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Selection of Optimum Working Fluid and Cycle Configuration of Organic Rankine Cycle (ORC) as Bottoming Binary Cycle at Wayang Windu Geothermal Power Plant

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ABSTRACT

This research presents the thermo-economic approach for determining the optimal setting of Organic Rankine Cycle (ORC) as the proposed bottoming binary cycle for the existing Wayang Windu geothermal power plant. The ratio of the total heat transfer area to net power output (γ) and the ratio of the total specific equipment investment costs to net power output (SICp) are selected as the optimization parameters. The working fluids and cycle configurations are varied in the optimization process. Three working fluids are selected: isopentane, isobutane, and n-pentane. Two-cycle configurations are compared: basic ORC and recuperative ORC system. Each model is assessed on its thermodynamic performance (thermal efficiency and net power output) and economic performance (levelized cost of energy and discounted payback period). Aspen Hysys v10 is employed to gather the technical and economic data of the various ORC settings. Further calculations are conducted to analyze the simulation data. The results show that n-pentane provides the highest net power output as well as the lowest specific investment cost for the Wayang Windu brine characteristic. The results also indicate that it is economically more beneficial to operate under the basic ORC system configuration rather than the recuperative ORC system.

1. INTRODUCTION

Indonesia still relies on fossil fuels as the largest source for electricity generation. In 2015, the Ministry of Energy and Mineral Resources (MEMR) reported that 89.5% of the electricity in Indonesia was produced from coal, gas and oil (MEMR, 2017). The utilization of fossil fuel for generating electricity in Indonesia is related to energy security and climate change issues. In terms of energy security, currently Indonesia's fossil fuel reserve has been depleted. It is estimated that the current proven reserve of coal, gas, and oil is only enough for 82, 33, and 12 years, respectively (MEMR, 2017), whereas, the electricity demand in Indonesia is projected to increase significantly by 6.86% per annum (MEMR, 2018). Therefore, there is a need to obtain energy from alternative resources to solve the energy security problem in Indonesia. On the other side, it is also known that the use of fossil fuel to generate electricity releases quite a high amount of greenhouse gas (GHG) emissions. Sims et al. (2003) suggested that the carbon emission produced from generating energy using coal is around 150 gr-C/kWh. In contrast, by using renewable energy, the amount of carbon emission produced could be reduced to zero. Hence, renewable energy could not only be an alternative to support energy security, but also a better option to reduce the emissions caused by the electricity sector. In addition, the Indonesian government has planned to increase the contribution of renewable energy resources in electricity generation to 23% by 2025 (MEMR, 2017).

As a country that is located within the Ring of Fire, geothermal energy potential in Indonesia is tremendous (more than 28,000 GW) with only less than 5% having been utilized (Pambudi, 2018). Therefore, geothermal energy could be an alternative to take over the role of fossil fuels as the largest supplier for electricity generation in Indonesia. However, the average geothermal power plant efficiency is only 12%, which is relatively low compared to the other power plants, such as coal-fired power plants (35%), natural fired gas power stations (40%), and nuclear power plants (33%) (Zarrouk & Moon, 2014).One of the techniques that has been proven to increase the power generation and conversion efficiency of the geothermal power plant is installing the bottoming binary cycle, since more energy could be extracted from the geothermal brine effluent (DiPippo, 2016; Luo et al., 2017). Furthermore, the utilization of the binary system provides some benefits, such as having no direct emission into the environment and being able to generate electricity from relatively low-temperature resources (Hettiarachchi, Golubovic, & Worek, 2007).

In spite of these facts, only one binary power plant has been built in Indonesia, which is in the Lahendong geothermal field, North Sulawesi (Pambudi, 2018). Furthermore, only few studies have been done to assess the utilization of the binary system for geothermal power plants in Indonesia (Pambudi, Itoi, Jalilinasrabady, & Sirait, 2015; Pasek, Soelaiman, & Gunawan, 2011; Prananto et al., 2018). And, only one of these studies evaluate the economic aspect of installing a binary cycle for geothermal power plants in Indonesia (Putera, Hidayah, & Subiantoro, 2019) Therefore, there is a necessity to conduct further research that particularly discusses the application of the bottoming binary cycle for an existing geothermal power plant in Indonesia that covers not only the technical aspect but also the economic point of view.

Hettiarachchi et al. (2007) advise that it is critical to assess the binary systems based on both the technical and economic aspects, especially in case of utilizing low to medium heat source temperature. When extracting the same amount of energy from low to medium heat source, a larger heat exchanger area is required. As a result, the total investment cost to build the binary system increases as well. Furthermore, some studies suggest that the results of the binary system optimization which only rely on the technical aspect can differ significantly compared to the optimization that covers both the technical and economic aspects (Quoilin, Declaye, Tchanche, & Lemort, 2011; J. Wang, Yan, Wang, Ma, & Dai, 2013; Zare, 2015). Hence, in this study, the optimization of the binary system is properly analyzed by considering both the technical and economic aspects by applying the thermo-economic approach.

In this study, the ORC system is selected as it has been widely used as the geothermal binary cycle. As mentioned by Toffolo et al. (2014) and Uehara & Ikegami (1990), the main cost of the ORC system for low-medium heat source comes from the heat exchanger equipment. Therefore, in this study, the optimization of the system focuses on the heat exchanger equipment: preheater, evaporator, and condenser. The optimization of the heat exchanger equipment could be done either by changing some related variables or by modifying system configurations.

The thermodynamics performance of the ORC system could be improved by adjusting some variables. For instance, several studies suggest that the working fluid is an essential factor affecting the binary power plant performance (Putera et al., 2019; Zare, 2015; Zhang & Jiang, 2012). The other technique to improve the performance of ORC is by installing a different cycle configuration. One of the common ORC configurations is the recuperative system. Several studies imply that a recuperative ORC cycle has a better thermodynamics efficiency compared to the basic ORC system (Braimakis & Karellas, 2018; Mohammadzadeh, Jalilinasrabady, & Fujii, 2017; E. Wang, Zhang, Fan, & Wu, 2012; Zare, 2015). In this study, these two measures, selecting the best working fluid and the best cycle configuration system, are proposed to optimise the ORC system for the application at Wayang Windu geothermal power plant. Each measure is evaluated based on its thermodynamic and economic performance. The results of this research are expected to provide information on how each measure impacts the technical and economic performance of the system.

2. WAYANG WINDU GEOTHERMAL POWER PLANT

2.1 Status and current research

Wayang Windu power plant is one of the biggest geothermal power plants in Indonesia, which has been proven to operate with a capacity factor above 95% for more than ten years (Purnanto & Purwakusumah, 2015). The data from the Wayang Windu field showed that the temperature of the geothermal brine from the existing power plant is still relatively high, about 180°C (Prananto, Soelaiman, & Aziz, 2017). Therefore, the geothermal brine still contains a considerable amount of energy that could be extracted further. Due to these facts, Wayang Windu geothermal power plant is selected as the study case for assessing the implementation of bottoming binary cycle in Indonesia. Other than that, Wayang Windu geothermal power plant was the first geothermal power plant with an installed capacity of more than 100 MW, and it has been operating successfully for more than 15 years (Purnanto & Purwakusumah, 2015). It is reported that the capacity factor of Wayang Windu geothermal power plant is always above 95%, which is higher than the average worldwide capacity factor for single flash-dry steam plants (80.1%) (Zarrouk & Moon, 2014). Furthermore, this plant also has a very favorable reliability and availability factor, which always exceeds 99.5% and 96%, respectively.

A study which analyses the feasibility study of using bottoming binary cycle at Wayang Windu power plant had been done by Prananto (2017). In his research, Prananto (2017) selects Kalina cycle as the binary system. The result shows that the Kalina cycle could produce up to 1660 kW of electricity with a system efficiency of 13.20%. Also, Putera et al. (2019) had conducted a pre-feasibility study of ORC in Wayang Windu geothermal power plant. It concludes that n-pentane is the best working fluid compared to R-254 and n-butane. Other than that, there are also some studies about the application of binary cycle in other geothermal power plant in Indonesia. For instance, the assessment of installing binary system for utilizing waste brine from Lahendong geothermal power plant is conducted by Pasek et al. (2011) with maximum output as the objective. Pambudi et al. (2015) also evaluates the feasibility of installing a single flash – binary system at Dieng geothermal power plant based on the thermodynamic performance. In addition, Pikra et al. (2015) also conduct the feasibility of installing the binary cycle for extracting energy from low temperature geothermal sources in Indonesia, such as hot springs.

2.2 Geothermal brine characteristic

Wayang Windu geothermal power plant is a vapor-dominated geothermal resource. Therefore, only small amounts of brine effluent resulted from the flashing process in the separator. However, this geothermal brine still carries a considerable amount of energy as well as a high concentration of silica as can be seen in Table 1.

Table 1 Geothermal brine parameters at Wayang Windu geothermal power plant (Prananto, 2017)

Parameter	Value	Unit
Brine temperature	180.7	°C
Brine pressure	1.02	MPa
Discharge rate	48	kg/s
SiO2 content	853	mg/L

Zarrouk and Moon (2014) suggest that the temperature of the geothermal brine outlet needs to be kept under the maximum allowable Silica Saturation Index (SSI) value to ensure no scaling and corrosion happens in the system. SSI is an indicator of the potential for silica scale deposition. The SSI is calculated using Equation (1) which shows the ratio between measured silica in solution (CI) to the solubility of amorphous silica at a given temperature (C) (Brown, 2011).

$$SSI = \frac{CI}{C} \quad (1)$$

The solubility of amorphous silica at a given temperature (C) is calculated using Equation (2) by Fournier & Rowe (1977), which is valid for temperature between 0 – 250°C. In this formula, C is the soluble silica concentration in ppm and T is the temperature in degree Celsius. The data for CI is obtained from Table 1 that shows the information of the brine as the output of the existing geothermal power plant (Prananto, 2017).

$$log_{10}[C] = -\frac{731}{(T+273.15)} + 4.52 \quad (2)$$

According to Zarrouk and Moon (2014), the SSI for a binary power plant should be kept under 2 to prevent scaling. From the calculation result, it is found that the minimum allowable brine outlet temperature to keep the SSI within that standard is 114°C.

3. THERMODYNAMICS MODEL

The basic Organic Rankine Cycle (ORC) system is selected as the initial system for the bottoming binary cycle in this research. Figure 1 illustrates the typical schematic of the basic ORC. As described by its name, ORC uses organic fluid as the medium to take the heat from the heat source. The organic fluid can evaporate at low temperature, which makes it possible to extract more heat from lower temperature heat sources.

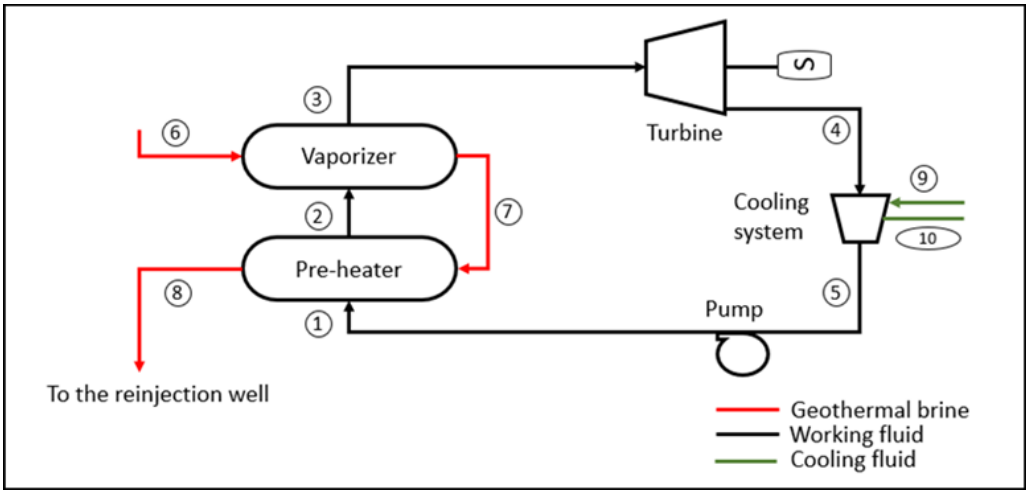

Figure 1: Basic Organic Rankine Cycle (ORC) configuration

The cycle starts by utilizing the brine as the effluent of the existing geothermal power plant, shown by a red line in the schematic. The brine first enters the vaporizer and transfers its heat to the working fluid. The brine then moves to the preheater to transfer more of its heat to preheat the working fluid before it enters the vaporizer. The heated working fluid which already turns into vapor will be delivered to rotate the turbine for generating electricity. After the energy from the working fluid is extracted, the working fluid leaves the turbine at a lower pressure with moderate temperature. The remaining heat from the working fluid will be released to the atmosphere through the cooling system. So, the working fluid will be in full liquid phase before entering the pump. The pump then works to increase the pressure of the working fluid before it moves to the pre-heater to receive heat from the brine. This cycle will be repeated continuously.

4. OPTIMIZATION MEASURES

4.1 Selecting optimum working fluid

Several studies suggest that the properties of the working fluid are an essential factor that affect the binary power plant performance and cost (Hettiarachchi et al., 2007; Putera et al., 2019; Zare, 2015; Zhang & Jiang, 2012). Thus, several studies have been done to evaluate the performance of the binary system based on various working fluids. Zare (2015) recommends using n-pentane as the working fluid for ORC configuration since it produces the highest thermal efficiency and the lowest total equipment cost. Similarly, Quoilin et al. (2011) advice that n-pentane has the lowest specific investment cost (SIC). Putera et al. (2019) suggest that n-pentane has better thermodynamics and economic performance than R-254 and isobutane. In addition, Lahendong geothermal power plant as the only geothermal binary power plant in Indonesia also utilizes n-pentane as its working fluid (Pambudi, 2018).

The other working fluids that are already widely used worldwide in the existing geothermal binary power plants is isobutane and isopentane. Gawlik et al. (2000)lists in their report of Small-Scale Geothermal Power Plants in the Western United States that most of the binary power plants use isobutane as the working fluids, and the rest use isopentane. Moreover, (Kanoglu, 2002)also mentions that the existing binary geothermal power plant in Northern Nevada, USA utilizes isopentane as the working fluid. Toffolo et al. (2014) suggest that the optimum ORC configuration is obtained by using isobutane as the working fluid. Furthermore, several studies also recommend utilizing isobutane for extracting heat from sources that have a temperature between 145 – 170°C as it yields maximum power output (Dai, Wang, & Gao, 2009; Heberle & Brüggemann, 2010; J. Wang et al., 2013)

In this study, three working fluids (isobutane, isopentane, and n-pentane) are selected and assessed based on their thermodynamic and economic performance. All these working fluids are categorized as dry working fluid. As the dry type working fluid, these organic fluids have a positive slope which ensures the turbine outlet to be at superheated vapor condition. It would be a desirable condition in which the corrosion could be prevented. Therefore, there are no liquid droplets created while the turbine expands. The fluid properties of each organic fluid are listed in Table 2.

Table 2 Fluid properties of Isopentane, Isobutane, and n-pentane

Working Fluid	Isopentane (R601a)	Isobutane (R600a)	n-pentane
Molecular formula	$C5H12$	$C4H10$	$C5H12$
$T_{critical}$ (°C)	187.2	134.9	196.5
$P_{critical}$ (kPa)	3334	3648	3375
Ozone Depletion Potential (ODP)	0	0	n.a
Global Warming Potential (GWP)	11	3	n.a

4.2 Selecting optimum cycle configuration

The second measure that is proposed to optimize the heat transfer area of the ORC system is by selecting the optimum cycle configuration. Two cycle configurations, basic ORC and recuperative ORC, are compared in this study. The recuperative ORC is a basic ORC with an additional internal heat exchanger (IHE) or a recuperator device. The recuperator can extract more heat from the working fluid leaving the turbine and transfer the heat to preheat the working fluid before it enters the preheater. The benefits of installing the recuperative ORC system are: having a higher geothermal brine outlet temperature which could prevent scaling problems in the reinjection well and can be operated under lower heat source temperatures (Mohammadzadeh et al., 2017).

The schematic diagram of a recuperative ORC system can be seen in Figure 2. The working fluid that exits the turbine at point 4 remains in a relatively high-temperature condition. The heat from this point 4 is transferred to the working fluid at point 7 (before entering the pre-heater). Thus, both the cooling system and the preheater is operated with lower heat duty. As a result, it would require smaller equipment size.

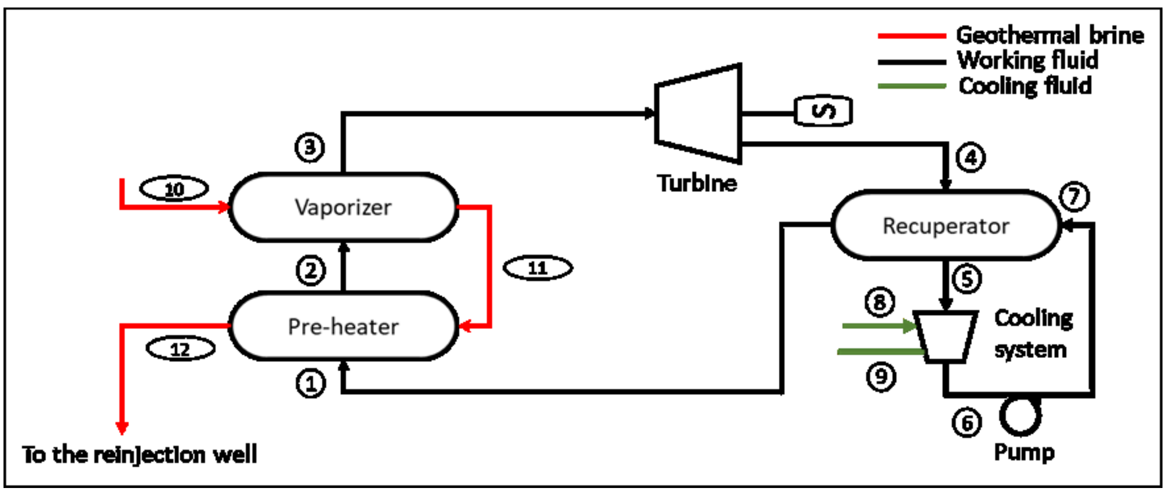

Figure 2: Recuperative ORC system configuration

Figure 3 shows the comparison of the T-s diagram between a basic ORC system (left) and a recuperative ORC system (right). It can be seen from Figure 6 that the condensing process in the basic ORC system (point 4 – point 5) takes longer than in the recuperative ORC system (point 5 – point 6). Therefore, the heat that needs to be released from the recuperative ORC system is lower than from the basic ORC system. As a result, the cooling system required for the recuperative ORC system is smaller compared to the one needed for the basic ORC system. Similarly, the pre-heater size also reduces in the recuperative ORC system because the working fluid enters the pre-heater (point 1) at a higher temperature. However, it should be noted that the reduction on the heat exchanger (cooling system and pre-heater) size is followed by adding an equipment (recuperator). Therefore, it is important to assess the performance of adding on a recuperator to the system based on thermo-economic approach.

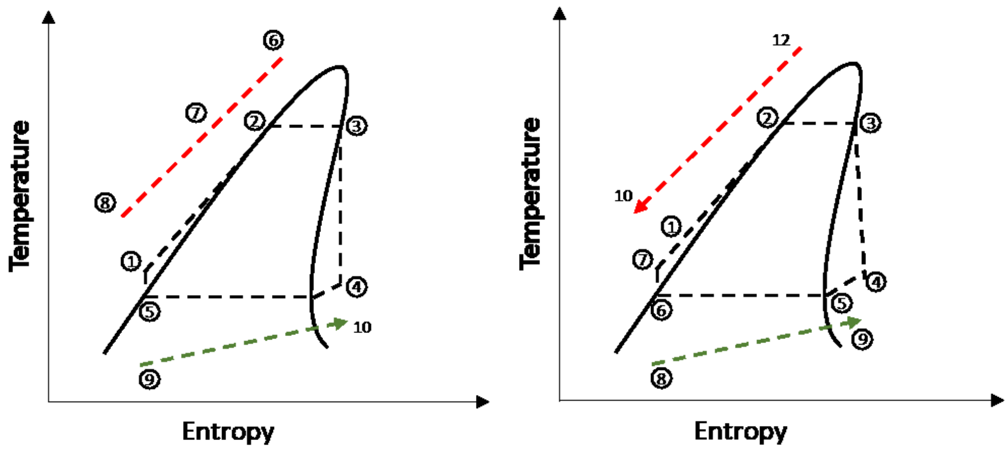

Figure 3: T-s diagram comparison of a basic ORC system (left) and a recuperative ORC system (right)

The result from some previous researches imply that a recuperative ORC system has a better thermal efficiency compared to the basic ORC system (Braimakis & Karellas, 2018; Mohammadzadeh et al., 2017; Zare, 2015). Zare (2015) and Mohammadzadeh et al. (2017) include the economic indicators as its objective function to assess the system performance. Zare (2015) applies total product cost minimization as its objective criteria and uses total capital cost and payback period to assess the economic performance of the ORC system. Mohammadzadeh et al. (2017) use total production cost as a ratio between net power output and the total cost of equipment as the optimization objective. Both studies provide a contradictory result regarding the economic performance. The results of the research conducted by Zare (2015) suggest that the total capital cost for a recuperative ORC system is higher than the basic ORC system. Thus, the recuperative ORC system has a longer payback period, whereas Mohammadzadeh et al. (2017) state that both thermal efficiency and economic optimization of recuperative ORC systems are better than standard ORC systems. Hence, further study is required to carefully compare the thermodynamics and economic performance of basic ORC and recuperative ORC for Wayang Windu geothermal power plant.

5. OPTMIZATION APPROACH

In general, there are two approaches in optimising ORC systems: the thermodynamic and the thermo-economic approach. Several researches optimise and assess the ORC system performance in utilizing geothermal resource based on the thermodynamics approach only (Braimakis & Karellas, 2018; He et al., 2012; E. Wang et al., 2012), the other applies thermo-economic approach (Hettiarachchi et al., 2007; Lecompte, Huisseune, Broek, Schampheleire, & Paepe, 2013; Toffolo et al., 2014; J. Wang et al., 2013).

5.1 Thermodynamics approach

The optimization with thermodynamics approach is done by maximizing the thermal efficiency or total net power output of the binary system. In this approach, the heat extraction is maximized and thus, less energy is wasted. The thermal efficiency of the ORC system is calculated using Equation (3).

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} \times 100\% \tag{3}$$

where η_{th} is the thermal efficiency in percentage, $\dot{W}_{net}$ is the net power output of the system in kW as stated in Equation (4) and $\dot{Q}_{in}$ is the total heat transferred by the geothermal brine to the system, which can be calculated using Equation (6).

$$\dot{W}_{net} = \dot{W}_{turbine} - \dot{W}_{parasitic\ load} \tag{4}$$

$$\dot{W}_{parasitic\ load} = \dot{W}_{pump} + \dot{W}_{fan} \tag{5}$$

$$\dot{Q}_{in} = \dot{m}_{geo,in} \left(h_{geo,in} + h_{geo,out}\right) \tag{6}$$

Even though this approach has been widely used, some studies suggest that relying on the thermal efficiency or net power output value only would possibly lead to less economically optimal outcome as the result using the thermodynamics approach can differ significantly compared to the thermo-economic approach (Quoilin et al., 2011; J. Wang et al., 2013; Zare, 2015). Therefore, a thorough optimization of ORC system should also be performed considering the economic aspect by applying the thermo-economic approach.

5.2 Thermo-economics approach

The thermo-economic approach considers both the technical and economic aspect for optimizing the ORC system. It is done by comparing the equipment size, which represents the total equipment cost, to the net power output. Toffolo et al. (2014) suggest that the total cost for heat exchangers (evaporator, preheater, and condenser) are the main cost of the ORC system. Therefore, it can be considered as the representative of the overall system cost. This is the basic assumption of using the specific area objective function (γ) as an indicator in assessing the thermo-economic performance of the ORC system as it calculates the ratio between the net heat transfer surface area and the net power output. Other than that, Toffolo et al. (2014) also apply two other common economic criteria for assessing the performance of the ORC system, that are the specific investment cost (SIC) and levelized cost of energy (LCOE). He argues that both criteria have a higher accuracy level than the specific area objective function. Hence, in this research, all the thermo-economic criteria mentioned above (specific area objective function, SIC, and LCOE) are applied to assess the performance of the ORC system.

5.2.1 Specific area objective function (γ)

The specific area objective function (γ) is an excellent indicator of the total equipment cost of a system as it is based on the heat transfer surface area used in the system (Hettiarachchi et al., 2007). The specific area objective function is the ratio between the total heat transfer surface area and the total net power output. In case of the ORC system, the total heat transfer surface area includes the preheater, evaporator, and the condenser. The equation of the specific area objective function is shown in Equation (7).

$$\gamma = \frac{A}{W_{net}} \tag{7}$$

where γ represents the specific area objective function with unit m^2/kW. A represents the total heat transfer surface area in m^2.

5.2.2 Ratio of the total specific equipment investment costs to net power output (SICp)

The specific mechanical equipment cost ($SICP$), as mentioned by Toffolo et al. (2014), is calculated by dividing the total purchased equipment cost (PEC) by the total net power output of the system as shown in Equation (8). The unit for $SICP$ is in $/kW.

$$SIC_P = \frac{PEC}{W_{net}} \tag{8}$$

In this study, the PEC is obtained from the Aspen Hysys simulation by activating the Aspen Process Economic Analyzer (APEA) tool. As the $SICP$ only considers the PEC, it is considered to be part of the total SIC (Specific Investment Cost) factor.

6. METHODOLOGY

6.1 Initial working condition

6.1.1 Working fluid

Isopentane, isobutane and n-pentane are selected as the working fluids and evaluated based on the thermo-economic approach. The fluid properties of each working fluid are listed on Table 2 in subsection 4.1.

6.1.2 Evaporation temperature (T_{evap})

Bao & Zhao (2013) suggest that the organic fluid would be chemically unstable near its critical point. It means a significant change on pressure could happen if there is a slight temperature change. Therefore, in this research, the evaporation temperature is set at about 15 – 30°C below the critical temperature. The calculation is also done by considering the specific heat ratio of the turbine, based on Aspen Hysys simulation results.

6.1.3 Inlet turbine pressure

The research conducted by Mago et al. (2008) suggests that the optimum operating condition of ORC system is attained by setting the working fluid pressure in its saturation point. Furthermore, Dai et al. (2009) and Toffolo et al. (2014) state that the maximum net power output for the dry and isentropic fluids is achieved by setting the evaporation pressure at its saturation point. Therefore, in this study, the inlet turbine pressure or evaporation pressure (P_{evap}) will be set at the saturation pressure for the specified T_{evap}.

6.1.4 Condenser pressure (P_{cond})

Pei et al. (2011) suggest that the ORC system efficiency gets higher by lowering turbine outlet pressure or condenser pressure (P_{cond}). Hence, in the initial condition, the condenser pressure is set as low as possible. The lower limit of P_{cond} is set such that a fully liquid phase is ensured to be created at the condenser outlet. In addition, it is also recommended to keep the condenser pressure above the atmosphere pressure (1 atm) to prevent air entering the system which could reduce the system performance (Bao & Zhao, 2013). Therefore, the pressure is also kept above the atmosphere pressure.

6.1.5 Mass flow rate

The working fluid mass flow rate ($\dot{m}_{WF}$) is calculated after Tevap, Pevap and Pcond has been specified as mentioned above. The calculation is performed by using the numerical approach. For the initial condition, the $\dot{m}_{WF}$ is calculated by considering the maximum net power output as the objective. It is presumed that the higher the $\dot{m}_{WF}$, the higher the net power output. However, there is another consideration on determining the $\dot{m}_{WF}$ which is related to the heat exchanger specification, in this case the FT correction factor. The FT correction is the correction factor of log mean temperature difference (LMTD), which is an important parameter in calculating the heat duty of the heat exchanger. Thus, the $\dot{m}_{WF}$ should be kept within the correct FT correction factor range.

6.2 Simulation and Calculation

6.2.1 Process simulation

The process of the ORC system is modelled using Aspen Hysys version 10 software. The modelling of the process is performed to evaluate the technical feasibility and to estimate the power production and consumption of various proposed models. Also, the modelling result provides the approximate equipment size along with the total purchased equipment costs. The model simulated in this study does not completely represent the real process. Several assumptions are applied to build a simple model that could represent the real process. However, this model could be an acceptable representation to learn about the plant process behaviour (Poe, W. A.; Mokhatab, 2017). Aspen Hysys had been utilised in some studies that assess the ORC system implementation in geothermal binary power plant, diesel engine etc. (Ghasemi, Paci, Tizzanini, & Mitsos, 2013; Meinel, Wieland, & Spliethoff, 2014; Yu, Shu, Tian, Wei, & Liu, 2013).

In the process modelling using Aspen Hysys software, selecting a correct equation of state (EOS) is one of the crucial steps. The EOS is used to determine the specific volume of a gaseous mixture of chemicals at the specified temperature and pressure. The specific volume is essential to calculate the size and the cost of the system (Hamid, 2007). In this study, hydrocarbon fluids are used as the working fluids which are classified as a nonpolar component. Therefore, based on the decision tree illustrated by Hamid (2007) in Figure 11, the Soave-Redlich-Kwon (SRK) is selected as the EOS in the simulation. The SRK is developed from the ideal gas equation to address the process of chemical plants at extremely high pressures (Hamid, 2007).

6.2.2 Economic modelling

In this study, the PEC is retrieved from the Aspen Hysys simulation result by activating the Aspen Process Economic Analyzer (APEA) tool, whereas the total investment cost is calculated by following the cost breakdown list suggested by Lemmens (2016), as shown in Table 3.

Table 3 Total Purchase Cost (TPC) estimation for an ORC system (Lemmens, 2016)

	Cost breakdown	Percentage	of component
1	**Fixed-capital investment (FCI)**		
1.1	**Direct fixed-capital investment (DFCI)**		
1.1.1	Onsite costs (ONSC)		
	Purchased-equipment cost (PEC)		
	Purchased equipment installation	45%	PEC
	Piping	31%	PEC
	Instrumentation and controls	10%	PEC
	Electrical equipment and materials	11%	PEC
1.1.2	Offsite costs (OFSC)		
	Land	-	
	Civil, structural, and architectural work	44%	PEC
	Service facilities	20%	PEC
	Buildings	-	
	Yard improvements	-	
1.2	**Indirect fixed-capital investment (IFCI)**		
	Engineering and supervision	30%	PEC
	Construction costs including contractor's profit	15%	DCFI
	Contingencies	10%	FCI
	Legal costs	2%	FCI
2	**Other outlays**	10%	FCI
Total capital investment		100%	FCI+Other

6.2.3 Economic performance assessment

The economic performance is assessed by using two parameters: Levelized Cost of Electricity and Discounted payback period.

a. Levelized Cost of Electricity

Levelised cost of energy (LCOE) is chosen as an indicator to evaluate the economic aspect of the system because it is often used to assess the cost-effectiveness of emerging technologies (Branker, Pathak, & Pearce, 2011). LCOE could also be defined as "the average minimum price at which electricity must be sold in order to break-even over the lifetime of the project" (U.S Energy Information

Administration [EIA], 2019). The method shows the result as a ratio between the unit price per unit energy produced. The LCOE is calculated using the equation suggested by Branker et al. (2011) as can be seen in Equation (9).

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + Tax_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (9)$$

Where I_t = Investment cost in year t in USD
M_t = operation and maintenance cost in year t in USD
Tax_t= tax in year t in USD
E_t = electricity generation in year t in kWh
r = discount rate in %
n = lifetime of the system in years

In the real equation suggested by Branker et al. (2011), there is another variable called the fuel expenditure, which is assumed to be included in the operation and maintenance cost in this research. The numerator in the Equation (9) represents the net costs of the system, which include cash outflows, such as the initial investment, operation and maintenance cost. However, the net costs could also be modified to include the taxation and incentives into the equation (Darling, Seth B.; You, Fengqi; Veselka, Thomas; Velosa, 2011). In this research, the taxation will be included in the calculation of LCOE.

b. Discounted payback period

The other economic indicator used in this study is the discounted payback period (DPB). This indicator is chosen as it calculates the payback period that considers the value of money discounted over time (Yard, 2000). The value of DPB is determined in the year when the net present value (NPV) is equal to zero according to Equation (10).

$$NPV = \sum_{n=0}^{n=t} \frac{CF_n}{(1+r)^n} = 0 \quad (10)$$

The CFn is the cash flow in year n in USD, t is the project lifetime in year t, and r is the discount rate. Several assumptions are applied for calculating the NPV. The annual cash flow is calculated by considering the revenue, capital cost, operational and maintenance cost, and tax as described in Equation (11). The revenue is calculated using Equation (12) which multiplies the total generated electricity (W_{net}) in kWh by the purchased electricity price (PEP) in USD/kWh. The operational and maintenance cost is calculated by adding the equipment (pumps and fan) power consumption and an addition of 1 cent US$/kWh plant facilities O&M cost assumption for geothermal power plant in Indonesia as suggested by Wahjosoedibjo and Hasan (2018). The net cash flow for each year then will be discounted with year-0 as the basis, as can be seen on Equation (10).

$$CF_n = (1 - Tax) \times (R_n - (CapEx_n - OpEx_n)) \quad (11)$$

$$R_n = (W_{net} \times 8760\ h\ \times Capacity\ Factor) \times PET \quad (12)$$

where R_n = Total revenue at year n in USD
$CapEx_n$ = Total investment cost at year n in USD
$OpEx_n$ = Total operational and maintenance cost at year n in USD
PEP = Purchased electricity price in USD/kWh

Several assumptions are applied in the calculation which is gathered based on several existing literatures as listed in Table 4.

Table 4 Economic parameters used in economic performance calculations

Parameter	Value	Reference
Discount rate	6%	Trading Economics (2019)
Project lifetime	30 years	Walraven et al. (2015) and Budisulistyo et al. (2017)
Capacity ratio	95%	Purnanto and Purwakusumah (2015)
Tax	34%	Ministry of Finance (2017)
Purchased electricity price by PLN	9.4 c$/kWh	MEMR (2016)

7. RESULT AND CONCLUSION

7.1 Optimization result

7.1.1 Working fluid

The operating condition for each working fluid in the ORC system can be seen in Table 5. These working conditions are obtained by setting up several parameters.

Table 5 Operating condition for Isopentane, Isobutane, and n-pentane

Working fluid	$T_{evaporation}$ (^oC)	$P_{evaporation}$ (kPa)	P_{cond} (kPa)	m_{WF} (kg/s)	$T_{brine,outlet}$ (^oC)
Isopentane	156.9	2090	137	18.1	139.1
Isobutane	117.6	2750	497	18.1	149.4
n-pentane	164.4	2070	127	18.1	137.2

The results from the simulation and calculation for each working fluid are shown in Table 6. Net power output ($\dot{W_{net}}$), system efficiency and SIC are used to evaluate the performance of each working fluid. The ratio between the $\dot{W_{net}}$ per $\dot{m_{WF}}$ is also calculated and compared with the data from some existing literatures. This ratio explains the amount of power that could be generated in each kg/s of working fluid.

Table 6 Simulation and calculation result for Isopentane, Isobutane, and n-pentane

Working fluid	W_{net} (kWe)	System efficiency (%)	SIC (US$/kW)	W_{net}/m_{WF} (kW/kgs^{-1})
Isopentane	1335	15.37%	4,376	73.93
Isobutane	696	10.61%	8,559	38.53
n-pentane	1404	15.47%	4,251	77.78

The values of $\dot{W_{net}}$, per $\dot{m_{WF}}$ from existing literatures, as shown in Table 7, ranges from 46 – 69 kW/kgs-1. Similarly, the simulation provides a relatively close result that ranges between 38.5 – 73.9 kW/kgs-1. The slight difference occurred due to some dissimilar parameter set-ups in the model, such as heat source temperature, ambient temperature, $T_{evap}$and P_{cond}.

Table 7 Summary of working fluid mass flow rate of ORC system from several studies

Reference	Working fluid	$T_{geo,in}$ (^oC)	$m_{geo,in}$ (kg/s)	m_{WF} (kg/s)	T_{evap} (^oC)	W_{net} (kW)	W_{net}/m_{WF} (kW/kgs^{-1})
Tofollo et al. (2014)	Isobutane	180	100.00	114.50	152	6,045	52.79
Dai et al. (2009)	Butane	145	15.95	3.14	85.5	162	51.59
	Isobutane	145	15.95	3.61	87.1	168	46.49
Zare (2015)	Isobutane	165	82.16	76.09	160	5,000	65.71
El-Emam and Dincer (2013)	Isobutane	175	79.53	72.24	144.3	5,000	69.21
	Isobutane	170	81.59	74.15	141.4	5,000	67.43
	Isobutane	165	84.36	78.06	136.1	5,000	64.05

As can be seen from Table 6, n-pentane generates the highest power with the lowest specific investment cost (SIC), which means n-pentane is considered as the optimum working fluid based on the thermo-economic approach. This result is in line with some results from existing literatures. For instance, Zare (2015) argues that n-pentane produces the highest thermal efficiency with the lowest equipment costs. Furthermore, Quoilin et al. (2011) also state that n-pentane has the lowest specific investment cost (SIC). Therefore, n-pentane is chosen as the working fluid for further assessment in this study. The operating condition of the n-pentane shown in Table 5 will be the initial operating condition for the next optimization measure assessment.

7.1.2 Cycle configuration

The second measure to optimize the heat transfer area of the ORC system is by adding on a recuperator, also called a recuperative ORC system. Installing a recuperator means adding another heat exchanger into the system. However, the heat transfer area required for the cooling system will be lower as the working fluid has transferred some of its heat before entering the cooling system. Other than that, the required heat transfer area for the preheater will also reduce as the working fluid temperature has been increased due to receiving heat from the hot working fluid that leaves the turbine. The comparison of the thermo-economic performance between the recuperative and basic ORC system is presented in the following subsection.

a. Basic ORC system

As stated in the previous subsection, the operating condition of the system which uses n-pentane as the optimum working fluid is used as the initial condition for the basic scenario of the second optimization measures. However, in this case, the $T_{evap}$and P_{cond} of the base case are optimized using a thermo-economic approach. The optimization results show that the optimum $T_{evap}$and P_{cond} are achieved at 149°C and 157 kPa. Therefore, this parameter values will be used as the basic scenario set-up as shown in Table 8.

Table 8 Parameter set-up and simulation results of the basic ORC sytem

Parameter	Value	Unit
Parameter Set-up		
Evaporation Temperature	149.2	C
Evaporation Pressure	1,600	kPa
Working Fluid Mass Flow Rate	18.1	kg/s
Turbine Exhaust Pressure	157	kPa
Simulation Results		
Net Power Output	1,170	kW
Thermal Efficiency (η)	13.76	%
Specific Area Objective Function (γ)	2.067	m^2/kW
Equipment Specific Investment Cost (SICp)	892	US$/kW

b. Recuperative ORC system

All the parameters used in Section 7.1.1 for n-pentane are applied in this section, including the optimum value of $T_{evap}$and P_{cond} gathered from the basic scenario model. The analyzed scenario is the modification of the base scenario by adding on a recuperator, also called a recuperative ORC system. The schematic diagram of a recuperative ORC system can be seen in Figure 2. The parameter set-up and the simulation results for the recuperative ORC system are listed in Table 9.

Table 9 Parameter set-up and simulation results of the recuperative ORC system

Parameter	Value	Unit
Parameter Set-up		
Evaporation Temperature	149.2	C
Evaporation Pressure	1,600	bar
Working Fluid Mass Flow Rate	18.1	kg/s
Turbine Exhaust Pressure	157	kPa
Recuperator Hot Stream Outlet Temperature	80	C
Simulation Results		
Net Power Output	1,170	kW
Thermal Efficiency (η)	14.72	%
Specific Area Objective Function (γ)	2.325	m^2/kW
Equipment Specific Investment Cost (SICp)	942	US$/kW
Temperature Geothermal Brine Outlet	142.7	C

The pinch point temperature difference (PPTD) of the heat exchanger used as the recuperator is 30°C. Thus, the recuperator hot stream outlet temperature is set at 80°C. The total net power output in the recuperative ORC system is similar with the basic ORC system because both systems have the same $T_{evap}$and P_{cond}. As a result, the geothermal brine outlet temperature for the recuperative ORC system is higher than the basic ORC system. It happens because the system is able to receive more heat from the heat source due to the additional capacity from the recuperator. Consequently, the thermal efficiency of the recuperative ORC system also increases.

c. Recuperative ORC system with adjusted mass flow rate

A better comparison is done by keeping the geothermal brine outlet temperature at the same value, both for the base and the recuperative ORC system scenario. The geothermal brine outlet temperature of the base scenario is selected as the benchmark. In the second recuperative ORC system model, the mass flow rate of the working fluid is adjusted to meet the geothermal brine outlet temperature of the basic ORC system at 140°C. By keeping the outlet brine temperature under similar value, the amount of heat transferred from the geothermal brine to the system is the same for both scenarios. Therefore, the results can be evaluated under the same circumstances. The parameter set-up and the simulation results for the recuperative ORC system with adjusted working fluid mass flow rate are shown in Table 10.

Table 10 Parameter set-up and simulation results of recuperative ORC system with adjusted mass flow rate

Parameter	Value	Unit
Parameter Set-up		
Evaporation Temperature	149.2	C
Evaporation Pressure	1,600	bar
Working Fluid Mass Flow Rate	19.3	kg/s
Turbine Exhaust Pressure	157.0	kPa
Recuperator Hot Stream Outlet Temperature	80	C
Simulation Results		
Net Power Output	1,250	kW
Thermal Efficiency (η)	14.71	%
Specific Area Objective Function (γ)	2.375	m^2/kW
Equipment Specific Investment Cost (SICp)	941	US$/kW
Temperature Geothermal Brine Outlet	140	C

d. Thermo-economic performance comparison

Table 11 below shows the summary of the recuperative ORC system compared to the base scenario. The results from these simulations are divided into three scenarios: base scenario, recuperative ORC system, and recuperative ORC system with adjusted mass flow rate. LCOE and payback period are included to evaluate and compare the economic performance of the scenarios.

Table 11 Comparison between a basic ORC system and a recuperative ORC system with or without mass flow rate adjustment

Scenario	Base scenario	Recuperative ORC system	Recuperative ORC system with adjusted mass flow rate	Unit
Net Power Output	1,170	1,170	1,251	kW
Thermal Efficiency (η)	13.76	14.72	14.71	%
Specific Area Objective Fucntion (γ)	2.07	2.33	2.37	m^2/kW
Equipment Specific Investment Cost (SICp)	892	942	941	US$/kW
Levelised Cost of Energy (LCOE)	8.29	8.46	8.46	c$/kWh
Payback Period	Year-12	Year-13	Year-13	

From the results shown in Table 11, the ORC recuperative system has higher thermal efficiency compared to the basic ORC system. It is in line with the results from many studies which state that the thermodynamics performance of recuperative ORC system is higher than the basic ORC system (Braimakis & Karellas, 2018; Mohammadzadeh et al., 2017; Zare, 2015). On the other side, the γ and SICp by using a recuperative ORC system, both without and with adjusted mass flow rate, are higher than those in the base scenario (basic ORC system). These results also conformed with the LCOE and payback period calculation result which shows higher LCOE and a longer payback period for both scenarios. In addition, this result aligns with the study conducted by Zare (2015) which concludes that the simple ORC has better payback and the lowest capital cost compared to the recuperative ORC system. Therefore, the base scenario with basic ORC system is still considered as the best model.

7.2 Conclusion

The utilization of the geothermal binary system is recommended to improve the thermal efficiency and the net power output of the power plant. Nonetheless, optimization should be done to ensure the system operates in a thermodynamically and economically optimal condition. It is critical to apply the thermo-economic approach in assessing the geothermal binary system performance as it includes the economic assessment, which is an important indicator in pursuing a project. As the main component of the investment cost, the optimization should be prioritized for the heat exchanger area. Therefore, two measures are proposed to optimize the heat exchanger equipment by using the thermo-economic approach: selecting optimum working fluid and choosing an efficient cycle configuration.

Briefly, this report presents the thermo-economic approach for the optimal selection of working fluid and cycle configuration as the proposed geothermal binary system for the Wayang Windu geothermal power plant, using the methodology as follows.

- Simulating the proposed optimization measure models using Aspen Hysys v10 software to obtain technical and economic data.
- Optimizing the binary cycle plant design by analyzing the gathered data using the thermo-economic approach. The parameters used in the thermo-economic optimization are the specific area objective function (γ) and specific equipment investment cost (SICp).

These parameters present the ratio between the required heat exchanger area or total purchased equipment cost per each unit of electricity generated.

- Evaluating the performance of each optimized parameter based on thermodynamic and economic points of view. The thermodynamic indicators are the system thermal efficiency and net power output. The economic indicators are levelized cost of energy (LCOE) and discounted payback period.

This approach has been applied to assess and compare the performance of using isopentane, isobutane, and n-pentane as the working fluid of the ORC system. The result shows that n-pentane has the best thermodynamic and economic performance with a thermal efficiency of 15.47% and specific investment cost (SIC) of $4,251/kW. Therefore, considering the heat source and weather profile at Wayang Windu geothermal field, n-pentane is suggested as the optimum working fluid for the ORC system.

The results from this study also show that the recuperative ORC system shows a better thermal efficiency compared to the basic ORC system. However, based on the thermo-economic approach, it is economically more beneficial to operate under the basic ORC system configuration. The basic ORC system payback period is 1 year shorter compared to the recuperative ORC system, and it also has lower SICp and LCOE values. This result shows that the total heat transfer area to generate each unit of electricity in the recuperative ORC system is larger than in the basic ORC system. Consequently, the SICp and LCOE are also higher. Therefore, from thermo-economics point of view, basic ORC system is suggested to be utilized for Wayang Windu geothermal power plant.

8. FUTURE RESEARCH

This study only considers a steady heat source profile of Wayang Windu geothermal field with temperature of 180.7^{o}C and 48 kg/s geothermal fluid mass flow rate. It is recommended to also optimise the system by varying the heat source temperature, pressure, mass flow rate, and silica content to see the impact of changing the values of those parameters to the optimisation result. Other than that, it is also recommended to assess the thermo-economic impact of using different type and configuration of cooling system as it is one of the biggest cost components in geothermal binary power plant.

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