Economic and Thermodynamic Analysis for Preliminary Design of Dry Steam Geothermal Power Plant (GPP) with Multifarious Gas Removal System (GRS) in Kamojang, West Java, Indonesia

Aloysius Damar Pranadi, Sihana, Kutut Suryopratomo, Fiki Rahmatika Salis
Nuclear Engineering and Engineering Physics Department, Faculty of Engineering, Universitas Gadjah Mada, Jl. Grajaka 2, Sleman, Yogyakarta, Indonesia

E-mail: damarpranadi@gmail.com

Abstract. Indonesia has great number of geothermal potential separated by two kind of potential, 16.13 GW for high enthalpy and 7.88 GW for low enthalpy speculative resources [4]. In the end of 2013, Ministry of Energy and Mineral Resources stated that Geothermal Power Plant (GPP) in Indonesia have been built about 1.34 GW in capacity and wanted to seriously develop geothermal potential up to 6.64 GW by 2025 [8]. Cost is one of famous obstacle in Indonesia’s GPP Development. To reduce grand total cost of GPP, this paper will present the relation between thermodynamic and economic analysis in purpose to find the most economical gas removal system in GPP. By gleaning data at Kamojang Steam Field on behalf of PT Pertamina Geothermal Energy, this study will thermodynamically analyze and calculate a GPP preliminary design with software, named as Cycle Tempo 5.0. In additional, writers create motive steam calculator (based on C++ language) to enhance thermodynamic analysis for gas removal system (GRS) and adapted the results in Cycle Tempo 5.0. After thermodynamic analysis has been done, economic study will be undertaken by Net Present Value Analysis to compare the utilization cost of three different GRS and find which kind of GRS is more economical for nearly 30 years operation. For the result, Dual LRVP has higher performance than the others, spend less utilization cost and more economical for nearly 30 years operation. Moreover, the economic analysis for replacement of gas removal system shown in this paper too. In conclusion, GPP with Dual LRVP is proper to be developed in the future Geothermal Power Plant or to replace the existing GRS in some existing GPP in Indonesia.

1. Introduction
Indonesia is the only archipelago country with over seventeen thousand islands. It is strategically located between two continents (Asia and Australia) and two oceans (Hindi and Pacific), so geographically Indonesia stands among the eastern end of Mediterranean volcanic belt and western side of Circum Pacific volcanic belt [13]. By this, there are more than 200 volcanoes located along Sumatra, Java, Bali and the islands of eastern Indonesia [12]. It is well known as part of “Pacific Ring of Fire”, the terminology refers to the chain of volcanoes that was created by the upward intrusion of magma (molten rock) at the edge of the Pacific Plate. It makes Indonesia abundant of geothermal resources [16].

Based on calculation, Indonesia has great number of geothermal potential separated by two kind of potential, 16.13 GW for high enthalpy and 7.88 GW for low enthalpy speculative resources [4]. In the
end of 2013, Ministry of Energy and Mineral Resources stated that Geothermal Power Plant (GPP) have been existed about 1.34 GW and wanted to seriously develop geothermal potential up to 6.64 GW by 2025 [8]. Cost is one of famous obstacle in Indonesia’s GPP Development. To reduce grand total cost of GPP, this paper will present the relation between thermodynamic and economic analysis in purpose to find the most economical gas removal system in GPP. By gleaning data at Kamojang Steam Field on behalf of PT Pertamina Geothermal Energy, this study will thermodynamically analyze and calculate a GPP preliminary design with software, named as Cycle Tempo 5.0.

2. Thermodynamic Analysis
Thermodynamic analysis are fundamentally based on energy balance and mass balance which is stated in First Thermodynamic Law. This analysis are undergone for each apparatuses in Geothermal Power Plant and assisted by software calculation, Cycle Tempo.

2.1. Thermodynamic Laws
In thermodynamic system, there are two fundamental flows occurred into/out from it. They are mass and energy flow. Mass flow in a thermodynamic system depends on the inlet and outlet of it, so it can be written in mass balance as shown below in equation (1).

$$\frac{dm_{\text{system}}}{dt} = m_{\text{in}} - m_{\text{out}} \tag{1}$$

Energy flow that occurs in a thermodynamic system obeys the first law of thermodynamics. Quantity of energy in thermodynamic system is conserved, so energy which saved in system depends on the energy flow in to the system and from the system to the environment/other systems [2]. All of these should be written as energy balance in equation (2).

$$\frac{dE_{\text{system}}}{dt} = E_{\text{in}} - E_{\text{out}} \tag{2}$$

Energy flow is specifically occurred because of mass and energy transfers in form of heats and works. Total energy flow in a thermodynamic system can be written as equation (3).

$$\frac{dE_{\text{system}}}{dt} = E_{\text{m,in}} - E_{\text{m,out}} + Q_{\text{in}} + Q_{\text{out}} + W_{\text{in}} - W_{\text{out}} \tag{3}$$

2.2. Thermodynamic Laws Analysis for GPP
Further to the general scheme of GPP system, there are main apparatuses which is important to be analyzed using thermodynamic analysis:

1. Production well
2. Restriction Orifice and Master Control Valve
3. Separator/Demister
4. Turbine
5. Gas Removal System
6. Main Condenser
7. Auxiliary Condenser
8. Cooling Tower
9. Hot Well Pump

2.2.1. Production well. GPP process is begun with total energy flow from production well to GPP system. This flow can be written in equation (4).

$$\dot{m} h_{\text{out,well}} = f(P_{\text{opt}}, T_{\text{opt}}) \tag{4}$$

2.2.2. Restriction Orifice (RO) and Master Control Valve (MCV). In RO and MCV, steam is expanded into adiabatic isenthalpic condition. RO reduces pressure and temperature of geothermal fluid until
desired value has been reached. Equation (5) is a function of pressure difference ($\Delta P$) to find RO outlet mass flow.

$$\dot{m}_{out,RO} = f(\Delta P)$$  \hspace{1cm} (5)

Inlet pressure of well head and mass flow of RO are known, so outlet pressure can be determined by equation (6).

$$(\Delta P) = P_{out} - P_{in}$$  \hspace{1cm} (6)

2.2.3. Separator/Demister. Degree of dryness (vapor quality) in Kamojang steam is 99.9%, therefore Kamojang has dry steam production. Brine water from demister will be removed into brine pond and its ratio is only 0.1% from the inlet steam. Enthalpy from demister can be determined using vapor quality in the following equation [3].

$$x = \frac{h_{RO} - h_{brine}}{h_{turbine} - h_{brine}}$$  \hspace{1cm} (7)

2.2.4. Turbine. Steam will be separated before entering the turbine through governour valve. Some steam flow into turbine and the rest of steam will flow into ejector which extract NCG from condenser (GRS function). This node’s mass balance can be written in equation (8).

$$\dot{m}_{turbine} = \dot{m}_{out, demister} - \dot{m}_{motive, ejector}$$  \hspace{1cm} (8)

Energy production by turbine in isentropic condition can be written in equation (9).

$$w_{turbine} = (h_{in, turbine} - h_{out, ideal})$$  \hspace{1cm} (9)

Equation (10) will be determined by the value of enthalpy that produced by actual turbine condition. The isentropic efficiency of turbine is determined by designer, generally in 80%.

$$\eta_t = \frac{(h_{in, turbine} - h_{out, actual})}{(h_{in, turbine} - h_{out, isentropic})}$$  \hspace{1cm} (10)

The actual power output of turbine is determined using equations (11) as follow:

$$w_{actual} = \eta_t (h_{in, turbine} - h_{out, ideal})$$  \hspace{1cm} (11)

2.2.5. Gas Removal System. Actually, the most used gas removal system in GPP are ejector and liquid ring vacuum pump (LRVP). Mass balance in ejector can be written into equation (12).

$$\dot{m}_{SJE, out} = \dot{m}_{motive} + \dot{m}_{vapor} + \dot{m}_{NCG}$$  \hspace{1cm} (12)

Mass of NCG that being extracted from condenser is equal to NCG ratio in the main steams can be written in equation (13).

$$\dot{m}_{NCG} = x_{NCG} \dot{m}_{vapor}$$  \hspace{1cm} (13)

In this study, NCG and vapor are mixed under Dalton ideal gas mixture model can be written in equation (14).

$$P \dot{V}_{gas} = \dot{m}_{gas}RT$$  \hspace{1cm} (14)

NCG and vapor are mixed with Dalton model will have constant volume and temperature condition. Total pressure from condenser suction is a sum of NCG partial pressure with partial pressure of vapor.
\[ P_T = P_{NCG} + P_{wv} \]  

(15)

Generally, total of suction pressure is approximated with 90% of condenser pressure.

Mixing process is under fixed volume, so that the volume rate of NCG and vapour are equal to total volume rate or can be written into equation (16).

\[ \dot{V}_{\text{total}} = \dot{V}_{NCG} = \dot{V}_{wv} = \dot{V} = \dot{m}_{NCG}RT/(P_T - P_{wv}) \]  

(16)

The mass flow rate of suction vapour in following equation.

\[ \dot{m}_{wv} = \dot{V}_{wv}/\nu_{wv} \]  

(17)

After determining mass flow rate of vapor, mass flow rate of motive steam can be known using practical approximate. Average of molecular weight in overall wells can be written in equation (18).

\[ M_{r\text{average}} = \sum_{n=0}^{\infty} \frac{m_{\text{gas}}}{m_{\text{gas total}}} \times M_{r\text{specific gas}} \]  

(18)

After determining molecular weight, the next is determining the entertainment ratio (ER) of each gas with each molecular weight. \( ER_{nCG} \) and \( ER_{wv} \) can be found using equation (19) and (20). ER is used to find air rate that needed to draw a gas from condenser [14].

\[ ER_{nCG} = \left[ (5.737 \times 10^{-4} \times 18.37) + \frac{2.01 \times (M_{nCG})^{0.86}}{(18.37 + (M_{nCG})^{0.86})} \right] \]  

(19)

\[ ER_{wv} = \left[ (5.737 \times 10^{-4} \times 18.37) + \frac{2.01 \times (M_{wv})^{0.86}}{(18.37 + (M_{wv})^{0.86})} \right] \]  

(20)

After knowing ER of each gas, total air equivalent can be determined using the following equation [14].

\[ TAE = \left[ \frac{\dot{m}_{nCG}}{ER_{nCG}} + \frac{\dot{m}_{wv}}{ER_{wv}} \right] \]  

(21)

Air-vapor ratio can be found by using equation of compression ratio and expansion ratio and put into air-steam ratio graph in Figure 1.

\[ Er = \frac{P_{\text{motive steam}}}{P_{\text{suction}}} \]  

(22)

\[ Cr = \frac{P_{\text{outlet/discard}}}{P_{\text{suction}}} \]  

(23)

Air-vapor ratio can be obtained by the intersection two lines (expansion ratio line and also compression ratio line) in Figure 1. Motive steam mass can be determined using equation as follow:

\[ \dot{m}_{\text{motive}} = \frac{TAE}{AS} \]  

(24)

In LRVP, the mass balance of LRVP can be written in equation (25).

\[ \dot{m}_{\text{water.out}} = \dot{m}_{\text{water.in}} + \dot{m}_{\text{vapor.in}} \]  

(25)

The presence of motor and LRVP efficiency can be considered as additional power need in power plant which can be written in equation (26).

\[ W_{LRVP} = k \eta_{m\text{\textbar LRVP}} \frac{\dot{m}_{RT}}{M_r} \left[ \frac{(P_d)}{P} \right]^{k-1} - 1 \]  

(26)
2.2.6. Main condenser and Intercondenser. Direct contact condenser is the most effective condenser in GPP because the vapor and water are mixed directly [1]. The direct heat exchange can minimize the design of condenser and also reduce the needs of cooling water. Through this latent heat transfer, heat transfer will occur more rapidly and require smaller heat transfer area. In direct contact condenser, mass balance can be known using equation (27).

\[ \dot{m}_{\text{out}} = \dot{m}_{\text{cw}} + \dot{m}_{\text{vapor}} \]  

(27)

Energy balance in condenser can be written into equation (28).

\[ \dot{m}_{\text{out}} h_{\text{out}} = \dot{m}_{\text{cw}} h_{\text{cw}} + \dot{m}_{\text{vapor}} h_{\text{vapor}} \]  

(28)

Cooling water rate needs in condenser can be known by using mass and energy balance combination in the following equation.

\[ \dot{m}_{\text{cw}} = \dot{m}_{\text{vapor}} \frac{h_{\text{vapor}} - h_{\text{out}}}{h_{\text{out}} - h_{\text{cw}}} \]  

(29)

2.2.7. Cooling tower. There are two mass balances in cooling tower, they are water mass balance and air mass balance. In cooling tower, an amount of inlet air mass flow is equal to outlet air mass flow, so that can be written in the following equation.

\[ \dot{m}_{\text{air, in}} = \dot{m}_{\text{air, out}} = \dot{m}_{\text{air}} \]  

(30)

In water mass balance there is a change of amount water content because of evaporation process, so mass of inlet water in cooling tower is not equal anymore with mass of outlet water. Drift loss is negligible because it isn’t significant to others, water mass balance in cooling water can be written in equation (31).

\[ \dot{m}_{\text{water, in}} + \omega_{\text{air, in}} \dot{m}_{\text{air, in}} = \dot{m}_{\text{water, out}} + \omega_{\text{air, out}} \dot{m}_{\text{air, out}} \]  

(31)
In cooling process, water is sprayed into small water droplet and mixed with an air. The air flows into cooling tower by fan inducing. The fan power can be determined by the following equation.

\[ P_{fan} = \frac{m_{air} \Delta p}{\eta_{is} \eta_{motor} \rho_{air}} \]  

(32)

2.2.8. Hot well pump. Power of hot well pump is written into general form as following equation [1]:

\[ W_{HW P} = \frac{m_H}{\eta_m \eta_{pump}} \times 3.67 \times 10^5 \]  

(33)

2.3. System Performance Parameter

In this study, there are some performance parameters, which is by these parameters the system will be detected whether the system is in good condition or not. These are exergetic efficiency, gross specific steam consumption and net specific gross consumption which their equations has shown below, respectively [1].

\[ \eta_{Ex} = \frac{W_{nett}}{\sum m_{well} (h_{out} - h_{amb})} \]  

(34)

\[ SSC_{gross} = \frac{m_{steam}}{P_{gen}} \times 3600 \]  

(35)

\[ SSC_{net} = \frac{m_{steam}}{P_{gen} - P_{aux}} \times 3600 \]  

(36)

For GPP, there is another parameter called as parasitic load, which shown as total electricity consumption for auxilliary components in system, such as pump, fan and others. Parasitic load will be accounted totally to these simulations to get the net electricity produced and sold by GPP.

3. Economic & Performance Analysis

To calculate Gas Removal System (GRS) cost in Geothermal Power Plant (GPP), Performance Analysis for Preliminary Design must be described from the actual data of the other existed GPP in Kamojang. The most important performance properties in Economic Calculation is GPP’s availability factor. Availability factor is defined as the ratio of GPP’s operation time while really producing the electricity \( t_{operation} \) and the total operation time of plant \( t_{actual} \).

\[ AV_{factor} = \frac{t_{operation}}{t_{actual}} \times 100 \% \]  

(37)

In Preliminary Design, GPP is designed to achieve plant performance as equal as other existed plants. Based on data, other plants have 3 kinds of overhaul time, they are First Inspection Day, Minor Overhaul and Major Overhaul. First inspection day is the earliest overhaul time with estimated taking 24 x 26 days off-plant after the new power plant commissioned and firstly operated around 2 years. Minor Overhaul is the four-year maintenance which is firstly done 2 years after First Inspection Day. This overhaul only checks the small apparatuses (such as piping, sensor, separator) and just takes briefer time around 24 x 14 days. In the other hand, Major Overhaul is the four-year maintenance and overhaul for all plant apparatuses include turbines, condenser, cooling tower and other main apparatuses. This overhaul takes 24 x 26 days every 2 years after minor overhaul taken. Throughout 30 years existing \( t_{actual} \), this plant will be able to have 1 times First Inspection Day, 7 times Minor Overhaul and 7 times Major Overhaul. By this, the operation time will be known by equation (38).

\[ t_{operation} = t_{actual} - t_{overhaul} \]  

(38)

This availability factor is the basic of economic calculation of GRS cost comparison. By this, GRS will be operated as plant available time \( t_{operation} \). For LRVP, the cost will be calculated based on the
electricity consumption in 30 years and for ejector, the cost will be calculated based on steam potential loss in 30 years. Steam potential loss is steam which has no potential to produce electricity because it is used by the ejector. Actually it has potential to produce electricity if it is not used by the ejector. So, this steam potential loss can be calculated as electricity because of potential to be processed and changed to electricity on turbin. By this, the equation (39) will explain about electricity equivalent from those steams.

\[ P_{\text{equi}} = \dot{m}_{\text{motive}} \times 3600 / \text{SSC}_{\text{gross}} \]  

(39)

For double LRVP, the total power calculation will be written on equation (40).

\[ P_{\text{30\,years}} = (P_{\text{LRVP1}} + P_{\text{LRVP2}}) \times \text{Av\,factor} \times t_{\text{actual}} \]  

(40)

For hybrid GRS, the total power calculation will be written on equation (41).

\[ P_{\text{30\,years}} = (P_{\text{equi1}} + P_{\text{LRVP2}}) \times \text{Av\,factor} \times t_{\text{actual}} \]  

(41)

For double ejector, the total power calculation will be written on equation (42).

\[ P_{\text{30\,years}} = (P_{\text{equi1}} + P_{\text{equi2}}) \times \text{Av\,factor} \times t_{\text{actual}} \]  

(42)

After that, basic GRS cost calculation will be done by equation (43).

\[ C_{\text{GRS}} = P_{\text{30\,years}} \times \text{US\,Dollar/kWh} \]  

(43)

Not only from the calculation of GRS utilization cost, but also other costs is included as initial cost on Net Present Value (NPV) method. NPV method is one of economic method with most effective and accurate technique based on most modern books and courses [5]. Generally, NPV method can be defined in equation (44) and (45).

\[ NPV = FV - I \]  

(44)

\[ NPV = \sum_{n=0}^{n-1} PV \times (1 + r)^n - I \]  

(45)

On those equations, \( FV \) is future value of revenue (USD), \( I \) is for investment cost (USD), \( PV \) is for annual present value of revenue in this case is electricity sale revenue (USD), \( r \) is the number of interest rate in Bank of Indonesia averagely at 7.5% in last quarter of 2013 – December 2015 (BI Rate Data, 2016) and \( NPV \) is net present value of GPP revenue (USD).

Investment cost consists of operation and maintenance (O&M) cost, capital cost and GRS utilization cost. Capital cost comprises of two basic cost, aparatus initial cost (like ejector unit price) and installation cost. The installation cost will be predicted with Uppal’s Installation Factor provided on Table 1.

| Name                | IF  | Name            | IF  |
|---------------------|-----|-----------------|-----|
| Air Cooler          | 1.7 | Agitator        | 1.1 |
| Blower              | 1.1 | Boiler (package)| 0.9 |
| Bullets (pressured)| 0.9 | Centrifuge      | 1.5 |
| Compressor          | 1.2 | Cooling tower   | 0.6 |
| Cyclone             | 1.5 | Drums (horizontal)| 1.6 |
| Drum (vertical)     | 2.4 | Dryer           | 1.6 |
| Dust Collector      | 1.9 | Evaporator      | 2.2 |
| Exchanger           | 1.85| Filter (rotary) | 1.6 |
| Furnace (package)   | 1.2 | Hopper (bolted) | 1.5 |
For initial cost, data on the site is prohibited to be published, so the writers try to create the approximation of cost by the data which is taken from Geremew’s research on Alto Geothermal Power Plant with complete price from the manufacturer. This will assume that Kamojang GPP have the same product’s brand and specification for ejector & LRVP as listed in Table 2. The reference equipment condition was defined by 100 lb/hr air plus 20 lb/hr water vapor, 10 mmHg vacuum, 100 PSIG steam and 85 Fahrenheit Degree of water, while required equipment defined for minimum 1.539 kg/s plus 0.4178 kg/s water vapor, Maximum 2.64 kg/s plus 0.497 kg/s water vapor, up to 12.47 bar steam and 0.09 bar suction [5].

Table 2. Initial/equipment cost for GRS [5].

| No | Ref equipment specification | Ref Price USD | Required Equipment Specification                      | Scale Up Factor (SF) | Required Price USD |
|----|------------------------------|---------------|--------------------------------------------------------|----------------------|--------------------|
| 1  | Steam Ejector(G0.04 kg/s)   | $19,793       | Steam Ejector (1.97 kg/s)                              | 1.97                 | $38,992            |
|    |                              |               | Steam Ejector Hybrid (2.622 kg/s)                      | 2.622                | $51,897            |
| 2  | LRVP Vectra XL 35 6.3 HP     | $27,413       | LRVP (900 HP or 670 kW)                                | 14.29                | $391,614           |
|    |                              |               | LRVP Hybrid (352 HP or 262 kW)                         | 5.59                 | $153,165           |
| 3  | LRVP Vectra XL 45 8.6 HP     | $30,685       | LRVP (900 HP or 670 kW)                                | 10.47                | $321,122           |
|    |                              |               | LRVP Hybrid (352 HP or 262 kW)                         | 4.09                 | $125,594           |
| 4  | LRVP Vectra XL 60 17.5 HP    | $47,967       | LRVP (900 HP or 670 kW)                                | 5.14                 | $246,687           |
|    |                              |               | LRVP Hybrid (352 HP or 262 kW)                         | 2.01                 | $96,482            |

From those, the capital cost for each GRS will defined by equation (46).

\[ C_I = C_E + IF \times C_E \]  \hspace{1cm} (46)

In 2011, Teke has defined Maintenance Cost Factor (MCF) for plant’s simple economic calculation. MCF for ejector is 2% of Equipment/Initial Price \( (C_I) \) and LRVP’s MCF is 5% of Equipment/Initial Price \( (C_I) \) [5]. This simplification is parallel with actual maintenance, where ejector just need low additional spare parts (low prices) and simple actions, otherwise the LRVP needs higher price spareparts and more complicated works for maintenance. Operation & Maintenance Cost is determined as the cost to pay the laborer, parts retrofitting and replacement and also total major/minor inspection during 30 years operation. To simplify the calculation, Teke just create MCF to summarize the all cost to be annual cost [5]. So the annual cost of operation and maintenance can be written in equation (47).

\[ C_{O&M} = MCF \times C_E \]  \hspace{1cm} (47)

Operation and Maintenance (O&M) cost \( (C_{O&M}) \) is annual cost that must be calculated with NPV calculation. So equation (47) must be rewrite as equation (48) for 30 years calculation \( (n = 30) \).

\[ C_{O&M,30} = \sum_{0}^{n-1} PV \times (1 + r)^n \]  \hspace{1cm} (48)

In conclusion, investment \( (I) \) can be rewritten in equation (49).
After GRS calculation, the amount of electricity sale revenue must be defined as equation (50). So by this, the NPV after GRS investment will be obtained.

\[ PV = w_{\text{gen}} \times \text{US Dollar/kWh} \]

(50)

To know, the replacement effect in economic calculation (based on NPV method), the cost benefit analysis must be adapted in NPV method. Cost benefit will be described in 3 cases, such as Dual Ejector to Hybrid, Dual Ejector to Dual LRVP and Hybrid to Dual LRVP. So general equation for those replacements will defined in equation (51).

\[ NPV_{\text{replacement}} = NPV_{\text{after}} - NPV_{\text{before}} \]

(51)

4. Data and Basic Assumptions
Geothermal Power Plant Development Unit in Kamojang utilizes 4 main production wells, they are A, B, C and D in Table 3, and some process apparatuses listed in Table 4 [10].

**Table 3. Steam quality in each well (A, B, C, D).**

| Parameter                     | A            | B            | C            | D            |
|-------------------------------|--------------|--------------|--------------|--------------|
| Enthalpy (kJ/kg)              | 2781.29      | 2782.05      | 2781.78      | 2780.87      |
| Steam Flow (kg/s)             | 6.614        | 22.157       | 37.728       | 11.87        |
| Well Head Pressure (bar-a)    | 15.55        | 17.35        | 18.81        | 19.61        |
| RO Outlet Pressure (bar-a)    | 11.19        | 11.43        | 11.34        | 11.06        |

**Table 4. Components spesification in GPP dry steam unit at Kamojang, West Java [9, 10, 14].**

| No  | Component/Spesification | Amounts/Type                  |
|-----|-------------------------|-------------------------------|
| 1   | Demister                |                               |
|     | Pressure Loss (bar-a)   | 0.3                           |
|     | Pressure Inlet (bar-a)  | 9.7                           |
| 2   | Turbine                 |                               |
|     | Turbine Inlet Pressure (bar-a) | 6.5                         |
|     | Turbine Isentropic Efficiency | 80%                         |
|     | Turbine Inlet Temp. (Celcius) | 166                         |
| 3   | Generator               |                               |
|     | Generator Efficiency    | 97%                           |
| 4   | Condenser               |                               |
|     | Type                    | Direct contact                |
|     | Inlet Pressure (bar-a)  | 0.1                           |
|     | Outlet Water Temp. (Celcius) | 42.7                        |
|     | Cooling Water Temp. (Celcius) | 26                          |
| 5   | Cooling Tower           |                               |
|     | Type                    | Wet mechanical induced draft  |
|     | Input Air Temperature   | 20                            |
|     | Output Air Temperature  | 36.7                          |
|     | Relative Humidity       | 91%                           |
|     | Inlet Pressure of Fan (bar-a) | 0.85                       |
Outlet Pressure of Fan (bar-a) 0.8512
Water Output Temp. (Celcius) 26
Fan Isentropic Efficiency 70%
Fan Motor Efficiency 80%

6 Gas Removal System
Input Pressure Stage I (bar-a) 0.09
Input Pressure Stage II (bar-a) 0.35
Final Output Pressure (bar-a) 0.9
Input Temp. Stage I (Celcius) 30
Input Temp. Stage II (Celcius) 32
LRVP Eff. (Isentropic & Motor) 60%

5. Models and Simulations
Thermodynamics analysis which included mass balance and energy balance in GRS variations will be performed in software, Cycle Tempo 5.0. Input value in simulation refers to data as shown in table 3 and table 4. Simulation will be performed into 3 variations; dual LRVP, hybrid and dual ejector. One of those models is shown in Figure 2. In actual condition, the weight of NCG molecule in Kamojang is about 1% averagely, but to present the thermodynamic and economic effect of NCG content, it will be varied from 1% content until 5% content (the range of possible NCG contents in Indonesia). In this simulations, the average molecular weight of NCG is 39.5 kg/mol, based on its chemical properties.

For economic analysis, this research will use NPV method. The calculation boundaries, this research just provide GRS utilization cost depends on kWh power for LRVP and kWh equivalent to steam for ejector, because of the limitation of maintenance cost data for LRVP and ejector and the confidential data about both initial cost. The detail assumption have been explained at Economic and Performance Analysis.
Figure 2. Calculation of geothermal power plant by cycle tempo 5.0.
6. Results
Based on thermodynamic analysis, the increase of parasitic load was experienced in all GRS as NCG increased. The highest parasitic load is shown by Dual LRVP in the same NCG, such as in 1% NCG Dual LRVP has parasitic load close to 1.81 MW, Hybrid has 1.73 MW and Dual Ejector has 1.61 MW. The growth of 1% NCG is multifarious for each GRS. In Dual LRVP, each 1% NCG growth, parasitic load will increase nearly 409 kW, in the other hand the lowest growth is experienced by Dual Ejector with 206 kW per 1% NCG increased. In hybrid GRS, the parasitic load growth is in 323 kW per 1% NCG growth (Figure 3).

![Parasitic Load Increment in NCG variations of Difference Gas Removal Systems](image)

**Figure 3.** Parasitic load increment as NCG increasing in 3 GRS variations.

In this study, NCG contents are assumed to relatively affect the enthalpy change for its inlet turbine so there is no change for gross power result in dual LRVP. It is stagnated in 38 MW in any percentage of NCG content. In the meantime, hybrid and dual ejector diminish their gross power from the lower NCG content because of the motive steam needs increased. The gross power average reduction (per 1% NCG increased) is nearly 1.02 MW for hybrid and 2.18 MW for dual ejector system. As the results, in 1% NCG, gross power for hybrid GPP is 37.00 MW while for dual ejector GPP is 35.82 MW.

Because of parasitic load growth is undergone as long as NCG content increased, there is net production alteration in each GRS. In 1% NCG, Net Power for dual LRVP reached 36.19 MW, while hybrid producing 35.24 MW net power and dual ejector producing 34.21 MW net power. In the higher NCG contents, hybrid produces less 1.35 MW for each 1% growth. Dual LRVP losses its net power by 0.41 MW per 1% NCG growth and dual ejector, which is the highest one, decreasing its net power by 2.38 MW per 1% NCG growth. In 5% NCG, Net Power for dual LRVP reaches 34.55 MW, while hybrid producing net power for 29.86 MW and dual ejector producing for 24.69 MW. Gross and Net Power can be shown in Figure 4.
Specific steam consumption (SSC) in this study has also resulted from the simulation. The net and gross SSC in each GRS has decreased as NCG content increasing. In 1% NCG, net SSC of dual LRVP is 7.80 kg/kWh, hybrid is 8.01 kg/kWh and dual ejector is 8.25 kg/kWh. The net SSC reduction in each NCG content increasing is approximately 0.092 kg/kWh, 0.361 kg/kWh and 0.795 kg/kWh respectively. For gross SSC in 1% NCG, dual LRVP has shown the result in 7.43 kg/kWh, while hybrid in 7.63 kg/kWh and dual ejector in 7.88 kg/kWh. By the assumption (no effect for enthalpy change in turbine), gross SSC reduction stand in stagnant number, but hybrid and dual ejector has shown the reduction (per 1% NCG increasing) are close to 0.237 kg/kWh and 0.632 kg/kWh respectively.

The most important factor for GPP performance is exergetic efficiency, which by the NCG increasing efficiency exergetic will be decreased because net product has also been decreasing. Exergetic efficiency for GPP with dual LRVP change from 49.91% (1% NCG) to 47.65% (5% NCG). In the other results, for GPP with hybrid GRS change its exergetic efficiency from 48.61% (1% NCG) to 41.19% (5% NCG) and for GPP with dual ejector change its from 47.19% (1% NCG) to 34.05% (5% NCG). Exergetic Efficiency in GPP with GRS variations can be shown in Figure 5.

---

**Power Production in NCG Contents Variation for GPP Kamojang**

Figure 4. Power production in NCG variations.

**Exergetic Efficiency in Difference NCG Contents**

Figure 5. Exergetic efficiency of GPP in NCG and GRS types variations.
In another scenario, thermodynamic analysis are able to look for the effect of GRS selection to the steam need flows in system. Further to these analysis, the steam need is multifarious among the GRS variations. In dual LRVP, NCG growth has slightly rose the steam needs to produce the same net product. Steam needs has no additional steam flow while NCG is still in 2% and 3%, but in 4% NCG contents there is additional steam flow about 0.37 kg/s and in 5% NCG the additional steam flow is about 1.4 kg/s to produce 35 MW in any NCG contents. Another results show that dual ejector need additional steam about 1.68 kg/s to produce 35 MW in 1% NCG. In the higher NCG, the additional steam flow average increase about 4.14 kg/s. For hybrid, in 1% NCG there is no additional steam need, but in 2% NCG the additional steam need is around 2.3 kg/s, in 3% NCG the additional steam need is around 5.10 kg/s, in 4% NCG it will be 7.93 kg/s and 5% NCG the additional steam need will increase to 10.72 kg/s. The final results of this scene can be shown in Figure 6.

**Steam Flow Needs in GPP with Difference GRS**

![Figure 6. Steam needs increment due to NCG increment.](image)

Under economic calculation, the GRS cost with 1% NCG is calculated for all of GRSs throughout 30 years (availability factor 97.205%), where hybrid GRS needs 28,122,129 US $ (24 million US$ for steam cost, 4 million US$ for electricity cost), dual LRVP needs 9,901,668 US$ electricity cost and dual ejector needs 51,074,343 US$ steam cost). The simple results are shown on Table 5. From the calculation, Dual LRVP has the highest capital cost and operational cost from other GRSs. In comparison, Hybrid help the designer of GPP to reduce the initial cost, but this action will reduce the electricity production as the ransom. So by selling electricity 30 years, the NPV gross profit for the company is highest with Dual LRVP as its GRS. The NPV gross profit for Dual LRVP, Hybrid and Dual Ejector are USD 3,099,755,769; USD 3,003,092,570; and USD 2,892,174,218 respectively.

| Parameter                | Dual LRVP | Hybrid | Dual Ejector |
|--------------------------|-----------|--------|--------------|
| Gross Production (MW)    | 38.00     | 36.98  | 35.82        |
| Parasitic Load (MW)     | 1.81      | 1.73   | 1.61         |
| Net Production (MW)      | 36.19     | 35.24  | 34.21        |
| Exergetic Efficiency (%) | 51.13     | 49.81  | 48.34        |
| Gross SSC (%)            | 7.43      | 7.63   | 7.88         |
| LRVP Power Utilization 30 years (GWh) | 104.23 | 44.30 | 0.00 |
Electricity Loss caused by Ejector
30 years (GWh)
Total Electricity Loss by GRS
(GWh)
Electricity Selling 30 years (USD)
Capital Cost 30 years (USD)
O&M Cost 30 years (USD)
Utilization Cost 30 Years (USD)
NPV Gross Profit after 30 years
(USD)

0.00
252.78
537.62
104.23
297.08
537.62
USD
USD
USD
USD
USD
USD

3,113,781,398.11
3,032,628,602.45
2,943,609,208.79
USD
USD
USD
USD
USD
USD

1,307,469.00
441,410.00
172,689.10
USD
USD
USD
USD
USD
USD

2,816,491.16
872,493.46
187,957.37
USD
USD
USD
USD
USD
USD

9,901,668.40
28,222,128.77
51,074,343.44
USD
USD
USD
USD
USD
USD

3,099,755,769.55
3,003,092,570.22
2,892,174,218.88
USD
USD
USD
USD
USD
USD

To present the economic effect from NCG content, Figure 7 shows that the cost will have higher differences in higher NCG proportion on the steam. If NCG is about 5%, the cost of GRS with dual LRVP just spend approximately 50 millions US Dollar. The cost of GRS with Dual Ejector will spend greatest money about a quarter of billions US Dollar, while hybrid GRS is spending just under 150 million US Dollar.

Figure 7. Utilization cost on 3 GRS with different proportion of NCG in steam

For maximum replacement benefit analysis based on NPV method, the results will be represented on Table 5. In the table, NPV replacement in GPP with NCG 1% for Hybrid to Dual LRVP will take benefit for company around 96 million US Dollar for 30 years operation, for Dual Ejector to Hybrid is around 110 million US Dollar, and for Dual Ejector to Dual LRVP is around 207 million US Dollar. More NCG containtments on the steam will boost NPV replacement and replacement will be strongly recommended.
Table 6. Optimization Replacement Profit for GPP dry steam Kamojang

| NPV Profit for Replacement | NCG 1%  | NCG 2%  | NCG 3%  | NCG 4%  | NCG 5%  |
|----------------------------|---------|---------|---------|---------|---------|
| Hybrid to Dual LRVP        | USD 78,342,738.97 | USD 156,125,839.65 | USD 236,600,400.95 | USD 322,902,080.93 | USD 392,463,791.20 |
| Dual Ejector to Dual LRVP  | USD 166,408,875.63 | USD 331,915,956.72 | USD 501,986,709.37 | USD 676,304,938.09 | USD 833,758,694.98 |
| Dual Ejector to Hybrid     | USD 88,066,136.66  | USD 175,790,117.07 | USD 265,386,308.42 | USD 353,402,857.16 | USD 441,294,903.77 |

7. Conclusions
In conclusion, Net Power (NP) for dual LRVP reaches 36.19 MW, while hybrid GRS producing net power in 35.24 MW and dual ejector producing for 34.21 MW. Exergetic efficiency for GPP with dual LRVP is 49.91%, hybrid GRS is 48.61% and dual ejector is about 47.19%. Under economic calculation, the GRS cost is calculated for all of them throughout 30 years (availability factor 97.205%, NCG 1%), where hybrid GRS needs 28,122,129 US $ (24 million US$ for steam cost, 4 million US$ for electricity cost), dual LRVP needs 9,901,668 US$ electricity cost and dual ejector needs 51,074,343 US$ steam cost. The NPV gross profit for Dual LRVP, Hybrid and Dual Ejector are USD 3,099,755,769; USD 3,003,092,570; and USD 2,892,174,218 respectively.

The maximum replacement benefit in Kamojang GPP (1% NCG) for Hybrid to Dual LRVP will take benefit for company around 96 million US Dollar after 30 years operation, for Dual Ejector to Hybrid is around 110 million US Dollar, and for Dual Ejector to Dual LRVP is around 207 million US Dollar.

For conclusion, based on economic and thermodynamic analysis, Dual LRVP is the best GRS implemented in the future Dry Steam GPP although its NCG is just about 1% and it will be better implemented for more than 1% NCG Geothermal field. At last, Dual LRVP implementation will improve GPP production in the future, not only for Dry Steam GPP but also for Wet Steam GPP in Indonesia. So the research on Wet Steam GPP is strongly recommended to be implemented in the future.

8. Acknowledgments
We would like to show our greatest gratitude to Mr. Aris Kurniawan (Thesis Supervisor/ Sr. Prod. Staff), Mr. Roy Bandoro Swandaru (Prod. Manager) dan Mr. Riyanto T.P. (Prod. As. Manager) for their opportunity, supervisory time, advices and insight sharings in geothermal process and power plant which is greatly assisted by this research and Aloysius Damar Pranadi’s undergraduate thesis. This research was supported by PT Pertamina Geothermal Energy, Kamojang. Thank you so much for a home of newborn researcher, Nuclear Engineering and Engineering Physics Department, University of Gadjah Mada. We thank to Mr. Alexander Agung and Mr. Singgih H. for their pearl of wisdom and advices to revised the research results. We would like to thank to Delft University of Technology, Asimptote, and TNO which has developed Cycle Tempo 5.0 and very useful for international students learn more about power plant analysis [6, 11.15].

References
[1] Bagus, H. S., 2010. Basic Design of Lumut Balai 2 x 55 MW Geothermal Power Plant, Indonesia. Report 2010 Number 29 (Reykjavik, Iceland: United Nations University Geothermal Training Programme)
[2] Cengel Y A and Boles M A 2006 Thermodynamics: An Engineering Approach. 5th edn (New York: McGraw-Hill)
[3] DiPippo, R., 2012. Geothermal Power Plants: Principle, Application, and Case Study. Elsevier Science. pp. 450.
[4] Fauzi, Amir, 2015, Revision of Geothermal Resource Counting Presentation. *Presentation and Course Material.* (Bandung: ITB International Geothermal Workshop)

[5] Habtamu, G., 2012. A Study of Thermodynamic Modelling and Gas Extraction System Design for Aluto Langanano Geothermal Power Plant II in Ethiopia. *Report 2012 Number 10.* (Reykjavik, Iceland: United Nation University Geothermal Training Program)

[6] Introduction Cycle Tempo 5.0. *Technical Document* (TU Delft: Faculty of Mechanical, Maritime, and Materials Engineering Delft Institute of Technology)

[7] Millachine M A T 2011 *Guidelines for Optimum Gas Extraction System Selection* (University of Iceland: Faculty of Industrial Engineering, Mechanical Engineering and Computer Science)

[8] Nenny, S., 2015. Geothermal for Everyone. *Presentation in ITB International Geothermal Workshop* (Bandung, Indonesia: ITB International Geothermal Workshop)

[9] Perry B H and Green D W 2008 *Perry’s Chemical Engineers’ Handbook* (New York: McGraw-Hill)

[10] PT. Pertamina, 2015, Pertamina Geothermal Energy’s Data. *Technical Document.* (Kamojang: PT. Pertamina)

[11] Reference Guide. *Technical Document.* (TU Delft: Faculty of Mechanical, Maritime, and Materials Engineering Delft Institute of Technology)

[12] Suryadarma, Ibrahim, R.F., and Fauzi, A.(2005) The Progress of Geothermal Energy Resources Activities in Indonesia, *Proceedings of World Geothermal Congress 2005*, 24-29 April 2005, (Turkey: World Geothermal Congress 24-29 April 2005)

[13] Suryantoro, S., Dwipa, S., Ariati, R., and Darma S. (2005) Geothermal Deregulation and Energy Policy in Indonesia. *Proceedings of World Geothermal Congress 2005* (Turkey: World Geothermal Congress 24-29 April 2005)

[14] Swandaru, Roy B., 2006, Thermodynamic Analysis of Preliminary Design of Power Plant Unit I Patuha, West Java, Indonesia. *Report 2006 Number 7.* (Reykjavik, Iceland: United Nation University Geothermal Training Program)

[15] Technical Notes. *Technical Document* (TU Delft: Faculty of Mechanical, Maritime, and Materials Engineering Delft Institute of Technology)

[16] Wijaya, Muhammad E. and Limmeechokchai B. Optimization of Indonesian Geothermal Energy Resources for Future Clean Electricity Supply: A Case of Java-Madura-Bali System. (Thailand: King Mongkut’s University of Technology Thonburi Paper)