PROCEEDINGS, 48th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 6-8, 2023
SGP-TR-224

Thermodynamic and Economic Comparison of Organic Rankine Cycle and Kalina Cycle as Bottoming Unit to Utilize Exhaust Steam from Back Pressure Turbine Geothermal Power Plant

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Keywords: thermodynamic analysis, organic rankine cycle, kalina cycle, back pressure turbine, levelized cost of electricity.

ABSTRACT

Binary cycle using Organic Rankine Cycle or Kalina Cycle System has been applied in geothermal and some other industrial processes to recover waste energy to generate electricity. Two units of the power plants in Flores Island, Indonesia, used back-pressure turbines. The amount of exhaust stream available from these two units of the power plant is more than 62 tones per hour with enthalpy ranging from 2,430 to 2,435 kJ/kg. Instead of releasing the steam to the environment, it would be better to utilize the heat of the brine through a binary cycle, i.e., Kalina Cycle System (KCS) and Organic Rankine Cycle (ORC). The modeling and validation of KCS and ORC were carried out using the Aspen-HYSYS V12.1 software. Ekalina is chosen as KCS meanwhile several working fluids are chosen to find the optimum ORC system, such as butane, isobutane, pentane, isopentane, R-113, R-141b, and R-142b. The EKalina and simple ORC with basic components such as preheater, evaporator, expander, condenser, and pump is used in this research. The validation process of EKalina and ORC modeling resulted in a maximum error of 7.9% and 4.02 %, respectively. The result of optimization of EKalina has maximum net power and thermal efficiency is found at 99% ammonia fraction with the value of 4700.11 kW and 12.01%, respectively. But based on economic assessment 97% ammonia fraction has a better economic value than 99% with a Levelized Cost of Electricity (LCOE) of 2.024 cents/kWh. Meanwhile, the ORC resulted that R-141b is founded to have a maximum thermal efficiency of 10.65% with LCOE of 1.841 cents/kWh and R-113 has a minimum LCOE of 1.681 cents/kWh with the thermal efficiency of 10.26%. For the geothermal back pressure turbine unit, the EKalina has better thermal efficiency than ORC but has higher LCOE than ORC.

1. INTRODUCTION

As one of the nations with the most geothermal energy potential, Indonesia utilizes only 7.8 percent of its overall geothermal energy potential (Ditjen EBTKE 2020). The flores Island as a geothermal island in Indonesia, currently only have two Geothermal Power Plants (GPP) that located on Flores Island, namely Ulumbu GPP and Mataloko GPP. Ulumbu GPP, that located in Manggarai Regency, East Nusa Tenggara. consist of two condenser units and two back-pressure turbine units, with each unit having a generation capacity of 2.5 MW.

The Geothermal System in Ulumbu has a working area of 18280 ha and comes from a single reservoir whose upper border (top reservoir) is positioned between 200 and 600 meters above sea level. This reservoir has a temperature between 230°C and 250°C with a reserve of 100 MWe (Ditjen EBTKE 2017). In Ulumbu geothermal system, 3 wells with name of ULB-01, ULB-02, and ULB-03 have been drilled. However, only the ULB-02 well provides geothermal fluid to the four (4) producing units of the existing Ulumbu Geothermal Powerplant. (Kurniawan et al. 2019; PT. PLN (Persero) 2018).

The steam from the Back-pressure unit at Ulumbu GPP still contains a significant amount of thermal energy. The turbine unit 1 produces steam with a pressure of 98 kPa, an enthalpy of 2,435 kJ/kg, and a flow rate of 31,2 tons per hour. Meanwhile, the steam flow rate from unit 2 is 31,200 kilograms per hour at a pressure of 96 kPa and an enthalpy of 2,430 kJ/kg (Indonesia Power 2018; Mendive et al. 2014). The steam produced by the back-pressure turbine unit can be used for bottoming cycle such as Kalina Cycle System (KCS) or Organic Rankine Cycle (ORC) in ways other than just being released into the environment. Therefore, this research aims to optimize the optimum utilization of back-pressure turbine steam output from techno-economic view.

2. METHODOLOGY

Figure 1 is shown the flowchart of this research. The research started with data collection and then the simulation modeling in Aspen HYSYS v12.1. If the error is below 10%, then the model is considered valid. The KCS is optimized, and the optimum power output is used as ORC Modeling. In this process, the thermal efficiency was optimized. The economic parameter will be analyzed and then compared for each system.

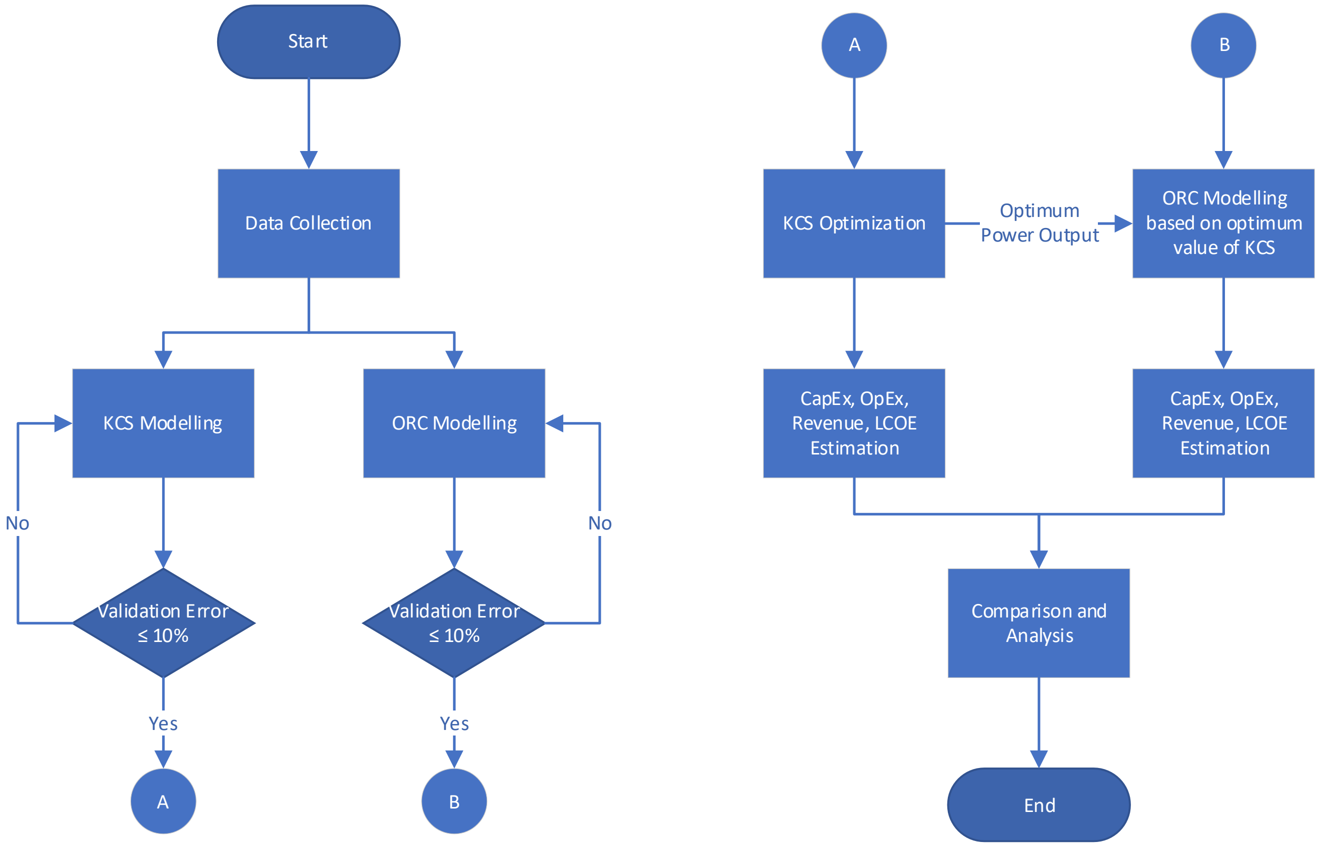


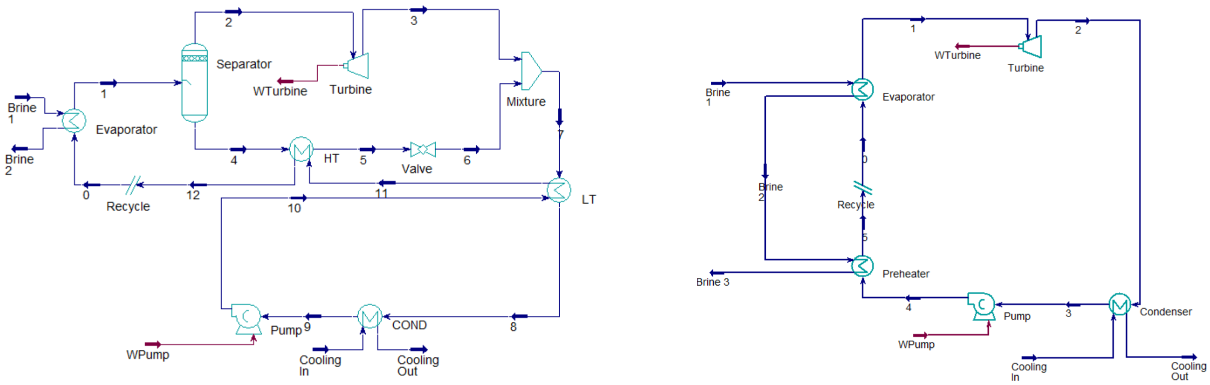
Figure 1: Thought Process of this Study

2.1. Thermodynamic Modelling

The study of the binary cycle requires the thermodynamic properties of the working fluid. Aspen-HYSYS was used to evaluate the binary cycle with the following assumptions are as follows:

- Geothermal fluid is pure water(Novotny and Kolovratnik 2016).
- The system of each component is analyzed at steady state (Moran et al. 2014).
- SRK is used as fluid properties (Rodríguez et al. 2012)
- Changes in potential and kinetic energy in each system are neglected (Moran et al. 2014).
- The condenser uses air cooling fluid with input and output temperatures of 25^{o}C and 40^{o}C respectively.
- The isentropic efficiency of turbine is 85% (DiPippo 2016)
- The adiabatic efficiency of pump is 75% (DiPippo 2016)
- No pressure drop in piping systems, heat exchanger components and separators (Li et al. 2013).
- No heat transfer between components and environment (Li et al. 2013).
- The mass flow rate of the working fluid in KCS is 45 kg/s, meanwhile the ORC is using data from
- Condensing temperature of ORC and KCS is 37°C (Campos Rodríguez et al. 2013)
- The specific power absorbed by the fans of the air-cooled condenser (ACC) is assumed to be 0.15 kW per kg/s of air (Toffolo et al. 2014)
- The pinch point temperature difference (PPTD) of the heat exchanger is 5°C

Kalian cycle used is EKalina cycle due to has more thermodynamic efficiency (Li et al. 2013). Li et al., (2013) and Nandaliarasyad et al., (2020) was used to validate the model. The simulation model of Aspen HYSYS is shown in Figure 2**.** Meanwhile, the thermal efficiency (η_{th}) is calculated by Equation (1) with $\dot{W}_{net}$ as net power and $\dot{Q}_{in}$ as thermal energy from the brine.



(a) (b)

Figure 2 Aspen HYSYS diagram. (a) EKalina cycle, (b) ORC

$$\eta_{th} = \dot{W}_{net}/\dot{Q}_{in} \tag{1}$$

2.2. Economic Modelling

Economics modeling was carried out by calculating the estimated capital costs of the optimum KCS and ORC. In addition, it is also calculated the Levelized Cost of Electricity (LCOE) of each scenario.

The module costing method was used to evaluate capital expenditure (CapEx) (Turton et al. 2018). The parameters needed to calculate the estimated cost of capital for each component depend on the different types and operating points. The main components that will be calculated are evaporator, recuperator, preheater, condenser, pump, turbine, and motor fan

Calculation of the basic cost of heat exchanger components using the heat exchanger surface area parameter (A). The surface area of the heat exchanger can be calculated using the Log Mean Temperature Difference (LTMD) equation which can be seen in Equation (2) (Incopera et al. 2013).

$$Q = UA\Delta T_{LMTD} \tag{2}$$

Where Q is the heat that moves from the hot flow to the cold flow in the heat exchanger, ΔT_{LMTD} is the difference in the average temperature, A is the area of the heat transfer, U is the overall heat transfer coefficient and the value of U is assumed to be constant for Evaporator, Preheater, recuperator, and Condenser is 1.1 kW/m^3, 1 kW/m^3, 1 kW/m^3 and 0.5 kW/m^3 respectively (Toffolo et al. 2014). In this paper, it is assumed that the heat exchanger used is counter-flow model.

The capital cost of each component, based on Turton et al. (2018) is the cost in 2001. Compared with the capital cost in the year this paper was made, the cost is already different. Cost adjustment is required using the Chemical Engineering Plant Cost Index (CEPCI). The CEPCI index in 2001 was 397 while the CEPCI index in late 2021 was 776.9 (Wang et al. 2022). Equation (3) is used to calculate cost in late 2021. The indirect cost is calculated based on the percentage of capital cost, as shown in Error! Reference source not found..

$$C_{2021} = \frac{I_{2021}}{I_{2001}} C_{2001} \tag{3}$$

The operation and maintenance (O&M) cost of the geothermal power plant is estimated at 1.65% of CapEx (Gao and Chen 2018). The gross revenue is calculated based on selling of electricity, and from operation and maintenance costs. The selling price of electricity used in this paper uses the cost of providing PT PLN's generation in 2018, which was taken from the Decree of the Minister of Energy and Mineral Resources of the Republic of Indonesia Number 55 K/20/MEM/2019, that is 14.5 cents USD/kWh (Menteri Energi dan Sumber Daya Mineral Republik Indonesia 2019). The working hours of a geothermal power plant used are 8616 hours (Energia News 2021). Meanwhile, the discount rate used is based on Asian Development Bank (Asian Development Bank 2021). Equation (4) is used to calculate the revenue. Meanwhile, Equation (5) is used to calculate the LCOE (Lai and McCulloch 2016)

Table 1: Indirect cost

Indirect cost components	Value (% total of main component capital cost)
Piping and installation	10
Control system and electricity	5
Construction	10
Engineer and supervisor services	5
Civil and structural works	30

$$\text{Gross Revenue} = \text{Electricity Tarif} \times \text{Working Hour} \times \text{Capacity} - \text{O\&M Cost} \quad (4)$$

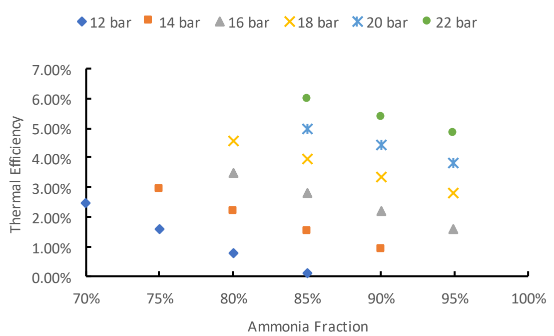
$$LCOE = \sum_{t=0}^{n} \frac{C_t + O_t}{(1+r)^t} \Big/ \sum_{t=0}^{n} \frac{E_t}{(1+r)^t} \quad (5)$$

3. RESULT AND DISCUSSION

3.1. Thermodynamic Analysis

Based on the simulation, the error of modeling is lower than 10%. EKalina and ORC modeling resulted in a maximum error of 7.9% and 4.02%. Therefore, the model can be considered valid and accepted. The highest error in Ekalina is heat in the preheater, meanwhile in ORC is from condenser outlet temperature.

The result of the thermodynamic analysis of Ekalina is shown in Figure 3. Higher ammonia fraction will lead to lower thermal efficiency at the same turbine inlet pressure due to higher condenser pressure that is bounded by saturated pressure at 37°C. Meanwhile, a higher ammonia fraction will lead to higher thermal efficiency at a constant pressure ratio. A higher ammonia fraction makes a higher-pressure ratio can be achieved due to lower saturated temperature at the same pressure. Ammonia has a lower saturated temperature than water; therefore, the saturated temperature of the mixture will be lower when ammonia fraction is higher. Higher net power also can be achieved due to a higher-pressure ratio that can be achieved. The maximum net power of EKalina is 5074.13 kW with a thermal efficiency of 12.01% at 99% ammonia fraction.



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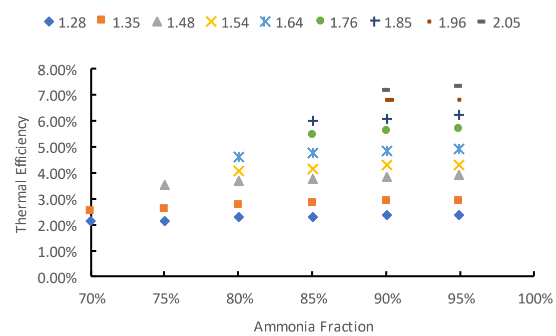

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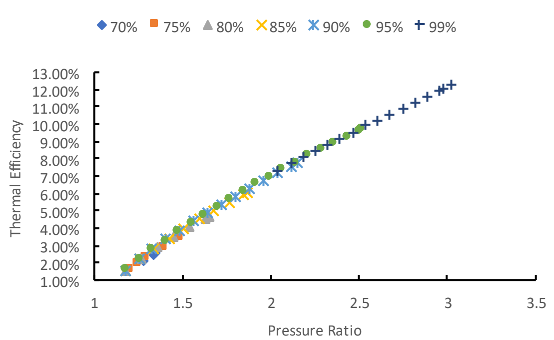
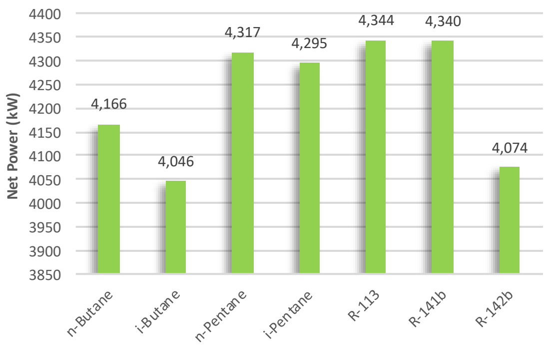


(c)

(d)

Figure 3: EKalina thermodynamic result (a) Thermal efficiency at constant turbine inlet pressure (b) thermal efficiency at constant pressure ratio (c) thermal efficiency in every pressure ratio. (d) maximum net power in every ammonia fraction

Figure 4 is shown the ORC thermodynamic result. Based on seven working fluids, it is found that the R-141b has the highest thermal efficiency with a value of 10.65%. Meanwhile, the R-113 has maximum net power output with a value of 4343.53 kW. R-141b has lower power output due to needing more fan power in the condenser.



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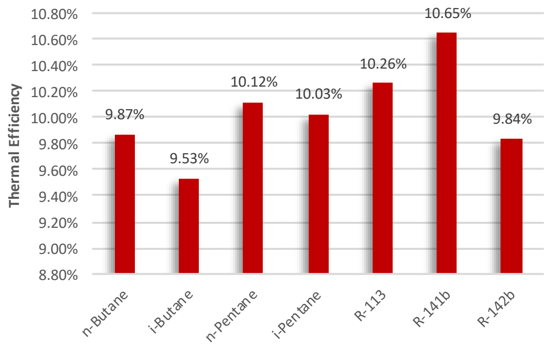


(b)

Figure 4: ORC thermodynamic results. (a) Net power (b) Thermal Efficiency

3.2. Economic Analysis

Detailed economics of EKalina and ORC are shown in Table 2 and Table 3**,** respectively. With more ammonia fraction, the capital cost will be higher due to the higher area needed in the condenser. The gross revenue also increases when the ammonia fraction is increasing due to more net power. However, the capital cost per kW has the lowest value at 97% ammonia fraction. Meanwhile, the capital cost and gross revenue at ORC are varied. The lowest capital cost is found in R-113 as a working fluid.

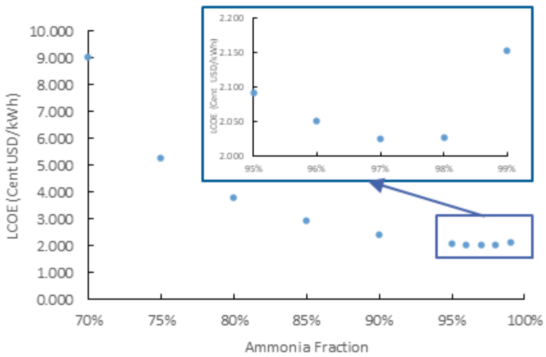
Table 2: Detailed Economic of EKalina (x1000 USD)

Ammonia Fraction	Capital Cost	Capital Cost/kW	O&M Cost	Gross Revenue
70%	$ 7,386	$ 11.442	$ 118	$ 688
75%	$ 7,130	$ 6.696	$ 114	$ 1,216
80%	$ 7,536	$ 4.810	$ 121	$ 1,837
85%	$ 8,083	$ 3.741	$ 129	$ 2,570
90%	$ 8,755	$ 3.063	$ 140	$ 3,431
95%	$ 9,837	$ 2.651	$ 157	$ 4,478
96%	$ 10,170	$ 2.600	$ 163	$ 4,725
97%	$ 10,615	$ 2.567	$ 170	$ 4,997
98%	$ 11,284	$ 2.569	$ 181	$ 5,308
99%	$ 12,831	$ 2.730	$ 205	$ 5,667

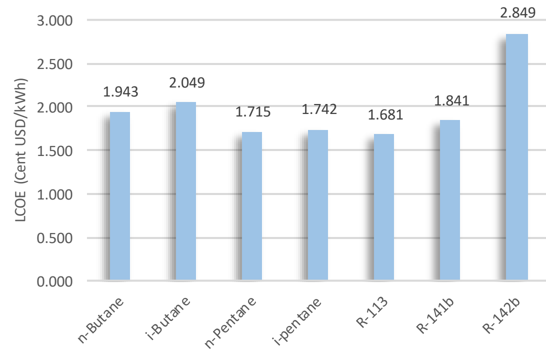
Table 3: Detailed Economic of ORC (x1000 USD)

Working Fluid	Capital Cost	Capital Cost/kW	O&M Cost	Gross Revenue
n-Butane	$ 10,267	$ 2.464	$ 164	$ 5,041
i-Butane	$ 10,514	$ 2.599	$ 168	$ 4,886
n-Pentane	$ 9,388	$ 2.175	$ 150	$ 5,244
i-Pentane	$ 9,488	$ 2.209	$ 152	$ 5,214
R-113	$ 9,259	$ 2.132	$ 148	$ 5,278
R-141b	$ 10,133	$ 2.334	$ 162	$ 5,261
R-142b	$ 14,716	$ 3.612	$ 235	$ 4,854

Figure 5 is shown the LCOE of each scenario. The lowest LCOE is found in 97% ammonia with value of 2.024 cents USD/kWh; meanwhile, R-113 has the lowest LCOE in ORC with a value of 1.681 cents USD/kWh. This result shows that ORC with R-113 working fluid is more feasible to utilize in the Ulumbu Geothermal Power Plant.



(a)



(b)

Figure 5: (a) LCOE of EKalina (b) LCOE of ORC

3.3. Comparison

It also found that the highest thermal efficiency does not guarantee the most economically feasible. The thermal efficiency of 99% ammonia fraction, 97% ammonia fraction, R-141b, and R-113 is 12.01%, 10.69%, 10.65%, and 10.26% respectively. Nevertheless, the LCOE for 99% ammonia fraction, 97% ammonia fraction, R-141b, and R-113 is 2.153 cents USD/kWh, 2.024 cents USD/kWh, 1.841 cents USD/kWh, 1.681 cents USD/kWh. This is caused by the higher capital cost of 99% ammonia fraction and R-113, and this lead to more operation and maintenance cost, as shown in Table 4. Kalina Cycle System (KCS) has lower economic parameters than Organic Rankine Cycle (ORC) due to the temperature pinch point difference. Steam exhaust from Ulumbu Power Plant has a temperature of about 99°C even though the thermal energy is high enough due to the vapor state. Kalina Cycle used two fluid that has different saturated temperature at the same pressure to make the system more efficient by using a recuperator. But in this study, it is found that the highest performance of KCS is above 95% ammonia fraction. Therefore, the KCS is not efficient enough and more like ORC.

Table 4: Detailed component cost for highest thermal efficiency and lowest LCOE

Component	R-113	R-141b	97% Ammonia	99% Ammonia
Evaporator	$ 1,917,345	$ 2,058,836	$ 1,933,082	$ 2,244,053
Preheater	$ 147,486	$ 132,423	$ 60,744	$ 48,319
Condenser	$ 1,136,304	$ 1,549,123	$ 1,913,381	$ 2,926,239
Pump	$ 45,787	$ 57,024	$ 186,895	$ 227,215
Turbine	$ 2,328,681	$ 2,328,681	$ 2,328,681	$ 2,363,898
Motor Fan	$ 211,162	$ 206,801	$ 211,476	$ 209,927
O&M Cost	$ 148,141	$ 162,122	$ 169,837	$ 205,303

4. CONCLUSION AND WAY FORWARD

The maximum thermal efficiency of KCS and ORC is 12.01% at 99% ammonia fraction and 10.65% at R-141b as working fluid. Meanwhile, the maximum net power output of KCS happened at a 99% fraction with value of 5074.13 kW, and R-113 as the maximum net power output of ORC with a working fluid of R-113.

Based on LCOE, the 97% ammonia fraction has the best performance compared to other ammonia fractions, with a LCOE of 2.024 cents USD/kWh. While R-113 has the lowest LCOE compared to other working fluids of the ORC and KCS with a value of 1.681 cents USD/kWh. It proposed that ORC with R-113 is more feasible to utilize steam exhaust of Ulumbu Power Plant with the estimated capital cost of USD 9,258,825, estimated gross revenue per year of USD 5,278,317, with a thermal efficiency of 10.26%, and a net power of 4.34 MW.

This paper is a preliminary study. Therefore, next research may be needed, such as performing exergy analysis, simulation about other mixtures in KCS, using another KCS, using other working fluids, and conducting an economic analysis with a more comprehensive cost component.

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6. APPENDICES

6.1. Appendix A. Validation Result

Table A.1: Validation Result of EKalina

Parameter	Unit	Reference Value (Li et al. 2013)	Modeling Value	Relative Error
Ammonia-Water Parameter				
Evaporator Inlet Temperature	°C	65.98	64.95	1.6%
Evaporator Outlet Temperature	°C	105.00	105.42	0.4%
Separator Outlet Temperature	°C	105.00	105.42	0.4%
Turbine Outlet Temperature	°C	71.20	74.06	4.0%
Preheater Outlet Temperature	°C	45.10	45.10	0.0%
Condenser Inlet Temperature	°C	66.08	67.14	1.6%
Condenser Outlet Temperature	°C	35.00	33.00	5.7%
Pump Outlet Temperature	°C	35.10	33.10	5.8%
Thermal Cycle Performance				
Heat in Evaporator	kW	164.15	174.84	6.5%
Heat in Preheater	kW	40.87	37.64	7.9%
Heat in Condenser	kW	151.38	161.43	6.6%
Turbine Power	kW	13.04	13.69	5.0%
Pump Power	kW	0.27	0.28	5.5%
Thermal Efficiency	%	7.78	7.67	1.4%
Geo Fluid Parameter				
Evaporator Outlet Vapor Fraction	%	56.00	58.81	5.0%
Preheater Outlet Vapor Fraction	%	40.00	42.26	5.7%

Table A.2: Validation Result of ORC

Parameter		Reference (Nandaliarasyad et al. 2020)	Modeling Value	Relative Error
Working Fluid Parameter				
Evaporator Outlet Temperature	°C	94.00	94.86	0.92%
Turbine Outlet Temperature	°C	58.87	60.77	3.22%
Condenser Outlet Temperature	°C	37.34	38.84	4.02%
Pump Outlet Temperature	°C	37.73	39.13	3.70%
Thermal Cycle Performance				
Heat Input	kJ/s	19230	19511	1.46%
Wnett	KW	2000	2010	0.52%
Thermal Efficiency	%	10.40	10.30	0.93%

6.2. Appendix B. Detailed Economic

Table B.1: Detailed Economic of EKalina

Ammonia Fraction	Capital Cost	Capital Cost/kW	O&M Cost	Gross Revenue
70%	$ 7,386,451.00	$ 11,441.98	$ 118,183.22	$ 688,324.43
75%	$ 7,130,284.76	$ 6,696.48	$ 114,084.56	$ 1,216,167.96
80%	$ 7,536,303.20	$ 4,809.72	$ 120,580.85	$ 1,836,967.44
85%	$ 8,082,921.59	$ 3,740.73	$ 129,326.75	$ 2,570,189.78
90%	$ 8,755,380.99	$ 3,062.96	$ 140,086.10	$ 3,431,058.52
95%	$ 9,836,504.35	$ 2,651.18	$ 157,384.07	$ 4,477,884.89
96%	$ 10,169,594.77	$ 2,599.62	$ 162,713.52	$ 4,724,566.79
97%	$ 10,614,814.72	$ 2,566.52	$ 169,837.04	$ 4,997,208.29
98%	$ 11,284,142.40	$ 2,568.72	$ 180,546.28	$ 5,307,588.34
99%	$ 12,831,440.47	$ 2,730.03	$ 205,303.05	$ 5,666,632.73

Table B.2: Detailed Economic of ORC

Working Fluid	Capital Cost	Capital Cost/kW	O&M Cost	Gross Revenue
n-Butane	$ 10,266,682.39	$ 2,464.16	$ 164,266.92	$ 5,040,905.14
i-Butane	$ 10,513,675.71	$ 2,598.71	$ 168,218.81	$ 4,886,200.14
n-Pentane	$ 9,388,456.33	$ 2,174.59	$ 150,215.30	$ 5,243,538.88
i-Pentane	$ 9,487,707.25	$ 2,209.05	$ 151,803.32	$ 5,213,939.78
R-113	$ 9,258,824.66	$ 2,131.64	$ 148,141.19	$ 5,278,317.33
R-141b	$ 10,132,619.98	$ 2,334.44	$ 162,121.92	$ 5,260,531.99
R-142b	$ 14,716,181.75	$ 3,612.17	$ 235,458.91	$ 4,854,339.84

Table B.3: Detailed component cost for highest thermal efficiency and lowest LCOE

Component	R-113	R-141b	97% Ammonia	99% Ammonia
Evaporator	$ 1,917,345.83	$ 2,058,835.59	$ 1,933,081.88	$ 2,244,052.93
Preheater	$ 147,486.08	$ 132,423.14	$ 60,743.72	$ 48,318.69
Condenser	$ 1,136,304.06	$ 1,549,123.01	$ 1,913,381.01	$ 2,926,238.54
Pump	$ 45,786.66	$ 57,023.86	$ 186,895.44	$ 227,214.95
Turbine	$ 2,328,681.15	$ 2,328,681.15	$ 2,328,681.15	$ 2,363,897.86
Motor Fan	$ 211,161.63	$ 206,800.74	$ 211,475.99	$ 209,927.32