JURNAL REKAYASA PROSES

Research article / Vol. 14, No. 1, 2020, pp. 30-46

Journal homepage: http://journal.ugm.ac.id/jrekpros

Evaluation on Energy Efficiency Improvement in Geothermal Power Plant with The Application of Load-based Gas Removal System and Cooling Water Pump Control System

Wibisono Yamin*, I.G.B. Ngurah Makertihartha, and Jenny Rizkiana

Department of Chemical Engineering, Faculty of Industrial Technology, Institut Teknologi Bandung

Jalan Ganesha No.10, Bandung, Jawa Barat, Indonesia 40132

*Corresponding author: wibisono.yamin@gmail.com

(Submission: 4 March 2020; Revision: 25 May 2020; Acceptance: 2 June 2020)

ABSTRACT

Efficient Geothermal Power Plant (GPP) operation can be achieved through the optimum use of steam for turbine and auxiliary (ejectors), and minimum possible condenser pressure for maximum energy conversion in the turbine. In all GPPs, a condenser vacuum is maintained by adequate circulation of cooling water and effective operation of ejectors, which absorb the accumulation of Non-Condensable Gas (NCG), mostly CO_2 and H_2S, and dispose it to the atmosphere. Typically, GPPs are designed for baseload (100% capacity) operation. Therefore, the performance of supporting equipment such as ejectors and cooling water pumps are not sensitive to load-set fluctuations or changes in NCG content. This fact consequently results in constant parasitic load and ejector's motive steam consumptions. Since 2017 many GPPs in Indonesia have no longer operated at constant full capacity following demand fluctuation, as stated in grid dispatcher's Daily Operating Plan. This condition brings up energy efficiency opportunity to reduce steam and electricity own use through modification or installation of the load-following controller in the ejector system and cooling water pumps. The study aimed to identify the best alternative in devising this adaptive feature in gas removal and circulating water systems from economic and technical aspects. Evaluation's methodology included the development of GPP process modeling and data validation, setting up an alternative framework, testing of GPP performance for each alternative with the calibrated model, and decision analysis from economic and technical aspects to select the best option. The evaluation showed that the ejector's motive steam flow controller was able to reduce auxiliary steam usage at maximum by 7% (equal to 0.7 MWe). In comparison, the circulation water flow controller with Variable Frequency Drive (VFD) could reduce pumps electricity use by 35% (0.76 MWe). The study results recommended the implementation of a motive steam flow controller over the pump's VFD, considering its economic performance, operation flexibility, and lower execution risk.

DOI: 10.22146/jrekpros.54656

Published online: 30 June 2020

e-ISSN 2549-1490 p-ISSN 1978-287X

Keywords: cooling system optimization; ejector control system; ejector simulation; gas removal system optimization; geothermal power plant

A B S T R A K

Operasi Pembangkit Listrik Tenaga Panas Bumi (PLTP) yang efisien dapat dicapai melalui penggunaan uap yang optimal pada turbin dan sistem pendukung (ejektor), serta pengaturan tekanan kondensor yang rendah untuk mencapai konversi energi maksimum di turbin. Pada hampir semua PLTP, kevakuman kondensor dijaga melalui sirkulasi air pendingin yang memadai, dan efektivitas operasi ejektor dalam menghisap akumulasi Non-Condensable Gas (NCG), yaitu CO_2*, dan* H_2S*, serta dispersinya ke atmosfer. Pada umumnya PLTP didesain untuk beroperasi pada basis bebannya (100% kapasitas) sehingga kinerja peralatan penunjang seperti ejektor dan pompa tidak sensitif terhadap fluktuasi beban pembangkitan maupun perubahan kandungan NCG dari sumur. Hal ini mengakibatkan pemakaian listrik sendiri dan konsumsi uap ejektor pada PLTP cenderung tetap. Sejak 2017 banyak PLTP di Indonesia tidak lagi beroperasi dengan kapasitas penuh karena mengikuti fluktuasi permintaan grid seperti yang dinyatakan dalam Rencana Operasi Harian dari pengatur beban. Kondisi ini memberi peluang upaya efisiensi energi untuk mengurangi konsumsi listrik dan uap melalui modifikasi dan instalasi pengontrol load-following pada sistem kerja ejektor dan pompa sirkulasi air pendingin. Studi ini bertujuan untuk mengidentifikasi alternatif terbaik dalam merancang fitur adaptif ini, baik dari aspek ekonomi maupun teknis. Metodologi evaluasi mencakup pengembangan pemodelan proses PLTP dan validasi datanya, menyiapkan kerangka evaluasi alternatif, pengujian kinerja PLTP untuk setiap alternatif dengan model yang terkalibrasi, dan analisis pemilihan opsi terbaik secara ekonomi dan teknis. Hasil evaluasi menunjukkan bahwa pengontrol aliran uap motif pada ejektor mampu mengurangi penggunaan uap maksimum sebesar 7% (setara 0,7 MWe), sedangkan pengontrol aliran air sirkulasi dengan Variable Frequency Drive (VFD) dapat mengurangi penggunaan pompa listrik sebesar 35% (0,76 MWe). Hasil studi merekomendasikan penerapan sistem pengontrol aliran uap motif pada ejektor dibandingkan aplikasi VFD pada pompa dengan mempertimbangkan kinerja ekonomi, fleksibilitas operasi, dan risiko eksekusinya yang lebih rendah.*

Kata kunci: pengoptimalan sistem pendinginan; pengoptimalan sistem penyisihan gas; PLTP; sistem kontrol ejektor

1. Introduction

Geothermal Power Plants (GPP), like other thermal energy-based power plants, operate by following the principle of the Rankine Cycle (DiPippo, 2016). The basic process flow of GPP and its thermodynamic cycle are represented in Figure 1 and 2 respectively.

The 2-phase steam from wells (1) is separated in steam separator into dry steam (2) and condensate (3) through the isenthalpic process. Dry steam is then expanded in the turbine (2 to 4) to produce work (electricity) that ideally occurs in the isentropic process. Exhaust steam (4) is condensed in the condenser (4 to 5) at constant pressure. Lastly, condensate is reinjected to earth to be naturally reboiled into 2-phase steam (1).

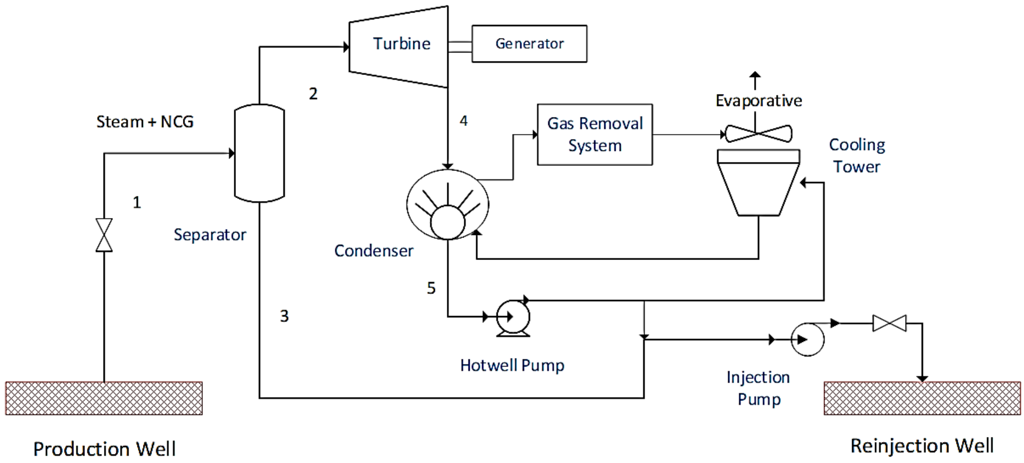


Figure 1. Geothermal power plant schematic diagram

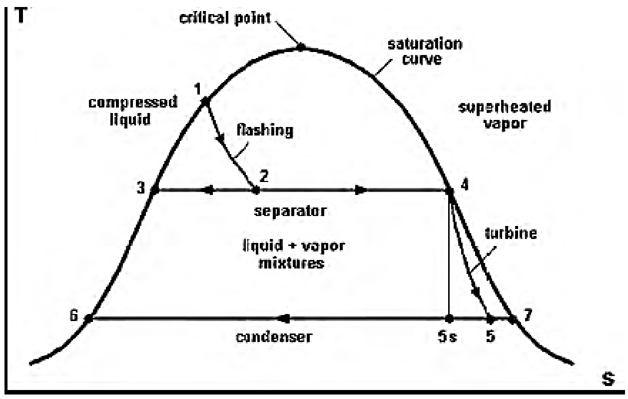


Figure 2. Geothermal power plant T-S diagram (DiPippo, 2007)

One of the factors that affect power plant efficiency is the amount of Non-Condensable Gas (NCG), such as CO_2 and H_2S, in steam supply. Almost all GPPs make use of Gas Removal System (GRS) that consists of the ejector(s) and vacuum pump(s) to maintain condenser pressure by extracting NCG accumulation and disposing it to the atmosphere. The GPP surface facilities design are typically started before the production wells drilling are entirely done. Therefore, the design basis of NCG contents used for sizing equipment could be two to three times the actual condition due to the high uncertainty of geofluid properties at the early stage of the project.

In general, GPPs are designed to work on a load basis (100% capacity) so that the performance of its utilities such as ejectors and pumps is not sensitive to fluctuations in generation loads or changes in NCG content (percent weight in total steam supply). Since 2017 many GPPs in Indonesia have no longer operated at 100% capacity after demand fluctuation, as stated in the grid dispatcher's Daily Operating Plan.

The daily plan requires the GPPs to reduce generation from the baseload to the minimum take-up provision as per schedule. Consequently, this has positioned the GPPs to be part of the load-following system, while typically, its house load remains constant throughout the period (Figure 3).

This condition brings up energy efficiency opportunities to reduce steam and electricity own use through the installation of a load-following controller in the ejector system and cooling water pumps.

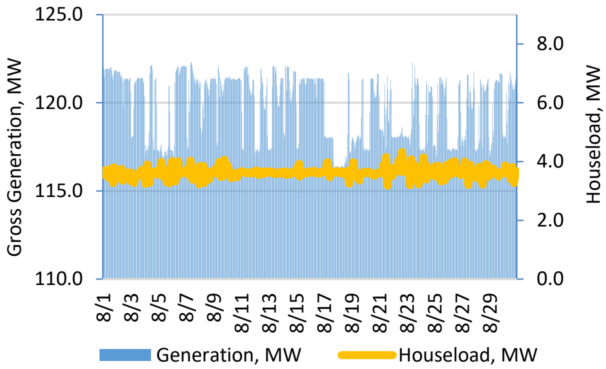


Figure 3. Example of generation and house load profile of GPP during load fluctuation

Among the substantial amount of works in literature, several studies were known to have analyzed the improvement of ejector performance and power plant efficiency. Hanafi et al. (2015) suggested an optimum point of motive fluid pressure was to be set as close to the critical pressure limit (choked flow) as possible to obtain the highest efficiency. Lines and Smith recommended the ejector's motive steam pressure not to exceed 20% above to maintain optimum operation (Lines and Smith, 2000). One of "off-design" GRS modifications for the adaptive operation was suggested by Blatchley, who proposed the use of an air pump with a ratio controller to adjust motive fluid flow-rate during low NCG load to meet operating conditions (Blatchley, 2017).

Energy efficiency in the circulating water system was evaluated in several studies. DiPippo observed practicality to regulate water flows through the condenser with Variable Frequency Drives (VFD) that provide flexible control and ability to save energy, given the pump affinity laws, where power is proportional to the cube of the motor speed (DiPippo, 2016). Sinaga et al. have modeled the application of VFD in 121 MW GPP that increase plant overall efficiency by 0.1% (Sinaga, et al., 2017). However, all the previous studies were only done on a steady-state basis, and no specific research has examined the stability of the control function under transient conditions during load changes.

Based on current GPP's operating mode as well as previous researches results and limitations, this study was commenced aiming at identifying the best alternative in devising load-following features in gas removal and circulating water systems (both in steady-state and dynamic point of view) by considering its economic and technical aspects. Two possible energy efficiency improvements being evaluated are (1) optimization of GRS motive steam usage with motive steam flow control, and (2) optimization of circulating water system with the application of pump VFD and circulating water flow controller.

2. Research Methodology

The methodology included the following steps: 1) developing GPP process modeling and data validation by using HYSYS software, setting up alternatives framework, 2) testing GPP performance for each alternative with the calibrated model for both the steady-state and transient conditions, 3) performing economic and technical (constructability, operability, and maintainability) assessments as part of decision analysis to select the best-recommended option.

2.1 Geothermal Plant Modeling

A complete plant process modeling was developed with Aspen HYSYS® V.10 software to analyze energy efficiency opportunities. The modeling was expected to be able to perform thermodynamic calculations, data validation and reconciliation, and steady-state and dynamic simulation. The model was made to represent the GPP process flow, as shown in Figure 4.

As shown in Figure 4, there are three series of ejectors in GRS. During regular operation, only the first and the second stage of ejectors are operated, while the last stage was standby unit, and it was not included in the evaluation.

Steam produced from wells containing impurities (NCG) that consists of CO_2 (90%wt.) and H_2S (~ 10%wt.). Therefore, it is required to select the right Equation of State (EOS) for modeling Vapor-Liquid Equilibrium (VLE) for H_2O-CO_2-H_2S mixtures. For this purpose, PRSV was chosen over several other compatible EOS in the software (Sour PR and Sour SRK) since it has the lowest error in predicting boiling temperature and heat capacity within the model, operating envelope (0.087– 17.27 bara). An example of a boiling point error calculation is shown in Figure 5.

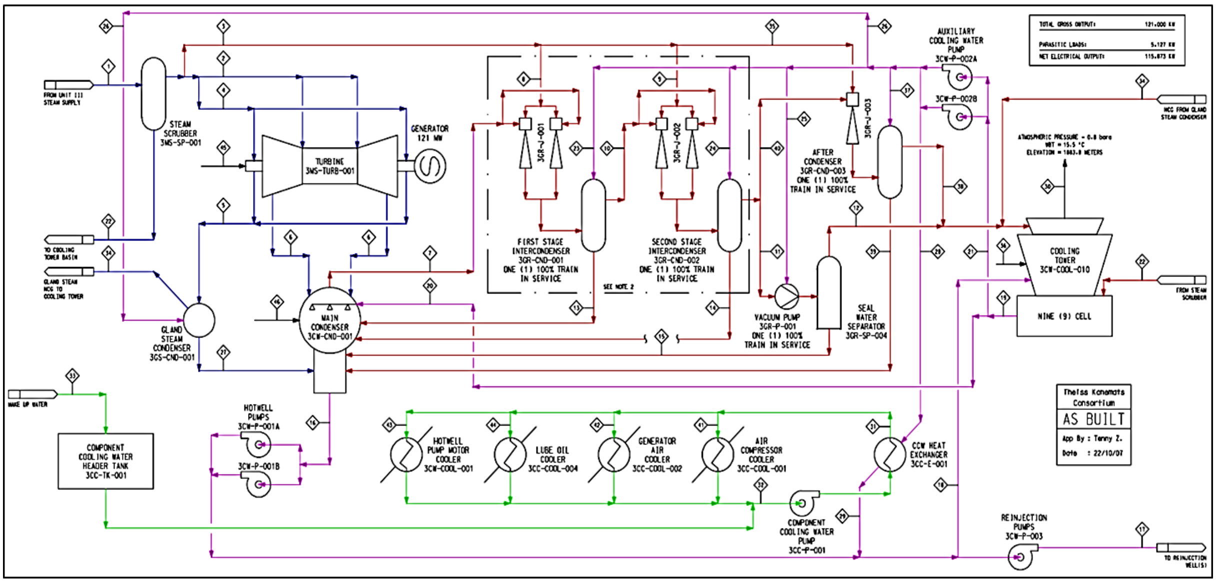


Figure 4. GPP process flow diagram proprietary of Star Energy Geothermal Darajat II, LIMITED

Figure 5. Boiling point error of EOS Sour PR, Sour SRK and PRSV vs. pressure (bara)

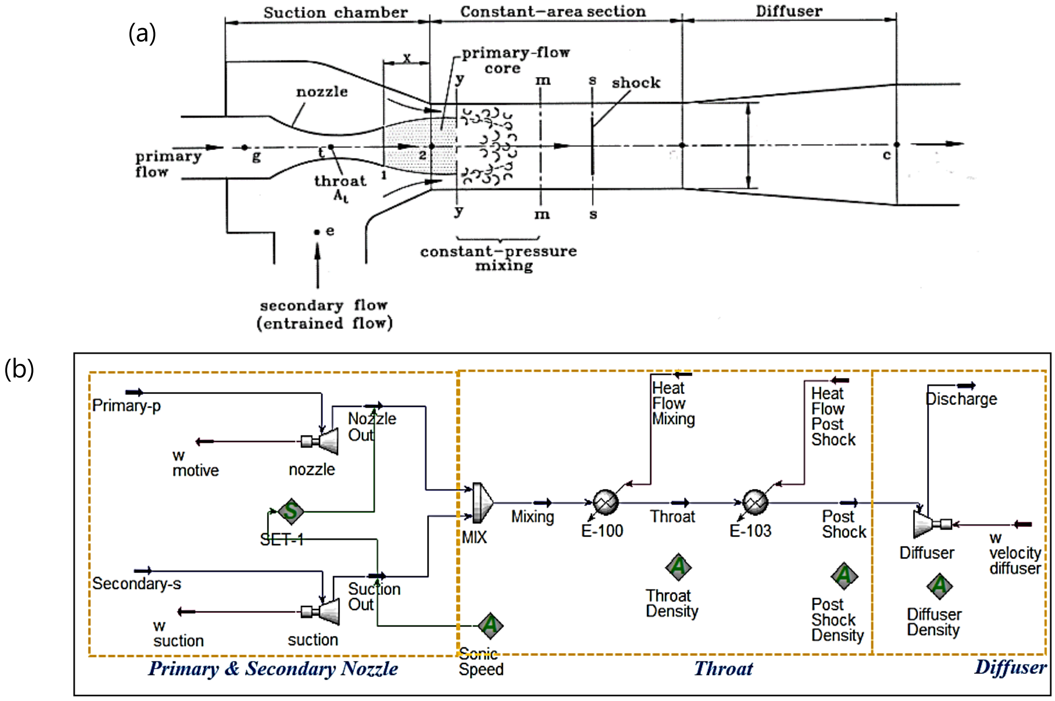


Figure 6. (a) Steam ejector design flow path (Huang et al., 1985) and (b) HYSYS model for ejector

Especially for equipment that is not readily available in HYSYS, such as ejector, the simulation was made by integrating several operating units to represent the essential parts (Figure 6). The ejector model used expander (nozzle), a heat exchanger (mixing throat), and a compressor (diffuser). The overall model was then made by integrating all equipment (Figure 4) into one complete simulation.

Once the base model was completed, actual operating data downloaded from the Plant Information System were inputted into the simulation. Since not all data were accurately available (i.e. instrumentation error), Data Validation and Reconciliation (DVR) was performed by using HYSYS Data Fit® feature. DVR is needed to reach the point of convergence and to obtain an acceptable degree of accuracy for meeting the requirements of heat and mass balance (error below 2%).

2.2 Optimization Alternatives Evaluation

Optimization focused on identifying the lowest possible energy usage in GRS and Cooling Water system during the load-following mode. With the developed GPP model, optimization evaluation was carried out according to the framework in Figure 7.

The proposed optimization in GRS was the installation of the control system for the flow rate adjustment of the motive steam (Figure 8). Flow Control Valve is installed on the motive steam supply line for each ejector stage, which will adjust the steam flow rate according to the system requirements, following instructions of the flow controller. Flow Controller is equipped with Flow Computer that determines the amount of steam motive needed by using the process. The benefit was defined as the difference in steam consumption compared to baseline conditions, especially during load fluctuation, and accumulated as the value of steam saving on an annual basis.

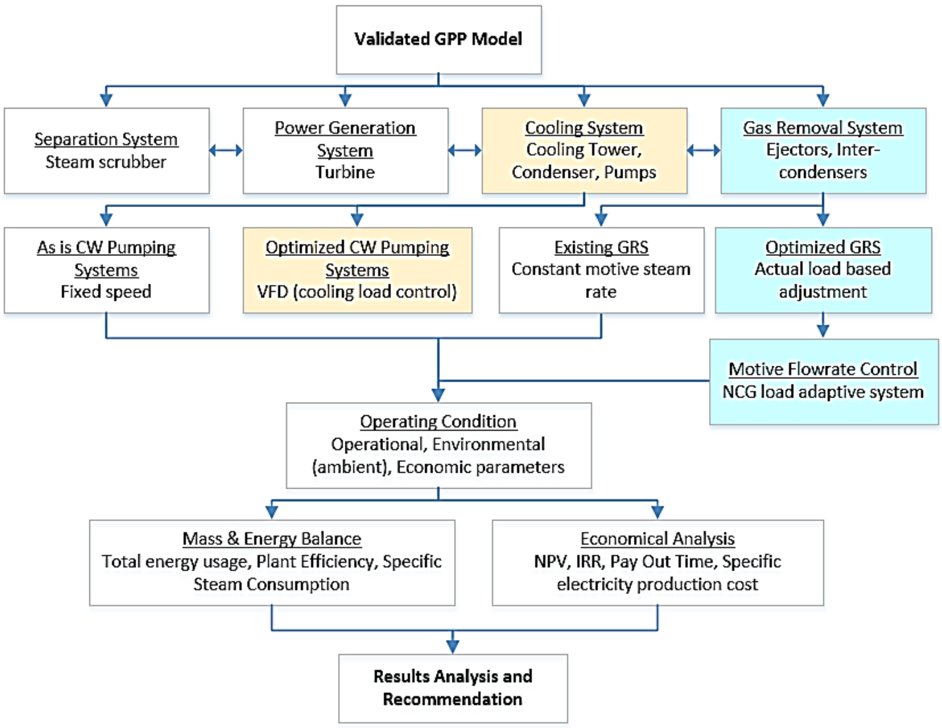


Figure 7. GPP optimization framework

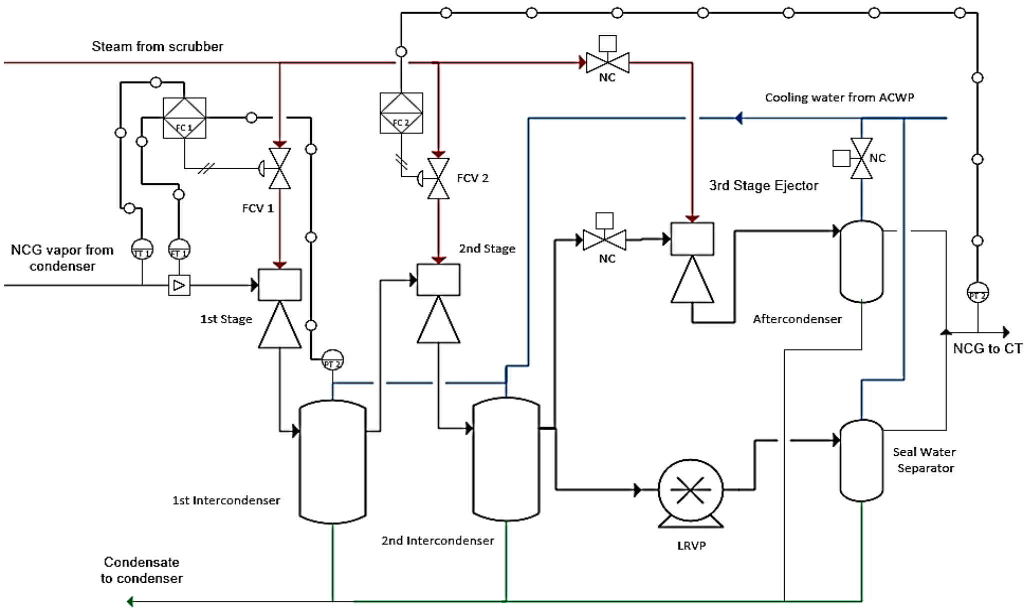


Figure 8. GRS Optimization with motive steam flow controller in the ejectors

In the cooling water pumping system, the scope of optimization implementations included: (1) VFD installation on both cooling water pumps (usually called Hot well Pumps (HWP) and (2) Installation of cooling water flow rate control. VFD installation will regulate pump speed to maintain the condenser level. The cooling water flow rate will adjust water flow-rate to keep the cooling and condensation process in the main condenser at optimum state by maintaining NCG and vapor flow rate to GRS at a fixed value at all times. This arrangement is shown in Figure 9.

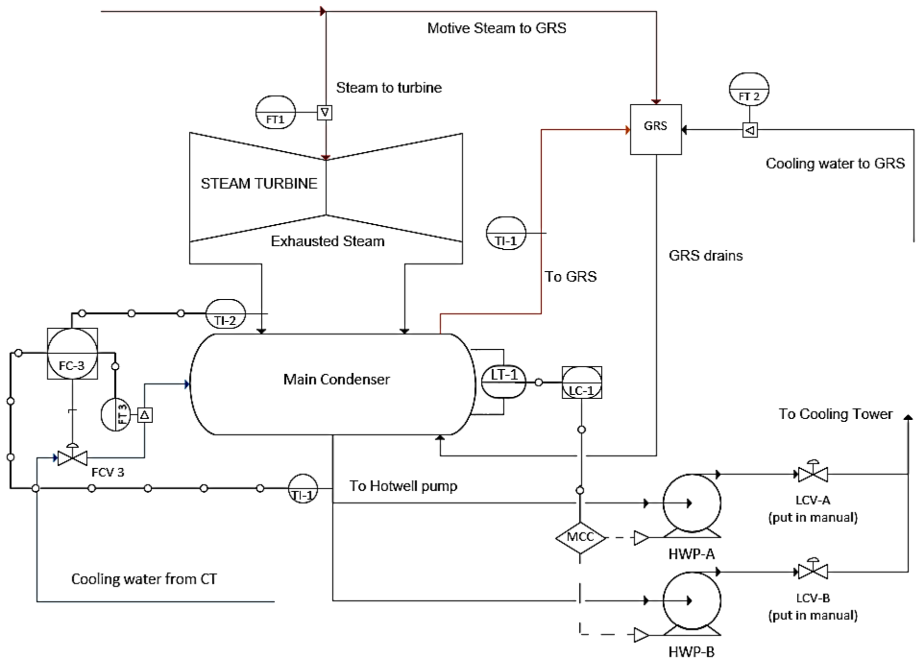


Figure 9. The cooling capacity controller in the condenser and Hot Well Pump

The benefit of the optimization was calculated as the energy-saving from baseline during low generation load and low cooling water temperature (at cold ambient temperature) and accumulated on an annual basis. The energy-saving was then monetized by multiplying the total saving with electricity prices.

2.3 Decision Analysis Method

The economic evaluation model used energy-saving results from simulations, estimated capital costs, and operation and maintenance (O&M) expense associated with the alternatives, to calculate Net Present Value (NPV) and Internal Rate of Return (IRR). The economic evaluation framework is shown in Figure 10.

The approach commonly used in project economic analysis, such as calculating the changes in future cash flow of the facility, is not typically applicable in assessing the financial performance of efficiency improvement in a GPP. The limitation of using typical cash flow calculation relates to GPP characteristic:

- The generation or output capacity strictly follows the Unit Rated Capacity (URC)
- The amount of electricity delivery to the grid has been determined in Energy Sales Contract
- Increasing the efficiency of generating units will only reduce steam consumption without directly impacting the company's revenue
- Lower steam consumption results in a decrease of the reservoir's exploitation rate so that the benefit will be treated as an increase of buffer (underground) steam and its impact on the addition of steam field plateau (surplus reserve), or in other words, an extension of exploitation period. This method is known as the **Loss Production Avoidance** approach with the extension period is illustrated in Figure 11.

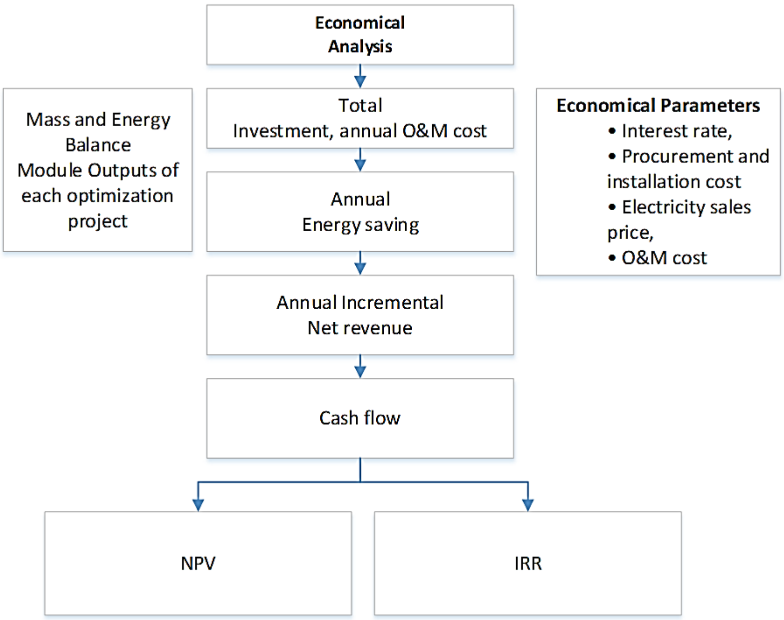


Figure 10. Economic evaluation flow diagram

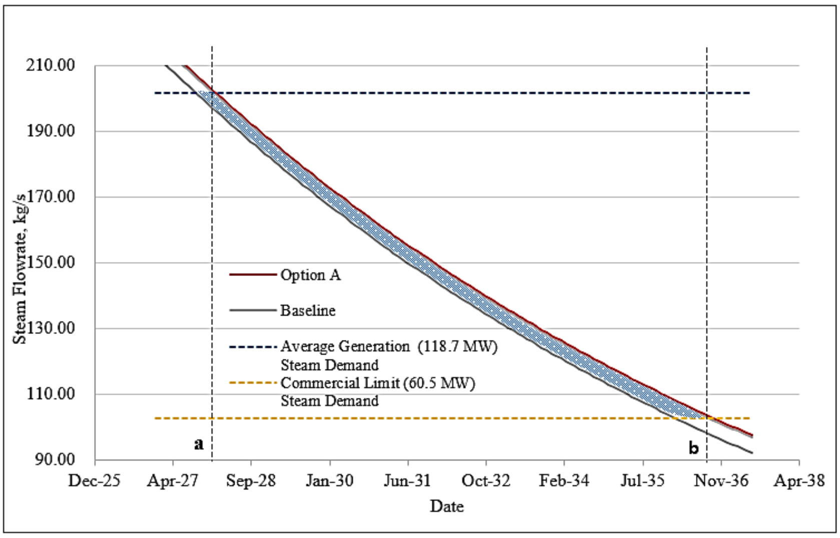


Figure 11. Loss of Production Avoidance impacted by the optimization program

The area between the baseline and optimized curves in Figure 11 on an interval [a, b] is calculated by solving Equation (1) (Waner et al., 2007):

$$A = \int_a^b |f(x) - g(x)| dx \quad (1)$$

With,

A : area between the baseline and optimized option curves, in kg-month/s, which is converted into MWh by multiplying it with 429.7 MWh/(kg-month/s).

f(x) : baseline steam production capacity equation

g(x) : optimized steam production capacity equation

a : time of steam short for average generation load (118.7 MW) on the optimized curve *b* : time to reach the commercial power-plant (60.5 MW) limit on the production optimized curve

The amount of loss production avoidance (the area between curves) will be treated as cash flow in the period t_B, and the Net Present Value (*NPV*) is calculated using Equation (2).

$$NPV = \sum \left[\frac{CF_n}{(1+i)^n} \right] \quad (2)$$

With,

NPV : Total NPV over project economic life span, US$

CF_n : cash flow at year n

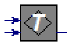
i : discount rate, 10%

n : length of periods (year), 20 years

Project or investment is considered economically feasible if the *NPV* is positive, meaning that the value of the revenues (cash inflows) is higher than the costs (cash outflows).

3. Results and Discussion

3.1 Geothermal Plant Modeling

Overall GPP model is shown in Figure 12 with GRS and cooling tower simulation placed in sub-flowsheets. The black squares with T letter () symbols in the PFD denote these two systems sub-flowsheets.

Cooling tower modeling in HYSYS was done by calculating the specific humidity of the air, both inlet and outlet of the cooling tower at the recorded wet bulb temperature range at the GPP. The cooling tower was modeled as successive multistage flashing units, as shown in Figure 13.

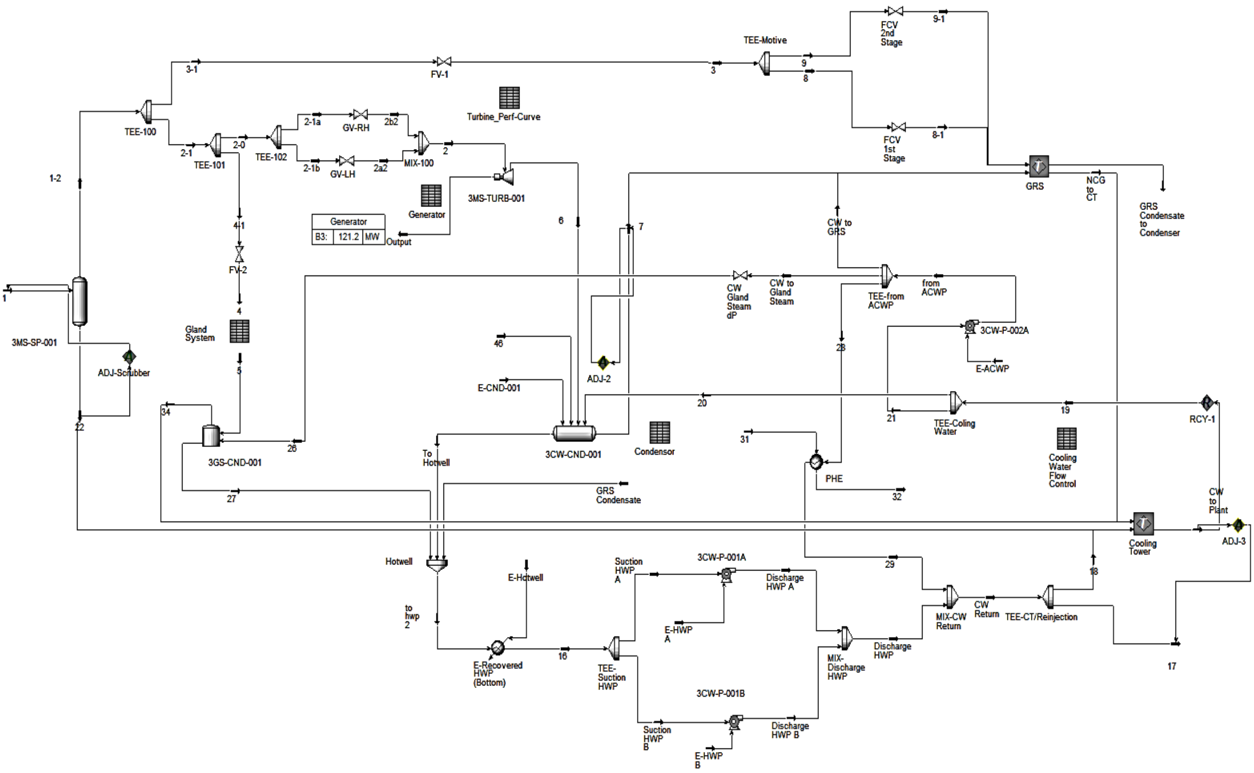


Figure 12. Overall GPP model with GRS and cooling tower model in sub flowsheets

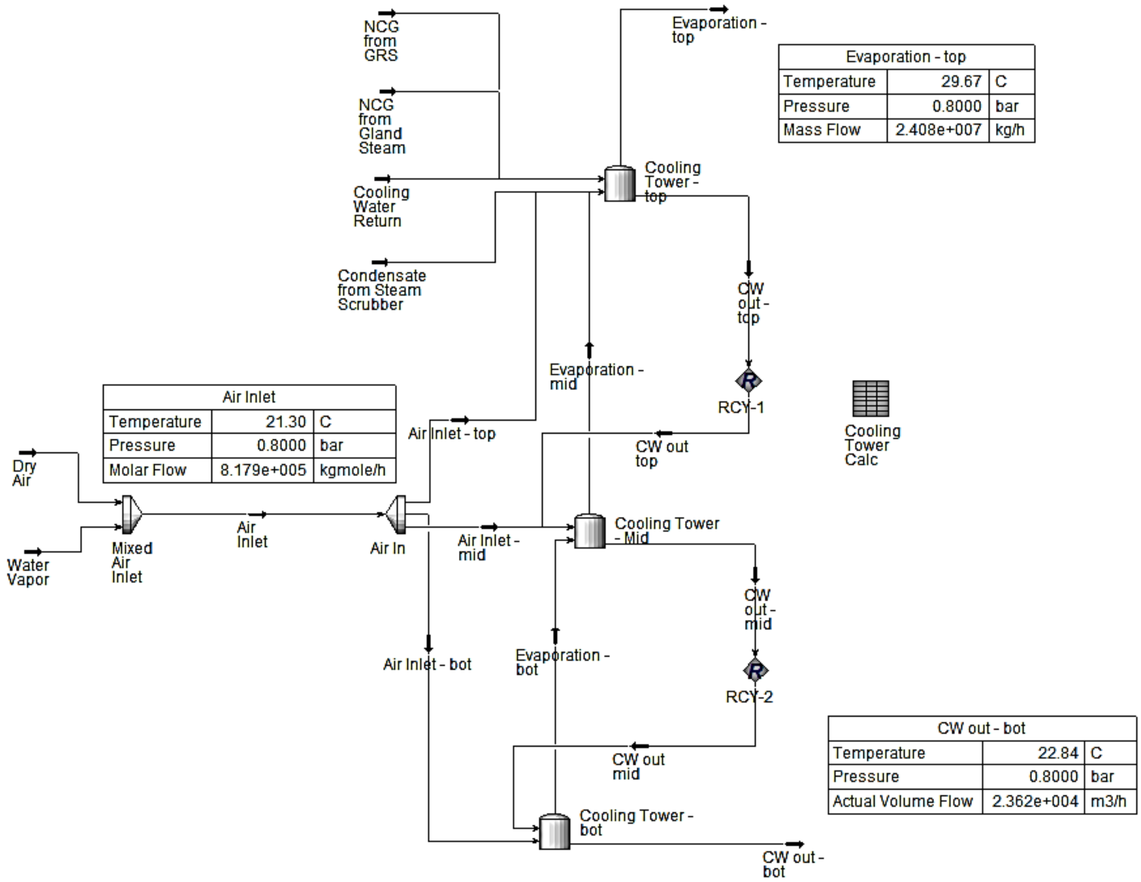
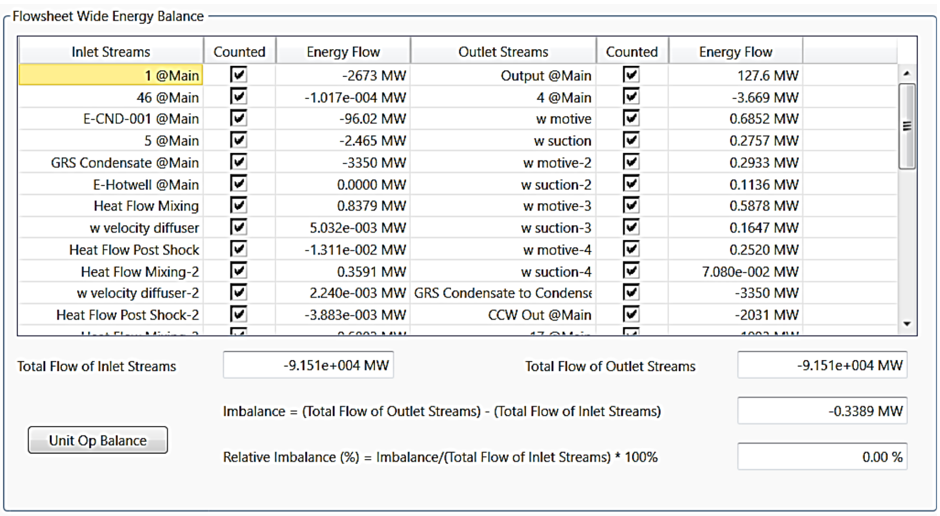


Figure 13. Cooling tower model as successive multistage flashing units



Flowsheet Wide Energy Balance

Inlet Streams	Counted	Energy Flow	Outlet Streams	Counted	Energy Flow
1 @Main	☑	-2673 MW	Output @Main	☑	127.6 MW
46 @Main	☑	-1.017e-004 MW	4 @Main	☑	-3.669 MW
E-CND-001 @Main	☑	-96.02 MW	w motive	☑	0.6852 MW
5 @Main	☑	-2.465 MW	w suction	☑	0.2757 MW
GRS Condensate @Main	☑	-3350 MW	w motive-2	☑	0.2933 MW
E-Hotwell @Main	☑	0.0000 MW	w suction-2	☑	0.1136 MW
Heat Flow Mixing	☑	0.8379 MW	w motive-3	☑	0.5878 MW
w velocity diffuser	☑	5.032e-003 MW	w suction-3	☑	0.1647 MW
Heat Flow Post Shock	☑	-1.311e-002 MW	w motive-4	☑	0.2520 MW
Heat Flow Mixing-2	☑	0.3591 MW	w suction-4	☑	7.080e-002 MW
w velocity diffuser-2	☑	2.240e-003 MW	GRS Condensate to Condens	☑	-3350 MW
Heat Flow Post Shock-2	☑	-3.883e-003 MW	CCW Out @Main	☑	-2031 MW

Total Flow of Inlet Streams: -9.151e+004 MW — Total Flow of Outlet Streams: -9.151e+004 MW

Imbalance = (Total Flow of Outlet Streams) - (Total Flow of Inlet Streams): -0.3389 MW

Unit Op Balance

Relative Imbalance (%) = Imbalance/(Total Flow of Inlet Streams) * 100%: 0.00 %

Figure 14. Flowsheet wide heat balance from HYSYS data fit

The model with actual data was then proceeded with the DVR to ensure correct mass and heat balance calculations. Several parameters such as NCG to GRS pressure, cooling water flow-rate, and circulating water pump flow-rate was calibrated accordingly through DVR. Figure 14 shows flowsheet heat balance resulted from HYSYS Data Fit DVR with negligible relative imbalance. This finding indicates that the model is accurate and ready for optimization simulation.

3.2 Alternatives Simulation

3.2.1 Gas removal system – ejector motive steam control

This option was considered viable since the actual NCG load in the GPP modeled was only 35% of the ejectors' design capacity. Another leveraging aspect is the fluctuation of ambient wet-bulb temperature, which directly affects cooling water temperature. Lower wet bulb temperature effects in colder cooling water thus reduce NCG-vapor flow rate from the condenser, which theoretically requires lower motive steam consumption. For this reason, the model was run at two wet-bulb conditions. Simulation results are listed in Table 1.

Data in Table 1 suggested that in full load (121 MW) condition, the total actual motive steam consumption was significantly higher than the process requirement. This fact is because the actual NCG content was only 35% of the ejector design capacity. At lower generation load, accumulated NCG flow-rate becomes less, which impacts lower energy dissemination during expansion in the ejector's throat. Subsequently, higher motive steam is needed to maintain adequate shockwave (during gas compression) in the ejector's diffuser, which is necessary to keep the ejector's discharge pressure above a certain limit. This action caused a reduction in the amount of steam savings as generation load decreased. This trend was also found in lower wet bulb temperature, with higher steam savings.

Table 1. Ejectors motive steam saving estimation

Scenario	Parameter	Gross Generation		
		121 MW Initial	121 MW Control Mode	117 MW Control Mode
1)	High wet bulb temperature: 20.8 C			
	NCG Vapor from condenser, kg/h	27841	27841	22965
	Total Motive Steam Saving, kg/h	-	4073	412
	Total Energy Saving, MWe	**-**	**0.70**	**0.11**
2)	Low wet bulb temperature: 14.3 C			
	NCG Vapor from condenser, kg/h	16529	16529	14723
	Total Motive Steam Saving, kg/h	-	4062	2424
	Total Energy Saving, MWe		**0.70**	**0.43**

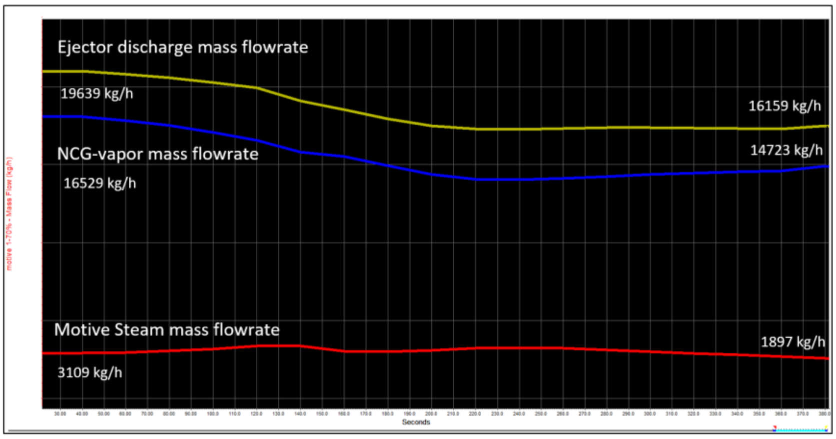


Figure 15. GRS dynamic model showing the response of the motive steam controller

Jurnal Rekayasa Proses, Vol. 14, No. 1, 2020, pp. 30-46

As part of feasibility evaluation, the dynamic simulation was done with HYSYS Dynamic simulation feature to check control system response during a change in NCG load-following generation change from 121 to 117 MW (in 30 minutes) as shown in Figure 15. At full generation (121 MW), the NCG-vapor flow rate from the condenser was 16529 kg/h, which was decreased to 14723 kg/h during the minimum generation (117 MW) following the daily operating plan.

The observation results suggested that the motive steam controller was able to optimize steam consumption from 3109 to 1897 kg/h. Process stabilization requires 5 minutes duration that was still below minimum load changes interval of 30 minutes; therefore, the controller stabilization was considered acceptable. In terms of implementation, the scope of motive steam controller installation is considered minimum since typically, GRS is already equipped with manual valves for regulating motive steam flow, complete with pneumatic actuation system.

3.2.2 Circulating Water System Optimization

The first step in the analysis proceeds with the creation of a pump's hypothetical performance curve by applying pump affinity laws for lower pump speed (Figure 16).

The next step was developing pump speed and cooling water flows control systems in HYSYS model. Pump speed (VFD) is controlled by condenser level controller LIC-100 while cooling water flow-rate was controlled by FIC-101 to maintain NCG-vapor flow-rate to GRS by Flow Control Valve (FCV) VLV-103. In the actual plant, the circulating water system consisted of two trains; each train had one condenser vessel and a pump. The dynamic model was tested for one train only, as shown in Figure 17.

With the known pump curves, modeling was then run at high and low wet-bulb conditions. The simulation result is listed in Table 2.

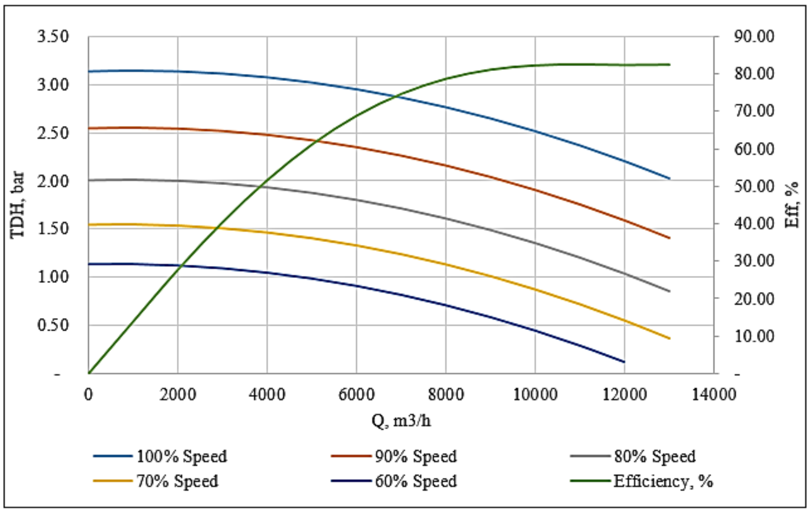


Figure 16. Hypothetical curves (VFD): Flow-rate vs. Total Dynamic Head

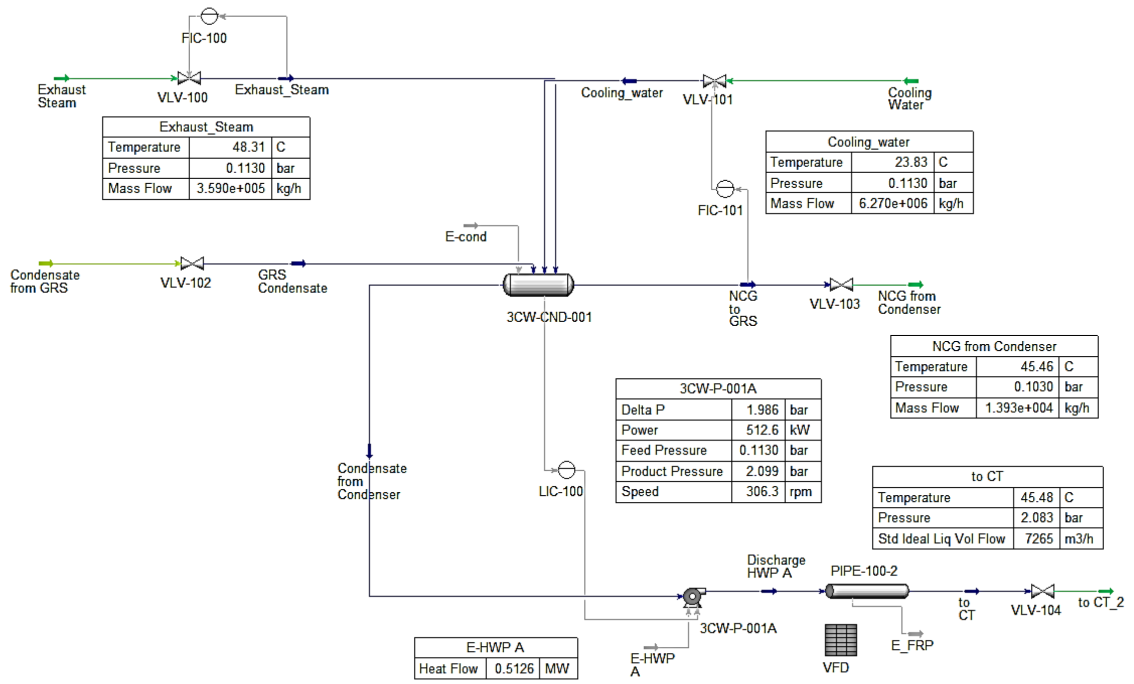


Figure 17. Process flow diagram of the condenser and Hot Well Pump in HYSYS Model

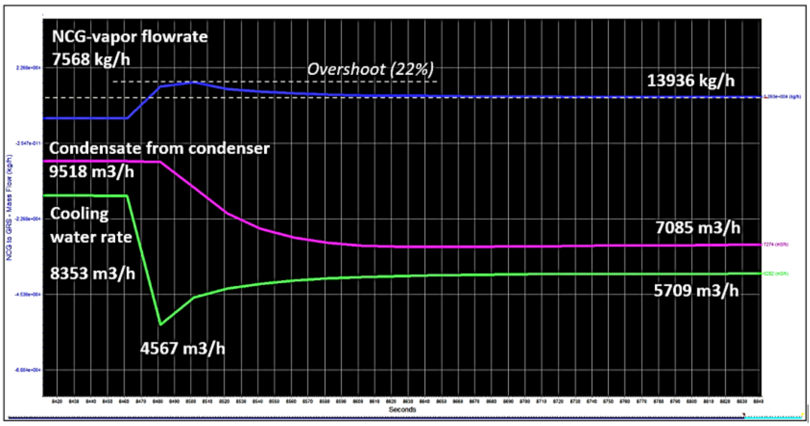


Figure 18. Dynamic simulation result (of one train) with VFD and FCV operation

Table 2. Power consumption saving with VFD and FCV applications

Scenario	Parameter	Unit	Gross Generation & Optimization Application	
			121 MW Actual	117 MW (VFD & FCV)
a	High Load (T wet bulb: 20.8 C)			
	Cooling Water Temp	C	27.9	27.56
	Two HWP Flowrate	m3/h	18,984	17,633
	HWP Speed	RPM	420	393.62
	Two HWP Power	MW	2.16	1.87
	HWP Power Saving	MW		**0.29**
b	Low Load (T wet bulb: 14.26 C)			
	Cooling Water Temp	C	23.83	23.37
	Two HWP Flowrate	m3/h	19,037	14,170
	HWP Speed	RPM	420	376.88
	Two HWP Power	MW	2.16	1.4
	HWP Power Saving	MW		**0.76**

The data in Table 2 shows that theoretically, the application of VFD and FCV was able to reduce pumps' total power consumption up to 0.76 MW, or 35% of the initial power. Controller capability was then tested in dynamic simulation to evaluate the controller's stability during changes in generation load (121 to 117 MW in 30 minutes) for one train.

Simulation results in Figure 18 suggested that VFD and FCV applications could decrease power consumption significantly (0.76 MW). However, it was identified that controller response to changes caused significant disruption in cooling water flow-rate, thus affecting the condenser level. Time for process stabilization took an extensive period (closed to 15 minutes), and this was one of the drawbacks of this alternative.

3.3 Decision Analysis

Economic analysis of the two optimization alternatives was carried out by calculating Net Present Value (NPV) and Internal Rate of Return (IRR) from associated Capital Expenditure, Operation and Maintenance Cost, and energy savings of each alternative. The summary of capital and operating expenses of the two options are listed in Table 3.

Option (a) capital cost is much cheaper than option (b) since in the GRS system, all valves and pneumatic systems are available; thus, the execution will only involve the installation of positioners and controllers. While in option (b), the highest cost is for VFD, which needs almost USD 600k for two pumps (2x1400 hp). Operating expenses were taken from historical data and information from several reference plants.

Table 3. Energy efficiency improvements capital and operating expenses estimation

Option	Title	Capital Investment, US$	Additional O&M Cost, US$/year
(a)	GRS Optimization with a motive steam flow controller	140,000	3,298
(b)	Cooling water system improvement with VFD and cooling water flow controller	1,035,000	16,091

Table 4. Energy saving in "steam buffer" value

Option	Title	Steam buffer in kg/s
(a)	GRS Optimization with a motive steam flow controller	0.80
(b)	Cooling water system with VFD and cooling water flow controller	0.81

Energy savings from Tables 1 and 2 were then converted into "steam buffer" (kg/s) with 1.7 kg/s/MW steam consumption rate. The results are listed in Table 4. Calculated **Loss Production Avoidance** of each option are listed in Table 5.

Table 5. Loss of Avoidance of each alternative

Option	The area between baseline and optimization curves, kg-month/s	Loss of Production Avoidance, MWh
(a)	83.8	36,013.6
(b)	86.5	37,168.1

With the calculated cash flow and capital investment cost, economic parameters such as *NPV* and *IRR* for each option can be determined. The results are tabulated in Table 6.

Table 6. Summary of alternatives to economic performance

Option	Title	Capital Cost, thousand US$	Loss Production Avoidance, MWh	NPV, kUS$	IRR, %
(a)	GRS Optimization with a motive steam flow controller	140.0	36,013.6	1,039.58	35.95
(b)	Cooling water system improvement with HWP VFD and cooling water flow controller	1,035.0	37,168.1	8.38	10.08

Observations on the economic performance analysis results suggest the following important information:

(i) Loss of Production Avoidance of option (b) was higher than option (a), however, in terms of NPV and IRR, option (a) showed better performance.

(ii) The advantage of the option (a) over option (b) was supported by low capital investment.

(iii) Higher benefit in the steam saving of option (b) was canceled out by the high investment cost of the VFD package (~US$ 600k). Although this must be treated on a case by case basis, as a rule of thumb, for throttle valve with opening ≥ 70%, VFD installation may not be economical.

4. Conclusions

Overall, the assessment recommends Option (a) - GRS Optimization with motive steam flow controller for implementation. This option shows advantages over other options concerning its economic performance. It also has the lowest execution risk as it does not involve high voltage electrical works (i.e., VFD installation). With the installation of a motive steam controller, GRS will still maintain high system flexibility in response to change in NCG load without losing the initial design capacity. The execution complexity is minimum since existing GRS already has manual valves for regulating motive steam flow. In terms of economic analysis, the Loss Production Avoidance approach is recommended for evaluating GPP energy efficiency improvement projects as it can rationally monetize the steam conservation impacted.

There are several gaps in current knowledge around geothermal power plant process modeling and energy efficiency analysis performed in this research. Therefore, opportunities are still open in further research to present a more detailed analysis of ejector efficiency. Besides, a more comprehensive evaluation of rotating equipment (such as Hot Well Pump and LRVP) performance is also needed by including derating characteristics. Furthermore, an in-depth exploration of how the VFD application may impact on plant reliability is still relevant to be explored. Moreover, the strategic optimization project's planning by incorporating subsurface data with regards to the NCG evolution forecast and steam supply scheme throughout the lifetime of the field.

Acknowledgements

The authors thank Star Energy Geothermal Darajat II, LIMITED, for sharing valuable information for this study case.

References

Hanafi, A. S., Mostafaa, G., Waheed, A., and Fathy, A., 2015, 1-D Mathematical

Modeling and CFD Investigation on Supersonic Steam Ejector in MED-TVC. The 7th International Conference on Applied Energy – ICAE 2015. Abu Dhabi: Energy Procedia, 75, 3239-3252.

Blatchley, C. G., 2017, Controlling Ejector Performance, Retrieved July 5, 2019, from Schutte & Koerting: https://www.s-k.com/technical-references/ejector_performance.pdf

DiPippo, R., 2007, Geothermal Power Plants - Principles, Applications, Case Studies and Environmental Impact. Massachusetts: Butterworth-Heinemann.

DiPippo, R., 2016, Overview of geothermal energy conversion systems: reservoir-wells-piping-plant-reinjection. In R. DiPippo, Geothermal Power Generation Developments and Innovation. Duxford: Woodhead Publishing, p. 211

Huang, B., Jiang, C. B., and Hu, F. L., 1985, Ejector performance characteristics and design analysis of jet refrigeration system, J. Eng. Gas Turbines Power, 107 (3), 792 - 802.

Lines, J. R. and Smith, R. T., 2000, Ejector system troubleshooting. Retrieved September 15, 2019, from Graham Corporation: https://www.graham-mfg.com/usr/pdf/TechLibVacuum/216.PDF

Sinaga, R. H., and Darmanto, P. S., 2017, Energy Optimization Modeling of Geothermal Power Plant (Case Study: Darajat Geothermal Field Unit III). 5th ITB International Geothermal Workshop (IIGW 2016). Bandung: IOP Publishing.

Waner, S. and Costenoble, S., 2007, Area Between Two Curves and Applications. In S. Waner, & S. Costenoble, Applied Calculus, Enhanced Review Edition. Belmont: Thomson Brooks/Cole, p. 487.