Performance Evaluation of Geothermal Power Production Using EES (Case Study Ulumbu Geothermal Power Production Unit 4 East Nusa Tenggara, Indonesia)

Prajamukti Ediatmaja, Prihadi Setyo Darmanto and Dimas Taha Maulana
Geothermal Engineering Master’s Program, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jl. Ganesha 10, Bandung 40132, Indonesia

Email: prajamukti.ediatmaja@gmail.com
https://orcid.org/0000-0002-3102-3753

Abstract. Ulumbu geothermal working area (GWA) is in Ruteng district, East Nusa Tenggara province, Indonesia. Ulumbu GWA is owned by PLN. There are four geothermal power plants (GPP) in Ulumbu, which capacity 4 x 2.5 MW. It has operated since 2013. Steam used to generate electricity comes from ULB-2 production well. Wellhead temperature and pressure were 180-200°C and 11 bar. Ulumbu GPP Unit 4 uses a condensing type turbine. It has specific steam consumption (SSC) during commissioning around 9.8 T/MW. After 6 (six) years of operation, SSC becomes 10.04 T/MW on average. It gives a chance to perform optimization in the GPP’s equipment. Before performing optimization, evaluation for every equipment based on as-built data is done by modeling using EES software. The method of evaluation is performed by thermodynamics analysis in each GPP’s equipment. EES is chosen due to its simplicity to arrange many equations in a single window. EES could communicatively display calculation results through a parametric table, solution window, and diagram window. Operation data give information that turbine inlet pressure is operated under its specification. Non-Condensable Gas (NCG) content also decreases based on the last ULB-2 well fluid sampling. Using EES, parameter changes in turbine inlet pressure and NCG content are simulated to get optimum power generation value. The simulation results indicate that optimum turbine inlet pressure is obtained at 9.3 bar with SSC 9.17 T/MW. Ulumbu GPP Unit 4 that operated in that condition could reach cycle efficiency of about 10.39%.

1. Introduction
Ulumbu GWA is located in Ruteng District, East Nusa Tenggara province, Indonesia. There are 4 x 2.5 MW of GPP in Ulumbu GWA operated by Cogindo, the sub-subsidiary of PLN. GPPs in Ulumbu are divided into two groups. Two units are using dry cycle back-pressure turbines, and the others are using dry cycle condensing turbines. The research was performed in Ulumbu GPP Unit 4 that uses a dry cycle condensing turbine. The Ulumbu GPP Unit 4 started to supply electricity to the local grid in 2013. The final performance test by PLN Jaser before the commercial operation date stated the SSC for Ulumbu 4 was 9.8 T/MW [1]. The steam for all four units in Ulumbu is supplied from ULB-2 production well. PLN UIP Kitring Nusra carried out production well testing for ULB-2 with the results WHP range from 10.8-19.6 barg, steam mass flow rate 117.25-75.23 T/h, reservoir temperature 240°C,
and enthalpy 2773-2787 kJ/kg [2]. The background of this study is to analyze Ulumbu Unit 4 GPP using modeling software. The dry cycle condensing turbine equation model was built in EES (SN#5706) based on Ulumbu Heat Balance Diagram to calculate the generation output. Thermodynamics’ Second Law is used to assist the analytical evaluation for this cycle. Heat Balance Diagram Ulumbu provides design value for all equipment, and it could be used as an input of the model. Using the EES model, simulation for change in turbine inlet pressure and NCG content could be known.

2. Methods
In this study, the methods to create Ulumbu Unit 4 model in EES, firstly literature study about the dry steam cycle that uses condensing turbine. Secondly, collecting operation data, equipment specifications, and steam chemistry composition needed for input to the model (i.e., turbine pressure and temperature; condenser pressure and temperature). Operation data is taken for 4 (four) months when the unit is operated in full load condition. The equation modeling in EES is built based on heat balance diagram data. After finishing the equation model, it is followed by running the equation model and matching the actual operational data results. The flow chart diagram of this method is simplified in (Figure 1).

![Flow chart diagram of study method.](image)

3. Dry Cycle Condensing Turbine
The working cycle in GPP is included in the Rankine cycle. Ideal Rankine cycle happens when working fluid through a turbine, condenser, pump, and boiler without irreversible process, pressure change due to friction inside the condenser is neglected, heat transfer from system to the environment or otherwise is neglected, and process inside the turbine is assumed isentropic [3]. Rankine cycle is expressed in temperature $T$ and entropy $s$ diagram. The plotting $T$-s diagram for Ulumbu Unit 4 is shown in (Figure 2). Process 2-3s is isentropic expansion inside the turbine from saturated steam in Point 2 into condenser pressure in Point 3s. Process 2-3 is actual expansion inside the turbine from saturated steam into condenser pressure. Process 3-4 is a heat transfer process from working fluid flow inside the condenser to the cooling tower in the constant pressure and temperature to Point 4.

3.1. Thermodynamic Analysis
GPP development plan is started by resource calculation, choosing an appropriate thermodynamic cycle, power plant design, and determining every equipment specification, then simulate all parameters to get the optimum output power [4]. ULB-2 production well could produce dry steam with the quality is 99.99%. NCG content for the Ulumbu Unit 4 GPP design is assumed around 3%. Based
on the Ulumbu Unit 4 T-s diagram and the Second Law Thermodynamics, the following Equations (1) and (2) could be used to determine electric power production.

\[ W_t = m_s (h_2 - h_3) = m_s \eta_t (h_2 - h_{3s}) \]  
\[ W_{gen} = \eta_g W_t \] (1) (2)

\[ \eta_t = \frac{W_{gen}}{\eta_g m_s (h_2 - h_{3s})} \] (3)

Where \( W_t \) and \( W_{gen} \) are turbine and generator power, respectively (kW), \( m_s \) is steam flow rate (kg/s), \( h \) is enthalpy (kJ/kg) and \( \eta_g \) is generator efficiency (%). It could use Equation (3) to determine turbine efficiency.

Using real generator output with the assumption of \( \eta_g \) 98%, the turbine efficiency of Ulumbu Unit 4 is around 66 – 68 %.

The cooling water mass flow rate through the main condenser is estimated by using the energy balance law. The simulation results diagram in Appendix A1 shows that the main condenser's energy balance equation is stated as Equation (4).

\[ (m_3 + m_{3NCG})h_3_{mix} + m_7 h_{w7} = m_{16NCG}h_{NCG} + m_4 h_{w7} \] (4)

Where \( m_3, m_7, m_4 \) are a mass flow for steam, cooling water, and condensate respectively (kg/s). Subscript NCG means for NCG. \( h_{3_{mix}} \) is the enthalpy of mixture between steam and NCG while \( h_{w7} \) is the enthalpy of cooling water (kJ/kg).
Table 1 shows the operation and design parameters of Ulumbu Unit 4. By applying Equations (1) until (3), the generator power gross output was 2514 kW for main steam flow 20.6 T/h using design parameter input. SSC calculation for Ulumbu GPP is determined by Equation (5).

$$SSC = \frac{m_s}{W_{gen\,gross}}$$

(5)

where $m_s$ is steam flow to the turbine (kg/s) and $W_{gen\,gross}$ is generator power (kW). SSC calculation based on simulation and Ulumbu Heat Balance Diagram is 8.19 and 8.20 (T/MW), respectively.

### Table 1: Parameter of Ulumbu Unit 4 GPP.

| Parameter                  | Unit   | Operation | Design          |
|----------------------------|--------|-----------|-----------------|
| Generator Output Gross     | kW     | 2531      | 2500-3000       |
| Generator Output Net       | kW     | 2228      | 2229-2729       |
| Steam flow rate            | T/h    | 23.9      | 20.6-27.5       |
| Temperature inlet turbine  | °C     | 176       | 186             |
| Condenser pressure         | MPa    | 0.015     | 0.012           |
| Condenser temperature      | °C     | 53        | 49              |
| NCG content                | %      | 2.2       | 3.0             |
| $\eta_{generator}$         | %      | 96        | 96              |
| $\eta_{pump}$              | %      | 86        | 86              |

3.2. Steam Jet Ejector (SJE)

SJE is designed to eject NCG content carried over in steam into the turbine and finally accumulate in the condenser. If the NCG is not ejected from the inside of the condenser, it could cause a disturbance for the expansion process from the turbine to the condenser. The design of SJE is unique for every GPP, depending on the amount of NCG content, main condenser pressure, and atmospheric pressure in the environment of GPP. When SJE operates, as long as the amount of motive steam is sufficient to accommodate NCG content in the condenser, the condenser’s pressure would be kept stable. However, when the NCG content in the steam increases, the amount of motive steam required also increases. This situation will increase steam consumption from the production well.

Motive steam capacity could be calculated using the following step [5]. Firstly, determine the entrainment ratio NCG to steam water. Entrainment ratio ($E$) is the ratio of gas weight to the equivalent weight of steam water. $E$ is determined by Equations (6) and (7).

$$E_{NCG} = (5.73 \times 10^{-4} \times 18.36) + \frac{2.01 \times M_{NCG}^{0.86}}{18.36 + M_{NCG}^{0.86}}$$

(6)

$$E_{H2O} = (5.73 \times 10^{-4} \times 18.36) + \frac{2.01 \times M_{H2O}^{0.86}}{18.36 + M_{H2O}^{0.86}}$$

(7)

$M_{NCG}$ and $M_{H2O}$ are molecular mass from NCG and steam water. NCG gas is dominant with CO$_2$. Therefore $TAE$, $CR$, and $ER$ could be determined by Equations (8) to (10).

$$Total \, air \, equivalent \, (TAE) = \frac{m_{water \, vapour}}{E_{H2O}} + \frac{m_{NCG}}{E_{NCG}}$$

(8)

$$Compression \, Ratio \, (CR) = \frac{P_{Outlet \, ejector}}{P_{Suction}}$$

(9)

$$Expansion \, Ratio \, (ER) = \frac{P_{Motive \, fluid}}{P_{Suction}}$$

(10)
By using \( CR \) and \( ER \) values, air to the steam ratio \( U \) could be determined by using the graphic in (Figure 3) [5]. Motive steam mass flow is calculated by Equation (11).

\[
m_{\text{motive steam}} = \frac{TAE}{U}
\]  

(11)

Figure 3. Air to steam ratio graphic [5].

3.3. Cooling Tower (CT)
CT is equipment for cooling the condensate water from the main condenser, 1st mix-condenser, and 2nd mix condenser become cooling water. Cooling water is supplied then to all of the condenser and equipment’s heat exchanger. Inside the direct contact condenser, cooling water is sprayed using a nozzle to produce mist in the condenser. The mist increases effective surface contact with steam in the condenser. CT performance is characterized by Approach \( A \), Range \( R \), and cooling efficiency [6]. These CT performance parameters are expressed in Equations (12) to (16).

\[
A = t_{c2} - t_{wb}
\]  

(12)
\[ R = t_c^1 - t_c^2 \]  
\[ \eta_{\text{cooling eff}} = \frac{t_c^1 - t_c^2}{t_c^1 - t_w} \]  
\[ G = \frac{m_{cw} C_w (t_c^1 - t_c^2)}{[(h_2 - h_1)]} \]  
\[ \frac{L}{G} = \frac{h_2 - h_1}{c_{\text{air}} (t_c^1 - t_c^2)} \]  

Where \( t_c^1 \) and \( t_c^2 \) are the temperature of condensate water entering CT and cooling water from CT (°C), \( t_w \) is ambient wet bulb temperature (°C), \( \eta_{\text{cooling eff}} \) is CT efficiency, \( G \) is airflow through CT (kg/s), \( m_{cw} \) is condensate cooling water flow (kg/s), \( C_w \) is cooling water specific heat (kJ/kg °C), \( h_1 \) and \( h_2 \) are inlet and outlet air enthalpy through CT (kJ/kg). While \( \frac{L}{G} \) is the ratio between water (L or \( m_{cw} \)) and air mass flow (G). \( \frac{L}{G} \) the ratio in CT is unique for every design of CT that will be installed in an area with the specific weather condition.

To calculate CT fan power, Leeper has an approach formula based on the rule of thumb [7]. Equations (17) and (18) are used to estimate CT fan power regarding British Units.

\[ P_{\text{Fan}} = \frac{F}{8000} \]  
\[ F = \frac{(1 + H_t)}{60 \rho_{\text{mix}}} G \]  

where \( P_{\text{Fan}} \) is fan power (hp), \( F \) is the airflow rate in acfm (actual cubic feet of air per minute), \( H_t \) is air humidity (lbs H2O/lbs dry air), \( \rho_{\text{mix}} \) is the density of moist air (lbs/ft3), and \( G \) is the airflow rate (lbs air/hr.).

3.4. Circulating Water Pump (CWP)
Uluumbu GPP Unit 4 has 2 × 50% CWP that is used to discharge condensate water from the hot well to the cooling tower. CWP has the biggest share in parasitic load. If the pump load could be optimized, the power consumption of CWP motor could be reduced. The pump load is influenced by the amount of condensate water from the main condenser, 1st stage mixing condenser, and 2nd stage mixing condenser. CWP motor power calculation could be approached by Equation (19) [8].

\[ W_{\text{motor}} = \frac{m_{cw} g H}{\eta_{\text{pump}} \eta_{\text{motor}}} \]  

where \( W_{\text{motor}} \) is CWP motor power (kW), \( m_{cw} \) is cooling water flow (kg/s), \( g \) is the gravity constant (m/s²), \( H \) is pump head (m), and \( \eta \) is the pump and motor efficiencies.

4. Build Equation Model in EES
Engineering Equation Solver (EES) is a tool that could facilitate the solution of the large set of coupled equations that result from the analysis of a typical engineering system [9]. Four screen displays are often used to solve the equations in EES. To create an overall equation uses the Equation Window screen for the first time we open EES. The calculation result would be displayed in Solution Window or Diagram Window. To perform analytics related to the change of some working parameters, Parametric Table could facilitate this work. EES is also equipped with built-in mathematics, thermodynamics, and mechanical design function that could be called if necessary.

Modeling Uluumbu GPP Unit 4 dry cycle in EES is created by entering about 210 equations. There are 22 station points used to describe the condition in every GPP’s equipment (see Appendix A1 and A2). The overall Uluumbu Unit 4 GPP system is divided into smaller part to make it easier when creating the equations. Figure 4 is an example of a small part of the Uluumbu system created when it was being analyzed.
Figure 5 is part of the equations used to calculate the work of Ulumbu Unit 4 GPP system. These equations are written in Equation Window. No special syntax or wording needed to be followed when the equations are written. It just likes common typing in Microsoft Word.

Figure 4. Dividing Ulumbu Unit 4 GPP overall system into a small part of the system.
Before solving the equations, EES has a facility to check the written equations. EES will check the equality of used variables and units. When the number of equations and variables are equal, the equations could be solved. Calculation of every state would be displayed in an Array Table and Solution. Parametric Table could be used to know the effect of some parameter changing into a general arrangement of equations results. To compare the initial results and that after some parameter is changed, the overlay plot could be used. Figure 6 presents the calculation result after changing the main steam flow ($m_\text{s}$) parameter.

## 5. Result and Discussion

The agreement between the calculation of performance parameters (the turbine output power, SSC, and condensate water flow rate) using the EES developed model with the design conditions has been obtained. Using the EES proposed model, the turbine efficiency could also be evaluated and value around 66-68%. During the operation period in 2019, the variation of SSC is presented in Figure 7. The fluctuation value of SSC is in the range of 9.2 up to 11.8 T/MW. The average value of SSC during this operational period is 10.04 T/MW. However, based on Heat Balance, where other operational parameters and assumptions are kept constant, the EES simulation result shows that SSC Ulumbu Unit
4 could reach 8.2 T/MW when turbine inlet pressure is set at 11 bara. In this case, the value of SSC is not influenced by the variation of steam mass flow. The steam mass flow rate variation is proportional to the delivered power, and there is an optimum condition, as mentioned by Di Pippo [10].

The Ulumbu 4 installed turbine’s technical design specification is 3360 kW maximum output at inlet steam pressure 11 bara and 27.5 T/h of steam flow rate. Unfortunately, this turbine was coupled with a generator that could only deliver 3000 kW of maximum power. Finally, this pair turbine generator has a maximum output power of 3000 kW. Considering the generator’s maximum capacity, the maximum allowable steam flow rate that could be delivered to the turbine is 24.48 T/h (6.78 kg/s). In this condition, the cycle efficiency could reach 12.29% (see Figure 8) while the reference value is 16-17% for dry cycle condensing for reservoir enthalpy of 2650 – 2850 kJ/kg [11]. Our simulation result with a turbine inlet steam flow of 20.6 T/h (5.72 kg/s) gives a cycle efficiency of about 11.93% (see. Appendix A1).

![Figure 7. Ulumbu Unit 4 GPP’s SSC and load trending during 2019.](image)

![Figure 8. General Efficiency vs. Inlet Turbine Steam Flow.](image)
Ulumbu Unit 4 GPP is designed with the assumption that maximum NCG content is 3%. After the commercial operation, the amount of NCG content of ULB-2 production well decreases to the average value of about 2.2% [12]. Besides the decrease of NCG content, due to the change of operating wellhead pressure, the steam pressure at the inlet scrubber becomes 9.6 bar. Consequently, the inlet turbine operation pressure of Ulumbu Unit 4 GPP becomes 8.6 bar. Using these real operation parameters (i.e., turbine inlet pressure, condenser pressure, condenser temperature, NCG content, and environment temperature), the power plant performance simulation is repeated, and the results are given in (Figure 9).

In contrast, the calculation of mass and heat balance is given in (Appendix A2). Figure 9a shows that every 1% change of NCG content will affect the SSC value of around 0.1 T/MW. The variation of NCG content is in line with the change of the ejector’s motive steam consumption. Every 1% change of NCG content will increase the overall steam required for Ulumbu Unit 4 of about 5-7%. However, the condenser pressure can still be maintained constant if the motive steam supply can be met.

![Figure 8](image_url)
Figure 9. Effects of NCG content to generated power, SSC, general efficiency (a), and motive steam consumption (b).

Increasing turbine inlet steam pressure will increase cycle efficiency and decrease SSC. However, increasing turbine inlet steam pressure will result in a parabolic pattern where the optimum generator output will occur [10].

Using current conditions as an input parameter of the proposed EES model, variations in turbine inlet pressure from 7 to 10.1 bar will result in variations in power, cycle efficiency, and SSC, as shown in Figure 10. The simulation results give information that the optimum turbine inlet steam pressure is 9.3 bar. In that condition, the SSC is 9.17 T/MW and cycle efficiency of about 10.39%. However, if the turbine inlet pressure is operated at a current 8.6 bar, the SSC is 9.3 T/MW, in which the cycle efficiency is around 10.69% (Figure 10).
6. Conclusion

EES simulation modeling based on Heat Balance Diagram and operation condition for Ulumbu Unit 4 GPP has been carried out. The performance evaluation using this proposed model could be used for predicting SSC and cycle efficiency with the variation of turbine inlet pressure and NCG content. The decrease of NCG by 1% could affect SSC about 0.1 T/MW. Based on the current operational conditions, the inlet turbine steam pressure should be set at 9.3 bar to get optimum generator output netto. Using this condition, the value of SSC and cycle efficiency will be 9.17 T/MW and 10.39%, respectively. However, if the turbine inlet steam pressure is set at 8.6 bar as determined during operation in 2019, the obtained SSC and cycle efficiency will be 9.3 T/MW and 10.69%, a bit more wasteful than the optimum conditions.

References

[1] PLN Jasa Sertifikasi 2013 Performance test report Ulumbu GPP, PT. PLN (Persero) Jasa Sertifikasi, Jakarta
[2] PLN UIP Kitring Nusra 2011 Flow test ULB-02 production well, Ulumbu Flores - NTT, Surabaya, Indonesia
[3] Moran M J, Shapiro H N, Munson B R and DeWitt D P 2002 Introduction to Thermal System Engineering (USA: John Willey & Sons, Inc)
[4] Siregar P H 2004 Optimization of Electrical Power Production Process for the Sibayak Geothermal Field, Indonesia Proc., The United Nations University Reykjavik
[5] Fresston D H 1996 Geothermal technology: teaching the teachers’ course stage III, Engineering Notes
[6] Nag P K 2002 Power Plant engineering 2nd Edition (India: Mc Graw Hill)
[7] Leeper Stephen A 1981 Wet cooling tower: rule of thumb design and simulation (US: Department of Energy)
[8] Sinaga R H M and Darmanto P S 2017 Energy optimization and gas removal selection of geothermal power plant Geothermics 48 ICSEE
[9] Klein S and Nellis G 2014 Mastering EES F-Chart Software (US: Madison)
[10] DiPippo Ronald 2011 Geothermal power plants: principles, applications, case studies, and environmental impact (UK: Oxford, Elsevier)
[11] Moon H and Zarrouk S J 2012 Efficiency of geothermal power plants: A worldwide review,
New Zealand Geothermal Workshop Proc.

[12] Geoservice 2016 Certificate of analysis Bandung
APPENDIX A1: Simulation Result for Ulumbu GPP Based on Heat Balance Diagram
APPENDIX A2: Simulation Result for Ulumbu GPP Based on Operational Data