MODELLING AND OPTIMISATION OF A BINARY POWER PLANT UTILISING A LOW TO MEDIUM TEMPERATURE GEOTHERMAL RESOURCE

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ABSTRACT

To help achieve sustainable geothermal energy development, one should also improve efficiency in the existing energy system. The latest state of the art in the development of models to assist the achievement of this goal is the combination of a reservoir model and surface modeling of the geothermal plant. A successful attempt has previously been made to create such a combined model as part of a digital twin technology application pathway for an existing geothermal binary plant for planning purposes. This work focuses on creating a high-fidelity digital process plant model of a geothermal binary plant using commercial process simulation software for optimisation.

By creating a thorough process model, one can achieve more value from the geothermal binary plant. The model would be a valuable tool in the detailed engineering design phase to predict operational problems before the plant is built. Instead of designing a binary plant that is ideal only for initial conditions, the binary plant can be designed to withstand the changes of reservoir conditions and operational parameters over the lifetime of the plant. That way, the plant can be more robust to changes, and operators can prepare ahead.

The binary plant process model is intended to be a master planning tool in geothermal binary plant development and become a framework for low to medium geothermal resource utilisation. This paper investigates the effect of operational parameter changes over the power plant's lifetime and conducting a sensitivity analysis on the model plant performance.

1. INTRODUCTION

The majority of the geothermal energy used for power production comprises single and double flash power plants (DiPippo, 2016b). They require high-temperature geothermal resources to be efficient and economically feasible, and most of these have already been utilised for current power production. As most of the geothermal resources around the world are relatively low to medium enthalpy resources, it is prudent to increase the utilisation of these resources for power generation (Jung & Krumdieck, 2014). However, low enthalpy geothermal resources do not have enough economic value when used as a typical flash geothermal power plant (DiPippo, 2016a). In addition, low-temperature geothermal brine does not produce much steam for power generation and will be more prone to calcite and silica scaling if used for low-pressure flash plants (Candido & Zarrouk, 2017).

Instead of using a typical flash power plant, a binary plant is one of the most promising alternatives to convert such resources (Coskun et al., 2014; Kaplan, 2007). A binary plant utilises the Organic Rankine Cycle (ORC), which uses an organic working fluid instead of the geothermal fluid itself, once the heat has been transferred from the geothermal fluid to the working fluid. This cycle can minimise the loss of heat rejected into the environment and maximise the heat utilisation contained in the geothermal fluid. However, as ORC power generation only makes up for less than 7% of total geothermal power production, there is still room for binary plant improvement (DiPippo, 2016a).

A geothermal plant will face challenges with declining geothermal reservoir conditions such as temperature, enthalpy, pressure, and flow rate of the geothermal fluid (Budisulistyo et al., 2017; Iswara et al., 2017). The plant operators need to maintain the flow rate of the geothermal fluid so that the power production target is still achieved during these conditions. The operators rely on the reservoir and surface facility model to complete this target.

A good surface facilities model can estimate the physical and thermodynamic state of the geothermal fluid of a site-wide geothermal power plant. The process model can predict the pressure, steam quality, and flow rate of the geothermal fluid from the wellheads up to the steam field pipelines, the separators, the vent lines, the turbine generator, and the reinjection lines. The model could predict the amount of power generated from the plant while adjusting the operating parameters of the steam field equipment. The model is created using spreadsheet software such as Microsoft Excel or commercial process modelling software such as Aspen Hysys, Honeywell Unisim, and or Schlumberger Symmetry.

The surface facilities model needs to be combined with the data acquired from the reservoir model. Operators can predict how well the power plant performs under certain conditions of the geothermal fluid by analysing both models. As reservoir conditions decrease and change over the years, operators can maintain the targeted power generation while simultaneously verifying that the power plant equipment can withstand those changes. For example, in the case of geothermal fluid enthalpy and temperature decrease, it will also decrease the vapour fraction of the fluid. This condition may overload the separators and condensate pots with more brine than designed for, causing unintended results such as increased silica carryover to the steam, and turbine scaling.

In conclusion, combined surface facilities and reservoir models are integral for operators analysing and responding to declining reservoir conditions. For example, operators can determine the best way to counter the increased pressure drop and condensation rate in steam fields by using the combined models. Several process models have shown that high pressure drop and condensation rate are counterproductive to power production (Proctor, 2015). The typical mitigation acts to counter those conditions are doubling the pipelines, adding condensate pots or separators in the steam field pipelines, or even reducing the turbine operating pressure.

Using the same approach as outlined in the previous section, albeit at a smaller scale, this paper will create a process model of a geothermal binary power plant to investigate the plant impact by the reservoir condition changes. This paper aims to achieve these targets:

- Construct a steady-state model of a geothermal binary plant with a low to medium-temperature geothermal fluid feed.
- Investigate the effect of operational condition changes over the power plant's lifetime and then perform sensitivity analysis. The changes are assumed to be lower geothermal fluid temperature and flow rate.

2. MODELLING

This paper will use Aspen Hysys process simulator software to build the model of a geothermal binary plant. HYSYS is one of the most popular process simulators and has been used extensively in almost all kinds of the industry worldwide. The fluid packages used to model the thermodynamic properties of the process fluids are typically equations of state or activity coefficient models (e.g. Peng-Robinson or Wilson), as it is used extensively in oil & gas and petrochemical industries.

For the purpose of this study, the chosen temperature for inlet geothermal brine is 150 °C. This temperature was chosen because it is considered relatively high compared to low-temperature resources but relatively low compared to other medium-temperature resources. This temperature is considered an excellent middle ground to represent a low to medium-temperature geothermal resource. Additionally, it is assumed that the enthalpy of geothermal brine is very low, which means the brine is entirely in the liquid phase. Consequently, the pressure is assumed to be at the saturation point. Table 1 shows the initial assumptions for the low-temperature geothermal fluid source.

Table 1: Initial Condition of Geothermal Brine

Condition	Value
Temperature	150 ºC
Pressure	18.23 bar
Mass Flow Rate	100 kg/s
Enthalpy	632 kJ/kg

The constructed binary plant process model is shown in Error! Reference source not found..

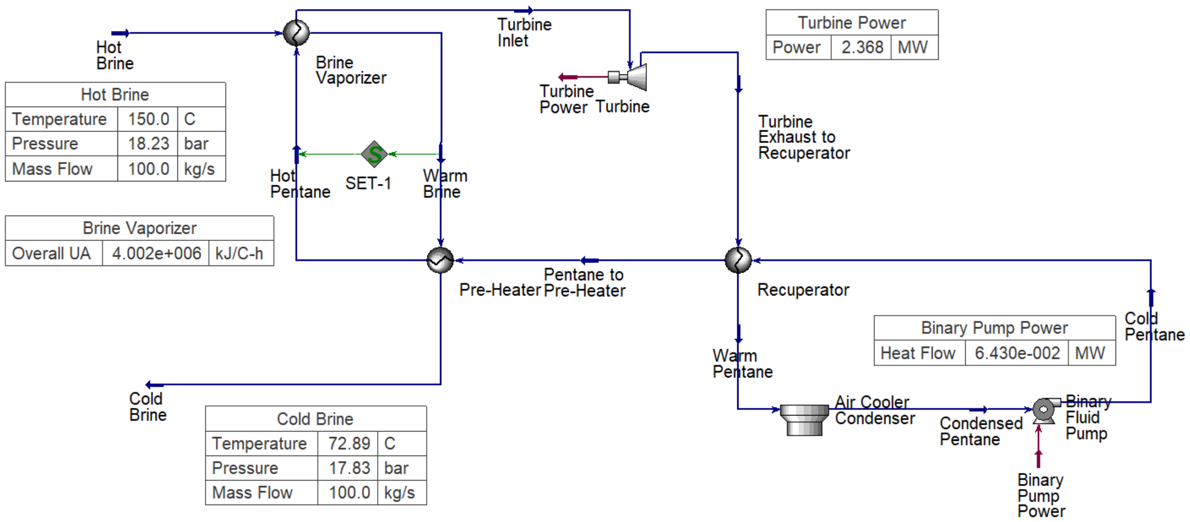

Figure 1: HYSYS model of the geothermal binary plant

The heat exchangers used in the model are described in Table 2.

Table 2: Assumptions and model type of each equipment in the model

Equipment	Model	Assumptions
Pre-Heater, Vaporiser, and Recuperator	• Shell & Tube Heat Exchanger • Countercurrent flow • Using simple endpoint calculation	• Fluid pressure drop is 0.2 bar
Turbine	• Turbo expander (ORC Turbine)	• 75% isentropic efficiency
Air Cooled Condenser	• Using simple endpoint calculation • Twelve fans	• Fluid pressure drop is 0.2 bar
Binary fluid pump	• Centrifugal pump	• 75% isentropic efficiency

Several overall heat transfer coefficients were assumed for the model, as shown in Table 3. The values are assumed considering the hot and cold fluid used in each heat exchanger. The heat transfer area for each piece of equipment can be determined using these heat transfer coefficient values.

Table 3: Overall Heat Transfer Coefficient Assumptions on Heat Exchangers (source: Çengel et al., 2017; Putera et al., 2019; Towler & Sinnott, 2008)

Equipment	Assumed U Value (W/m^2K)
Vaporiser	1000
Pre-Heater	1000
Recuperator	400
Air-Cooled Condenser	350

3. OPERATION CONDITION CHANGE IMPACTS

The paper will present three main investigation phases by utilising this base process model. Phase 1 is to find the optimal process conditions with respect to different turbine operating conditions and different vaporiser inlet temperatures. Phase 2 investigates the plant performance changes in response to different flow rates and temperatures of the geothermal brine feed during the plant lifetime. Phase 3 is to determine the coping mechanisms that can be taken to counter the power decline in Phase 2.

3.1 Phase 1 – Process performance

Table 4 shows the different cases to be studied in this project. Eighteen cases show five different turbine inlet pressures, each with three different temperatures set at their corresponding pressures. The cases are set up to study the effect of increasing turbine pressure on the objective functions while studying the increased turbine inlet temperature. The turbine inlet temperature is set at its saturation point with several Celsius degrees of superheating to investigate this theory in the model. Figure 2 shows the optimisation steps taken to optimise the model in Phase 1.

Table 4 : Study cases

Case	Turbine Inlet Pressure (bara)	Turbine Inlet Temp (°C)	Vaporiser Inlet Temp (°C)	Case	Turbine Inlet Pressure (bara)	Turbine Inlet Temp (°C)	Vaporiser Inlet Temp (°C)
1	4	83.5	85.4	**10**	7	107.6	108.9
2	4	90	85.4	**11**	7	110	108.9
3	4	110	85.4	**12**	7	130	108.9
4	5	92.7	94.4	**13**	8	113.8	114.9
5	5	110	94.4	**14**	8	120	114.9
6	5	130	94.4	**15**	8	130	114.9
7	6	100.6	102	**16**	8	113.8	110
8	6	110	102	**17**	8	113.8	100
9	6	130	102	**18**	8	113.8	90

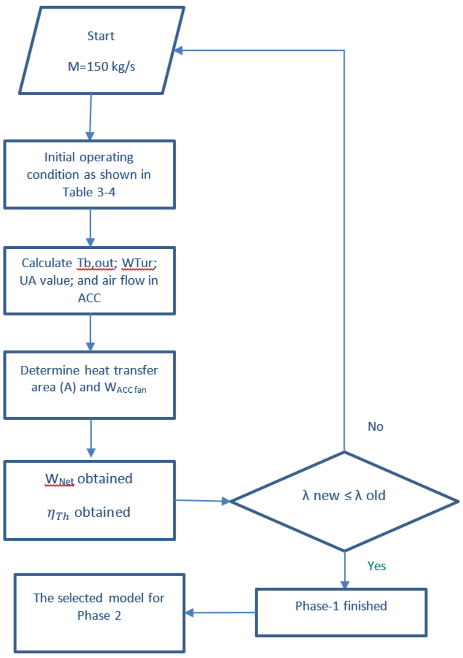

Figure 2: Phase 1 calculation steps

The net power, thermal efficiencies, and Heat Transfer area (HTA) to net power ratios for all eighteen cases are plotted in Figure 3. Case 18 is the optimal case with the highest net power and thermal efficiency and a low HTA to Net power ratio if considering all factors. Different places may have different electricity price ranges, which means the economic calculation may be unreliable depending on site-to-site conditions. Therefore, the Heat Transfer Area to Net Power Ratio (λ) is used to substitute for economic value. The lowest value of the ratio is considered the most economical, as a low heat transfer area will have lower capital expenditure. The graph shows that there is not much difference in the λ value between cases 5-18. One probable cause of this condition is that the heat transfer coefficient may need to be modelled in more detail for each case study. Bearing this in mind, the lowest λ value is found in case study 14 but it is important to note that case 14 does not necessarily produce the highest objective function value. Other cases, like case 18, have higher thermodynamic efficiency and net power compared to case 14.

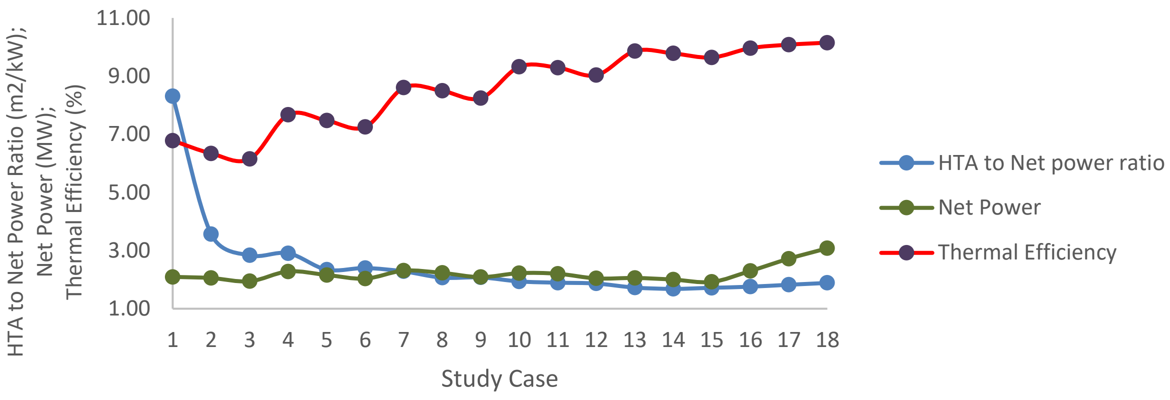

Figure 3: Results for all study cases

3.2 Phase 2 – Effect of Declining Geothermal Heat Resource

Budisulistyo et al. (2017) have written extensively regarding the lifetime design strategy for binary geothermal plants. They noted that the changes in the production well characteristics influence the attainable net power output over the plant's lifetime. Well characteristics such as temperature, flow rate, enthalpy, and composition of the geothermal resource will heavily influence the geothermal plant size and design variables.

The selected model (Case 14) in Phase 1 will be used to study a declining case of geothermal heat sources. The dimensions of the heat exchanger units are assumed to be represented by the calculated UA value from the initial model. This study utilises the geothermal resource decline acquired from historical data from forty years of exploitation and production of the Wairakei geothermal field (Clotworthy, 2000). The percentage of flow rate decline is described as a function of time (plant year) and shown in Eq. 1 (Budisulistyo et al., 2017).

$$F = 7.167 - 0.778Y + 0.027y^2 - 0.00029y^3 \qquad (1)$$

Where *F* is the flow rate in kg/s and *y* represents plant years. The reservoir temperature profile is assumed to be declining by as much as 0.5 ºC every year until plant year twenty. Afterward, the temperature decline is 0.2 ºC per year until the end of the plant's lifetime. Those equations are applied to the initial condition of the geothermal brine feed. After conducting the above sequences, the results from the power plant model are shown in Figure 4.

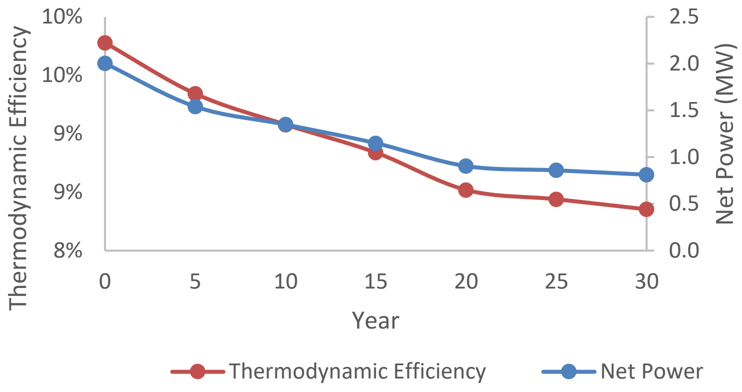

Figure 4: Thermodynamic efficiency and net power production declines

We can observe the declining net power generation and thermodynamic efficiency over the plant lifetime of thirty years. As the geothermal brine decreases to half of its initial flow rate at the end of 30 years, the net power production also decreases by the same amount. As the amount of heat extracted from the brine decreases, the *n*-pentane used in the system needs to be reduced. However, the decline of the thermodynamic efficiency is not as steep as the net power. This shows that thermodynamic efficiency is governed more by the reservoir enthalpy and temperature than its flow rate.

3.3 Phase 3 – Minimising the power decline

As shown by the power decline in Section 3.2, the decline will arrive at a point where the reduced heat is no longer sufficient to vaporise all of the binary fluid. Therefore, the binary fluid flow rate needs to be reduced, which eventually reduces the power production.

A geothermal operator typically drills another new well to compensate for decreasing the geothermal feed's flow rate or enthalpy change. The drawback of that solution is that the activity is very costly and has an inherent risk of drilling failure. Therefore, those plant operators need to provide a solution on the power plant to mitigate or minimise the decline of power production.

Even though the gross power production cannot be increased without introducing an additional heat source, the plant operator can still minimise the parasitic loads on the binary fluid pump and the air-cooled condenser fan. For example, equipment such as a variable speed drive (VSD) can be installed on to the pump to reduce the its rotational speed and therefore power consumption. In addition, several fans in the Air Cooler Condenser (ACC) can be turned off to reduce the fan power consumption. Therefore, net power production can still be maintained.

The operators can also change the operating conditions of the plant. Several steps that can be done are to derate the turbine operating pressure or decrease the superheated temperature up to its saturation point. However, each step's effectiveness still needs to be investigated as changes in operating conditions may reduce the mass flow rate, reducing the gross power production.

The first step is to increase the subcooled temperature on the condensed *n*-pentane. With the decrease of *n*-pentane flow rate over the years, the ACC's condensing duty will be lower than its design value. In other words, the ACC will have a substantial degree of subcooling over the years. As the ACC has twelve fans in the model, turning off some of them would increase the subcooled temperature to the condensation point. The model shows that seven fans can be turned off by Year 15 to reduce the parasitic load of the plant. The reduced parasitic load will increase thermodynamic efficiency significantly.

The second step is to reduce the superheated temperature of the turbine inlet. The superheated temperature is proven to be detrimental to net power production and thermal efficiency. By reducing the superheated vapour temperature, the system can use a bigger *n*-pentane flow rate, increasing power production and thermal efficiency. The previous design was chosen mainly based on the heat transfer area to net power ratio. Therefore, reducing the superheated temperature will not be detrimental to the plant. After the plant has been running for several years, it can be beneficial for the efficiency of the plant.

After taking these two steps, the results are compared with Phase 2 and shown in Fig. 5. The plant's net power can be increased up to 0.2 MW, and the thermal efficiency can be significantly increased up to almost 2%.

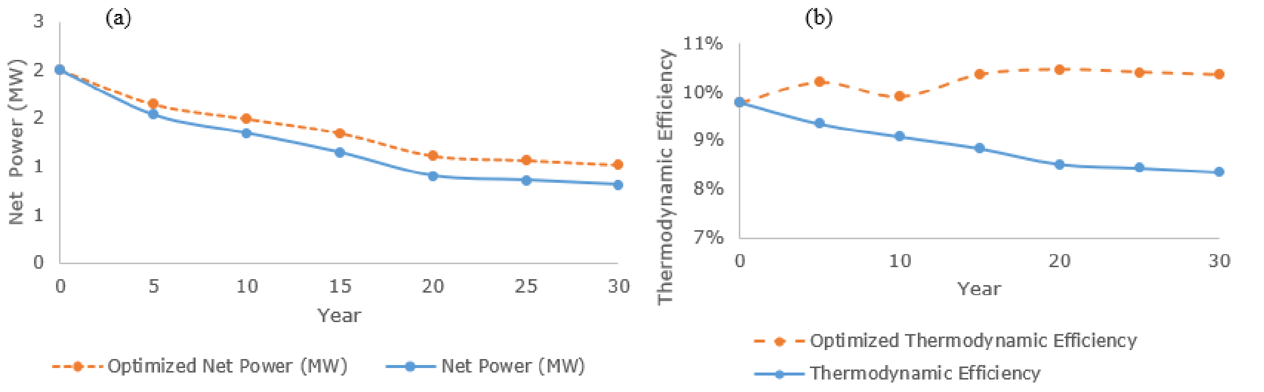

Figure 5: Comparing results in Phase 3 with Phase 2

4. CONCLUSIONS

In this paper, we investigate the impact of geothermal heat resource decline on a geothermal power plant through Aspen Hysys models. From eighteen study cases modelled, one optimal case is chosen to be the basis for the consequent investigation due to it having the lowest value of heat transfer area to net power ratio. The model is simulated for subsequent years of plant operation using an assumed temperature and flow rate decline of the geothermal brine to illustrate the declining impact on net power and thermal efficiency of the plant. Two strategies are suggested to increase or maintain the plant's net power and thermodynamic efficiency: i) reducing the superheating temperature at the turbine inlet, and ii) increasing the subcooled temperature of the condenser by turning off unused fin fans in the air-cooled-condenser. By implementing those two strategies, we found the plant can maintain the net power and thermal efficiency even when the geothermal heat resource declines over the years.

REFERENCES

Budisulistyo, D., Wong, C. S., & Krumdieck, S. (2017). Lifetime design strategy for binary geothermal plants considering degradation of geothermal resource productivity. Energy Conversion and Management, 132, 1–13. https://doi.org/10.1016/j.enconman.2016.10.027

Candido, C. A. S., & Zarrouk, S. J. (2017). Scaling Mitigations for the Binary Plant Vaporizer: Upper Mahiao, the Philippines. Proceedings 39th New Zealand Geothermal Workshop, 22-24 November. https://www.researchgate.net/publication/321278670

Çengel, Y. A., Cimbala, J. M., & Turner, R. H. (2017). Fundamentals of Thermal-Fluid Sciences (Issue 5th Ed). McGraw Hill Education.

Coskun, A., Bolatturk, A., & Kanoglu, M. (2014). Thermodynamic and economic analysis and optimization of power cycles for a medium temperature geothermal resource. Energy Conversion and Management, 78, 39–49. https://doi.org/10.1016/j.enconman.2013.10.045

Clotworthy, A. (2000). Response of Wairakei geothermal reservoir to 40 years of production. World Geothermal Congress, 2057–2062.

DiPippo, R. (2016a). Binary Cycle Power Plants. In Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact (Fourth Edi, pp. 193–239). https://doi.org/10.1016/B978-0-08-100879-9.00008-2

DiPippo, R. (2016b). Single-Flash Steam Power Plants. In Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact (Fourth Edi, pp. 107–142). Elsevier Ltd. https://doi.org/10.1016/b978-0-08-100879-9.00005-7

Iswara, G., De Groot, K., Henderson, S., & A, A. (2017). *Implementing Master Planning As Comprehensive Strategic Planning Tool for Geothermal Field Development*. Indonesia International Geothermal Convention and Exhibition 2017.

Jung, H. C., & Krumdieck, S. (2014). Modelling of organic Rankine cycle system and heat exchanger components. 6451. https://doi.org/10.1080/14786451.2013.770394

Kaplan, U. (2007). Organic Rankine Cycle Configurations. European Geothermal Congress 2007, 2007(June), 1–5. https://pangea.stanford.edu/ERE/pdf/IGAstandard/EGC/2007/098.pdf

Proctor, M. (2016). Modelling , Control and Optimisation of Geothermal Organic Rankine Cycle Power Plants, PhD thesis, University of Auckland.

Putera, A. D. P., Hidayah, A. N., & Subiantoro, A. (2019). Thermo-economic analysis of a geothermal binary power plant in Indonesia—a pre-feasibility case study of the Wayang Windu site. Energies, 12(22). https://doi.org/10.3390/en12224269

Towler, G., & Sinnott, R. K. (2008). Chemical Engineering Design Principles Practice and Economics of Plant and Process Design. Butterworth - Heinemann.