - h_4} \) | \( \dot{W}_p = \dot{E}_4 + \dot{E}_3 + \dot{E}_{pump,D} \) |

The KCS-34 is then evaluated using the same parameters from the Binary cycle and applying
the known thermodynamics principles. The cycle has additional components namely, the separator, Low
(LT) and high (HT) temperatures recuperators, and the throttling valve. NH3H2O (ammonia-water) is
used by the Kalina cycle instead of the n-pentane. For this paper, the concentration is assumed at 50%.
\[ \rho \dot{h}_w \left( h_{1w} - h_{lw} \right) = \dot{m}_{\text{mix}} \left( h_2 - h_1 \right) \]

\[ E_i - E_{\text{int}} = E_2 - E_1 + E_{\text{vap,D}} \]

\[ W_t = m_{\text{vap}} \left( h_3 - h_5 \right) \]

\[ \eta = \frac{h_3 - h_5}{h_3 - h_{5s}} \]

\[ E_3 = W_t + E_5 + E_{\text{turb,D}} \]

\[ m_{\text{mix}} \left( h_8 - h_9 \right) = m_{\text{mix}} \left( h_{12} - h_{11} \right) \]

\[ E_8 - E_9 = E_{11} - E_{12} + E_{\text{LIR,D}} \]

\[ m_{\text{mix}} \left( h_9 - h_{10} \right) = \dot{m}_{\text{cw}} c_p c_w \left( t_{w,\text{out}} - t_{w,\text{in}} \right) \]

\[ E_9 - E_{10} = E_{cw,\text{in}} - E_{cw,\text{out}} + E_{\text{Cond,D}} \]

\[ \dot{w}_p = v \left( P_4 - P_3 \right) \]

\[ \eta_p = \frac{h_3 - h_{5s}}{h_3 - h_4} \]

\[ W_p = E_{11} - E_{10} + E_{\text{pump,D}} \]

\[ m_{\text{iq}} \left( h_4 - h_6 \right) = m_{\text{mix}} \left( h_1 - h_{12} \right) \]

\[ E_4 - E_6 = E_{11} - E_{12} + E_{\text{HTR,D}} \]

\[ \dot{m}_{\text{vap}} h_6 = \dot{m}_{\text{vap}} h_7 \]

\[ E_6 = E_7 + E_{\text{TV,D}} \]

To better evaluate the performance of the process or the system, the exergetic efficiency \( \dot{\varepsilon} \) should be calculated. This is the relative exergy value between the product \( E_p \) and the fuel \( E_F \) [29]. The \( E_P \) is the combination of the exergy losses \( E_L \) and exergy destruction \( E_D = T_0 S_{\text{gen}} \).

\[ \dot{\varepsilon} = \frac{E_P}{E_F} = 1 - \frac{E_D + E_L}{E_F} \]  

(2)

2.2. Economic Analysis

The Purchase Equipment Cost (PEC) is only a part of the total costs needed for the estimation of the capital needed for the binary plant. The operation and maintenance costs, direct and indirect costs are all part of the investment costs that are needed for the completion of the plant cost estimation. The TCI is defined as the summation of the Fixed Capital Investment (FCI), which is the capital for the purchase of land, all the facilities needed, and installation of the different types of machinery and set of equipment for the system, and all other outlays. The outlays include the startup costs after the construction but before operation (SUC), working capital to sustain the operating expenses before payment (WC), the lump-sum cost for licensing, past research, and system or process development (LRD), and allowance or interest during the time period of construction (AFUDC) [30].

The following are the assumptions made for the estimation of the FCI based on the recommendation of Bejan, Tsatsaronis, and Moran [30]. The piping cost is assumed to be 35% of the PEC, the cost for the instrumentation is at 12%, the electrical cost is at 13%, the civil works are at 21% [31] while the land cost is at 10% of the PEC [30].

Another major cost of geothermal energy development is the drilling cost of the wells. In the Philippines, geothermal resources are mostly found in mountainous regions and the drilling of exploratory wells requires the opening of new roads and pad preparations which will include cutting of trees (requires permits from DENR). The cost also includes the drilling rig and third-party contractors specialized for the drilling activities. 3 exploratory wells will be assumed for the estimation at $3,200,000 per well [32].

The SUC includes expenditures to be used only during the startup time while the WC represents the needed funds for the operations of the plant. The AFUDC is calculated as 15% of the FCI minus the LRD. Dorj [33] provided a simple formula to determine the cost for the LRD which can be obtained 150 x turbine power.

With all of these, total net capital investment together with the total net capital investment, non-depreciable and depreciable capital investments can be estimated [30].
According to Tsatsaronis [29] the economic analysis that is performed in a thermoeconomic analysis is conducted on each component and determines the capital cost of the kth component $Z_k$ in the cost balance.

### 2.3. Thermoeconomic Evaluation

Thermoeconomics or exergoeconomics analysis is based on this exergy costing of the component of the plant. This type of costing involves cost balances for the parts of the system and is determined using the exergy costs of both the inlet and outlet rates. The complete cost rate related to the total exergy flow rate is denoted by $\dot{C}^{TOT}_n$ [29].

$$\dot{C}^{TOT}_n = c_n^T \dot{E}^{TOT}_n$$  \hspace{1cm} (3)

The cost balance for the plant at steady state is written as the total rate related to the product equal to the fuel and the total capital cost rate minus the loss. The cost rate $\dot{Z}$ is the combined value of the capital investment $Z^I$ and the operating and maintenance cost $Z^{OM}$. The exergy loss cost rate $\dot{C}_L$ embodies the system loss to the surrounding. So the cost balance of the plant becomes

$$\dot{C}_p = \dot{C}_F + \dot{Z} - \dot{C}_L$$  \hspace{1cm} (4)

The rate of exergy destruction is an unseen cost that can only be exposed through the use of thermoeconomic analysis [30]. The cost of destruction can be proven by relating the cost formula of loss stream and exergy destruction and exergy loss:

$$\dot{C}_{D,k} = \dot{C}_{D,F,k} = c_{F,k}\dot{E}_{D,k} \text{ when } \dot{E}_{F,k} = \text{constant}$$ \hspace{1cm} (5)

$$\dot{C}_{D,k} = \dot{C}_{D,P,k} = c_{P,k}\dot{E}_{D,k} \text{ when } \dot{E}_{F,k} = \text{constant}$$ \hspace{1cm} (6)

It is between these two equations that the true cost of exergy destruction is calculated.

The exergoeconomic factor provides the relative significance of the non-exergy-related costs which consists of the investment costs (including O&M) and the exergy destruction and loss costs.

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{P,k}(\dot{E}_{D,k} + \dot{E}_{L,k})}$$ \hspace{1cm} (7)

A low-value factor indicates that improvement of the efficiency may be necessary to realize savings. Whereas a high-value represents a lower component investment but with exergetic efficiency affected.

### 3. Results and Discussion

The summary of the results of the simulation of the two cycles considered for the geothermal resource in the vicinity of Mabini, Batangas is shown below. The Kalina Cycle System 34 has slightly higher efficiency as compared to the Binary since it has higher power output. The total costs of the Kalina cycle are also higher due to the additional equipment purchase costs that affected the capital investment but with higher power output it has more income compared to binary and with that, the payback period is slightly faster.
Table 3. Binary and Kalina Cycle Performance

| Performance Criteria         | Binary Cycle       | Kalina Cycle       |
|-----------------------------|--------------------|--------------------|
| Power Output, kW            | 9,502.00           | 10,257.70          |
| 1st Law Efficiency          | 15.13%             | 16.33%             |
| 2nd Law Efficiency          | 51.10%             | 63.55%             |
| Mass flow, Kg/s             | 118.70             | 30.87              |
| Total Surface Area, m²      | 4,066.10           | 5,064.37           |
| Total Capital Investment, US$| 30,177,390.00      | 31,183,224.00      |
| Income, US$                 | 4,413,000.00       | 4,756,000.00       |
| Payback Period, Years       | 7.0230             | 6.7380             |
| Cost flow Rate, US$/s       | 0.0250             | 0.0368             |
| Overall Destruction and Loss Ratio | 20.8130%          | 30.0693%           |

Table 4. Binary Cycle Thermoeconomic Evaluation

| Component     | Exergetic Efficiency, $\epsilon_k$, [%] | Investment Cost, $Z_k$, US$/s | Destruction Cost, $\tilde{C}_{D,k}$, US$/s$ | Cost Sum, US$/s$ | Exergoeconomic Factor, $f_k$, [%] |
|---------------|----------------------------------------|-------------------------------|---------------------------------------------|------------------|----------------------------------|
| Condenser     | 90.41                                  | 0.000914                      | 0.02667                                     | 0.02758          | 60.84                            |
| Evaporator    | 84.65                                  | 0.001209                      | 0.0007398                                   | 0.001283         | 99.91                            |
| Pre-heater    | 66.32                                  | 0.000717                      | 0.000594                                    | 0.001311         | 89.02                            |
| Pump          | 41.63                                  | 0.008614                      | 1.203                                       | 1.212            | 68.99                            |
| Turbine       | 22.58                                  | 0.013555                      | 0.002259                                    | 0.01581          | 98.29                            |

Table 5. Kalina Cycle Thermoeconomic Evaluation

| Component     | Exergetic Efficiency, $\epsilon_k$, [%] | Investment Cost, $Z_k$, US$/s$ | Destruction Cost, $\tilde{C}_{D,k}$, US$/s$ | Cost Sum, US$/s$ | Exergoeconomic Factor, $f_k$, [%] |
|---------------|----------------------------------------|-------------------------------|---------------------------------------------|------------------|----------------------------------|
| Condenser     | 97.88                                  | 0.0015227                     | 0.0005206                                   | 0.00157476       | 38.26                            |
| Evaporator    | 83.43                                  | 0.0015729                     | 0.002364                                    | 0.0039369        | 95.6                             |
| High Temp Recuperator | 9.082                               | 0.0000823                     | 0.004907                                   | 0.0049893        | 22.42                            |
| Low Temp Recuperator | 27.01                                 | 0.00005583                    | 0.003987                                   | 0.00404283       | 19.69                            |
| Pump          | 49.89                                  | 0.009177                      | 0.0071511                                  | 0.0098921        | 99.47                            |
| Separator     | 99.4                                   | 0.000014147                   | 0.0007529                                  | 8.94E-05         | 15.81                            |
| Turbine       | 90.83                                  | 0.014332                      | 0.00337                                    | 0.017702         | 92.79                            |
| Throttle Valve| 2.325                                  | 0.00000198                    | 4.74E-06                                   | 6.72E-06         | 29.31                            |

The sum of the cost rates indicates the component that requires design changes and for the Ormat cycle, the pump registered the highest sum with 1.212 US$/s$ while for the Kalina cycle the turbine has the highest sum amongst the components at 0.017702 US$/s$. Both components must be considered for
re-design to enhance the performance of the respective cycle they are involved with. Lastly, the exergoeconomic factor of the Ormat cycle evaporator and the KCS 34 turbine recorded the highest value at 99.91% and 99.47%, respectively. With both components also included in the redesign consideration, the exergoeconomic factor of these sets of equipment will be affected once the cost and energy components are re-evaluated in order to find the balance between the energy and cost performance.

4. Conclusion

The Kalina cycle system 34 1st efficiency is higher compared to the Ormat binary cycle but it is only about 1.2% higher. This is due to the higher power output that the Kalina Cycle can produce. This is also true for the 2nd law efficiency of the KCS 34 at 63.55% while the Ormat cycle has 51.10%. With the higher power generated of the Kalina cycle, the total capital investment of the plant at 31.18 M US$ is also higher than the Binary cycle at 30.18 M US$. It also has a higher income at 4.76 M US$ with the power output generated compared to the 4.41 M US$ of the binary cycle. The payback period is slightly faster by almost a quarter of a year than that of the Ormat cycle.

Based on the results of the thermoeconomic analysis, the Kalina cycle turbine and the Ormat Cycle pump required re-design as the two equipment registered high values of the sum of the cost rates. Improvements in the performance of the two cycles can be achieved by re-designing the said equipment and using simulation and optimization. The main difference of the Kalina and the Ormat cycle is the working fluid. Kalina Cycles are designed for ammonia-water mixture while the Ormat cycle uses n-pentane. The use of the ammonia-water mixture provides flexibility in terms of adjustable concentration.

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