Potential Utilization of Flue Gas Using Organic Rankine Cycle (Study Case PLTMG Balai Pungut-Duri)

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***Abstract* – PLTMG Balai Pungut-Duri is one of the largest gas engine type power plants in Riau with a capacity of 7x16 MW. The efficiency produced by the Balai Pungut-Duri PLTMG is 38% with the standards set by PT. PLN Efficiency in this type of generator is 45-47.5%. One of the factors that causes a reduction in the value of efficiency in power plants is that energy is converted into work and some is wasted, one of which is energy from flue gas. The purpose of this study is to examine the potential for utilizing flue gas using the Organic Rankine Cycle (ORC). The method used in this study is the law of thermodynamics 1 to determine the parameter values needed to determine the efficiency and power generated using the Engineering Equation Solver software. From the results of the calculations carried out, the Balai Pungut PLTMG produces an efficiency of 38.49% and a power of 14,530 kW under excited conditions. In utilizing flue gas using an organic rankine cycle it produces an efficiency of 19.97% with a power of 4,556 kW. the combined efficiency that can be produced by PLTMG Balai Pungut-Duri is 50.56% with a total power of 19,086 kW, with an efficiency increase of 12.07%. The results of the study show that the use of flue gas energy can increase efficiency according to PLN standards.**

Keywords: PLTMG, Organic Rankine Cycle, EES, Thermodynamics.

I. INTRODUCTION

The demand for electrical energy in Indonesia is currently increasing every year. Based on data from the Ministry of Energy and Mineral Resources (ESDM) in 2021, the amount of electricity consumption in Indonesia rose from 84,958.25 GWh to 94,441.84 GWh. Based on data from the Ministry of Energy and Mineral Resources in 2021 in Indonesia, current thermal power plants still dominate around 90.49% of the total national plants of 74,532.94 MW in meeting national electricity needs. The capacity of electrical energy that has been successfully generated based on the type of generation is at PLTU by 43.88%, PLTU MT by 3.05%, PLTU-M / G by 2.76%, PLTG by 7.18%, PLTGU by 16.65%, PLTMG by 4.3%, PLTD by 6.69%, PLTBm by 2.84%, PLTP by 3.07%, PLTSa by 0.04%[1]

Riau Province is one of 7 provinces that have the largest installed power plant capacity in Indonesia. The total installed capacity is 2,517.13 MW with various types of plants including PLTBm with a capacity of 1,249.44 MW, PLTU 363 MW, PLTMG 363.20 MW, PLTD 214.86 MW, and PLTG 165.80 MW [1]. Based on the ESDM metrical data, PLTMG is the third largest type of power plant in Riau.

The number of PLTMG units available in Riau is currently 17 units. Among them are 6 units at PLTMG Teluk Meranti, 2 units at PLTMG Siak, 2 units at PLTMG Rokan, and 7 units at PLTMG Balai Pungut-Duri. PLTMG Balai Pungut is a gas engine power plant with the largest number of units in Riau. PLTMG Balai Pungut-Duri is one of the providers of electrical energy within the scope of the Pekanbaru Power Plant Control Implementation Unit (UPDK Pekanbaru) from PT. PLN (Persero). This PLTMG has been operating since 2013 with a capacity of 7x16 MW and is the PLTMG with the largest capacity in Riau.

PLTMG Balai Pungut supplies electrical energy to the Sumatra region from Aceh to Lampung (interconnection). The fuel used in this PLTMG is diesel (HSD) and natural gas. During its operation, PLTMG Balai Pungut is more dominant in using gas mode than diesel mode. As long as it operates in gas mode, the fuel requirements used are 99% gas and 1% diesel. The 1% diesel was used as the initial starting engine before operating [2] .

During the PLTMG operation of this collection hall, the resulting thermal efficiency was 38% but this result was still below the efficiency standard set by PLN, which was 44 – 47,3% [3], [4] . One of the factors that affect the reduction in efficiency is the energy wasted during the operation of the plant, because of the fuel used there will be electrical energy and wasted energy.[5]

In increasing efficiency, steps were taken by PLTMG Balai Pungut-Duri by carrying out preventive maintenance and a major overhaul. And based on research conducted on related objects, the compression ratio affects the efficiency of the Balai Pungut PLTMG, the higher the compression ratio, the higher the efficiency that can be produced [6]. Based on the results of an interview with Mr. Naufal, the type of energy wasted during the electricity generation process carried out can be in the form of flue gas, and engine output gas. From this type of wasted energy, flue gas is a gas derived from combustion which is the largest source of exhaust heat in a generation system. Based on the results of an interview conducted with Mr. Naufal, PLTMG Balai Pungut-Duri produces flue gas with a temperature of around

494 ^{0}C. Reuse of exhaust heat generated from flue gas needs to be done to avoid environmental pollution resulting from flue gas. In addition, this flue gas can also be used to heat the working fluid in the generation system.

Based on research [7] that has been carried out related to the utilization of flue gas exhaust heat at power plants where flue gas with a temperature of 1300C can produce heat potential of 6034, kW. to produce additional electrical power for steam power plants (PLTU) with an additional capacity of 747.3 kW. According to Mr. Ruli as SPV HES PLTMG Balai Pungut, currently PLTMG Balai Pungut still has not utilized flue gas caused of design factors from equipment at the plant that does not support the reuse of flue gas which is currently only discharged into the environment. However, this does not rule out the possibility that flue gas from PLTMG can be reused by looking at the potential that exists now.

The utilization of flue gas can be done using various systems such as turbo-compounding, thermoelectric generators, and organic Rankine cycle [8]. What distinguishes the three systems is that the turbo compounding is solid with limited efficiency, the thermoelectric generator is solid with high cost but low efficiency, while the organic Rankine cycle system has shortcomings in the level of complexity, safety and durability factors but has the highest efficiency among the three systems [8]. Other advantages of using this organic Rankine cycle system compared to other conversion technologies are better system output, thermal efficiency and stable operation [9]. Organic Rankine Cycle is one system that can generate electricity by using a heat source with low temperatures and using organic fluids or refrigerants as its working fluid.

Several studies have discussed the use of flue gas. In research [7], the organic Rankine cycle is used in steam power plants for the utilization of flue gas exhaust heat. The purpose of this study is to determine the power generated from the right evaporator configuration in ORC installation by designing and calculating the exhaust gas pressure. The method used with the calculation of the first law of thermodynamics.

The study [10] discusses the utilization of exhaust gases from a PLTG with the GE type organic rankine cycle using cyclopentane working fluid. This study compares several types of GE gas turbines that are expected to find out which type of GE gas turbine has higher efficiency and extra electricity with the calculation method of thermodynamic laws. The study [11] aims to determine energy efficiency and exergy of heat utilization generated from chimney fluid of a single geothermal flash power plant using a two-stage organic Rankine cycle. The calculation method used is a thermodynamic mathematical model. As well as analyzing economic calculations with the Levelized Energy Cost (LEC) method. The next study [12] examined the utilization of exhaust heat using the organic Rankine cycle to increase EPG value. This study used thermodynamic analysis methods by testing six different refrigerants. The research [13] examines the use of exhaust heat waste from PLTU. This research is related to a combined system based on the organic Rankine cycle to recover heat waste with moderate to low temperatures from flue gas power plants with energy analysis and exergy and further exergy. Based on some of the research above, it discusses the use of flue gas in several types of thermal plants such as PLTU and PLTG. However, there has been no discussion regarding the use of flue gas at PLTMG. With flue gas produced from PLTMG, it is necessary to reuse the exhaust heat generated from the flue gas. Therefore, this study aims to determine the potential of electrical energy that can be generated through heat from flue gas at PLTMG Balai Pungut Duri.

This research uses the first law method of thermodynamics with the help of Engineering Equation Solver (EES) software to calculate the output power and efficiency generated from the Balai Pungut PLTMG in its existing state. Then, calculate the output power and efficiency produced by PLTMG Balai Pungut by utilizing Flue gas using the Organic Rankine Cycle and find out the efficiency and combined power of the two energy cycles.

II. METHODS

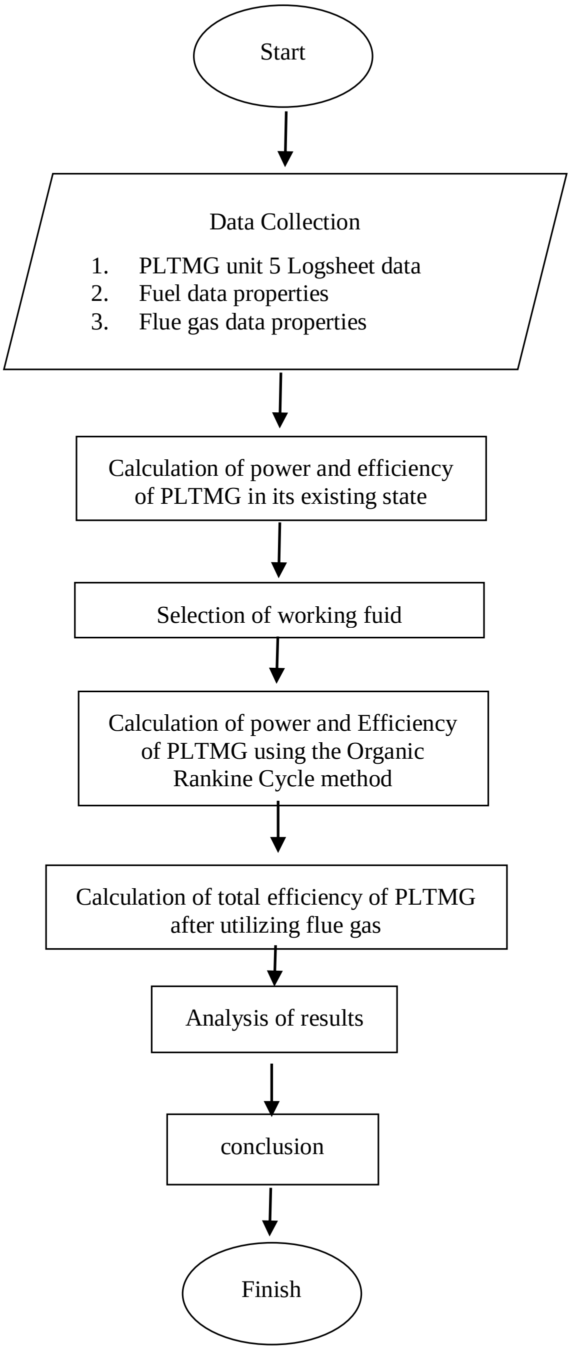

Figure 1. Research Flow Chart

This research is quantitative research with a descriptive approach supported by several sources from related journals, the collection of data related to power plants, and operations at PLTMG Balai Pungut. This study discusses the potential utilization of flue gas produced by PLTMG Balai Pungut for electrical energy. The following is the flow of implementation carried out in this study as follows.

A. Data Collection

At this data collection stage, it was carried out by direct interview method with PLTMG Balai Pungut.

Table 1. PLTMG unit 5 Logsheet data

Data	Value
Starting Temperature (T_1)	32^0C = 305 K
Air Mass Flow Rate	70 kg/s
Compression ratio	9

Table 2. Fuel data Properties

Data	Value
LHV of Fuel	49868,07 kj/kg
Temperature	$81{,}05^0$F
Pressure	682,69 PSIG
Flow Rate Mass	2726 kg/h = 0,757 kg/s

Table 3. Flue Gas data Properties PLTMG Balai Pungut

Data	Value
Temperature	494^0C

B. Calculation of PLTMG Electric Power and Efficiency using Otto Energy Cycle using EES Software

At this stage of calculation, the output produced is the value of the output power and the efficiency of the plant in its existing state. The stages of calculation that need to be done are as follows:

1. Conditions 1-2 are adiabatic processes, where during the process there is no heat entering and exiting. To determine the value of the specific volume of state 2 (Vr2) equation (1) is used. The value of Vr1 can be determined from the properties table in Table A-17 [14].

$$\frac{V_{r2}}{V_{r1}} = \frac{1}{r} \quad (1)$$

Desc:
V_{r1}= State Specific Volume 1
V_{r2}= State Specific Volume 2
r = Compression ratio

And to determine the value (T2) of the temperature of the second condition, equation (2) is used by the interpolation method which refers to the thermodynamic properties table Table A-17.

$$T_2 = T_x + \left(\frac{V_{r2}-V_{rx}}{V_{ry}-V_{rx}}\right)(T_y - T_x) \quad (2)$$

Keterangan:
T_2 = temperature state 2 (K)
T_x = upper-value temperature (K)
T_y = lower-value temperature (K)
V_{rx}= upper – value spesific volume
V_{ry}= lower – value spesific volume

2. Calculation of process 2-3, which is an isochoric process in which in this process to determine the temperature value at condition 3 (T3) equation (3) is used. The value of Cv can be determined from the property table in Table A-2 using the interpolation method

$$T_3 = T_2 + \frac{(\dot{m} \times LHV)_{fuel}}{(\dot{m} \times C_v)_{air}} \quad (3)$$

Keterangan:
T_3 = temperature state 3 (K)
$\dot{m}_{fuel}$ = mass flow rate fuel (kg/s)
LHV_{fuel} = Low heating value fuel (kJ/kg)
$\dot{m}_{air}$ = mass flow rate air (kg/s)
C_v = Spesific heat in constan volume (kJ/kg-K)

After getting the value of T3, the rate of energy entering the system (Qin) is calculated with equation (4)

$$\dot{q}_{in} = \dot{m}_{air} \times C_v \times (T_3 - T_2) \quad (4)$$

Keterangan :
$\dot{q}_{in}$ = laju energi masuk ke sistem (kW)
$\dot{m}_{air}$ = mass flow rate air (kg/s)
C_v =Spesific heat in constan volume (kJ/kg-K).

3. Calculation of processes 3-4, namely the isentropic expansion process which occurs to determine the temperature value of flue gas (T4), the equation (5) is used

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1} = \left(\frac{r}{1}\right)^{\gamma-1} \quad (5)$$

Keterangan :
γ = laplace’s constant (1,307)

4. Calculation in process 4-1, namely the isochoric process occurs and in this process can be calculated the amount of energy rate that comes out using equation (6)

$$\dot{q}_{out} = \dot{m}_{air} \times C_v \times (T_4 - T_1) \quad (6)$$

Keterangan:
$\dot{q}_{out}$ = flow rate of heat transfer out of system (kW)
$\dot{m}_{air}$ = mass flow rate of air (kg/s)
C_v = Spesific heat in constan volume (kJ/kg-K)

After obtaining the value of the outgoing energy rate, it can be determined the net work value with equation (7)

$$\dot{w}_{net} = \dot{q}_{in} - \dot{q}_{out} \quad (7)$$

Keterangan:
$\dot{w}_{net}$= the rate of energy transfer by work (kW)
$\dot{q}_{in}$ = flow rate of heat transfer in the system (kW)
$\dot{q}_{out}$= flow rate of heat transfer out of system (kW)

And to find out the efficiency produced by the plant can use equation (8)

$$\eta_{th} = \frac{\dot{w}_{net}}{\dot{q}_{in}} \quad (8)$$

Keterangan:
η_{th}= efficiency thermal
$\dot{w}_{net}$= the rate of energy transfer by work (kW)
$\dot{q}_{in}$ = flow rate of heat transfer in the system (kW)

Then to calculate the electrical power generated at the plant can use the equation (9)

$$P = \dot{w}_{net} \times \eta_{gen} \quad (9)$$

Keterangan :
P = Power (kW)
η_{gen} = efficiency of generator (%)
$\dot{w}_{net}$ = the rate of energy transfer by work (kW)

In calculating the value that will be found in this Otto energy cycle using the help of Engineering Equation Solver (EES) software. In this software will be inputted parameters that will be used to calculate efficiency and also the power generated at the plant.

The first step taken in using this software is to determine the system unit to be used, then start by inputting known parameters, writing equation algorithms, correcting errors if there are errors, then get the results of the desired calculations

C. Selection of working Fluid

Based on research [15] has examined good working fluids and suitable for use in ORC. the study compared several types of fluids such as R113, R134a, R11, R12, benzene, and ammonia the study concluded that the most suitable fluid used to utilize exhaust heat at low temperatures with isentropic characteristics.

In this study, R11 was chosen as the working fluid used in the organic Rankine cycle because of its isentropic character and this working fluid is non-toxic. Here are the properties of the working fluid R11.

Table 4. Working fluid properties of R11

Working Fluid	$T_{critical}$ (^{0}C)	P (MPa)	ṁ (Kg/s)	ekspansion
R11	197,96	1,5	34,58	isentropic

D. Calculation of PLTMG Electric Power and Efficiency using Organic Rankine Cycle using EES Software.

At this stage, calculations are carried out to obtain the value of power output and plant efficiency using the organic Rankine cycle using EES software programming.

1. In processes 1-2 this adiabatic process occurs. By using the value of mass flow rate in the working fluid, enthalpy point 1 and enthalpy point 2 to find out the working value of the pump used. To find out the working value of the pump, the following equation is used:

$$\frac{\dot{W}_{pompa}}{\dot{m}} = (h_2 - h_1) \quad (10)$$

Keterangan:
$\dot{W}_{pompa}$ = the rate of energy transfer by work on pump (kJ/kg)
$\dot{m}$ = mass flow rate of flue gas (kg/s)
h_1 = enthalpy state 1 (kJ/kg)
h_2 = enthalpy state 2 (kJ/kg)

2. Calculation of processes 2-3, that is, the evaporator with low temperature flows to the pump to the turbine inlet condition. In this process, the heat equilibrium value on the evaporator will be calculated using the following equation:

$$\frac{\dot{q}_{evaporator}}{\dot{m}} = (h_3 - h_2) \quad (11)$$

Keterangan:
$\dot{q}_{eva}$=Flow rate of heat transfer in evaporator (kW)
h_3 = enthalpy state 3 (kJ/kg)

3. Calculation in processes 3-4, superheated steam generated in the evaporator will pass through the turbine to drive the blades in the turbine to produce mechanical energy that will be channeled to the generator. In this process, the working value of the turbine will be found using the following equation:

$$\frac{\dot{W}_{turbin}}{\dot{m}} = (h_4 - h_3) \quad (12)$$

Keterangan:
$\dot{W}_{turbine}$= the rate of energy transfer by work on turbine (kJ/kg)
h_4 = enthalpy state 4 (kJ/kg)

4. Calculation in process 4-1, on the steam condenser that will be cooled in the condenser so that there is a change in pressure and there is heat wasted. So it is necessary to calculate the value of heat equilibrium on the condenser using the following equation:

$$\frac{\dot{q}_{kondensor}}{\dot{m}} = (h_1 - h_4) \quad (13)$$

Keterangan:
$\dot{q}_{con}$= flow rate of heat transfer in condensor (kW)

Then determine the output power value of this organic Rankine cycle process using the equation

$$\dot{W}_{SRO} = \dot{q}_{eva} \times \dot{q}_{kondensor} \quad (14)$$

Keterangan:
$\dot{W}_{SRO}$= the rate of energy transfer by work of ORC (kW)

Then determined the efficiency resulting from this organic Rankine cycle using the equation

$$\eta_{th} = \left(\frac{\dot{W}_{turbin} + \dot{W}_{pompa}}{\dot{q}_{evaporator}}\right) \times 100\% \quad (15)$$

Keterangan:
η_{th}= efficiency thermal (%)

After obtaining the output power of the Otto Energy cycle and the output power of the organic Rankine cycle, it can be determined the value of the combined efficiency using the equation

$$\eta = \left(\frac{\dot{W}_{net}+\dot{W}_{SRO}}{\dot{q}_{in}}\right) \quad (16)$$

Keterangan:
$\dot{W}_{net}$= the rate of energy transfer by work of Otto cycle(kW)
$\dot{W}_{SRO}$= the rate of energy transfer by work of ORC (kW)

In determining the value of output power and also the efficiency of this organic Rankine cycle, assistance from a software engineering equation solver (EES) is needed with the same steps as inputting the value of the Otto Energy cycle.

III. RESULT AND DISCUSSION

A. Organic Rankine Cycle Scheme

In the first stage, the heat from the flue gas in the exhaust gas will flow to the evaporator which will be evaporated, in this evaporator the working fluid will be heated and at this stage, there will be a change in the form of the working fluid from liquid to superheated steam.

Furthermore, further hot steam from the evaporator with high pressure and temperature will flow into the turbine to rotate the turbine so that it can produce work to produce electrical energy in the generator. In the process of rotating turbines, the pressure of the steam will drop and there will be a change in conditions from saturated steam to mixed phase

Steam from the turbine with low pressure will flow to the condenser, where there will be a process of heat release and phase change from steam to saturated liquid. in the next stage, the condensation results will be flowed to the pump and then pumped back to the evaporator along with the working fluid.

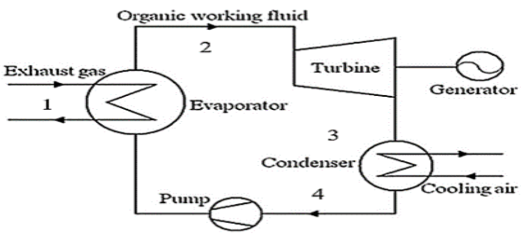

Figure 2. Organic Rankine Cycle Scheme [16]

B. The results of the calculation Otto Energy cycle and Organic Rankine cycle using EES software

The following results are obtained using the calculation of thermodynamic law 1 with the help of EES software.

Table 5. Otto Energy Cycle Calculation Result

Parameters	Result
T_1	305 K
T_2	713,34 K
T_3	1464,43 K
T_4	767 K
$\dot{q}_{in}$	37.750 kW
$\dot{q}_{out}$	23.220 kW
$\dot{w}_{net}$	14.530 kW
Efficiency Plant	38,49 %
Power	14.021 kW

Based on calculations performed at the plant of unit 5, using the first law of thermodynamics with the help of EES software. The value obtained from the networking rate produced by PLTMG Balai Pungut amounted to 14,530 kW with electrical power generated at 14,021 kW. For the efficiency produced in this calculation amounted to 38.49%, which results are close to the results of interviews and also the data that has been collected.

Then the calculation of the potential of the Organic Rankine cycle using the first law of thermodynamics with the help of EES software obtained the following results:

Table 6. Organic Rankine Cycle Calculation Result

Parameters	Result
$\dot{w}_{pump}$	41,04 kW
$\dot{q}_{in}$	23.220 kW
$\dot{w}_{turbine}$	4.597 kW
$\dot{q}_{out}$	18.664 kW
$\dot{w}_{sro}$	4.556 kW
Efficiency Plant	19,97 %

Based on Table 4 above, the work of the pump produced from the organic Rankine cycle is 41.04 kW with heat entering the evaporator of 23,220 kW and work on the turbine that can be produced of 4,597 kW and heat output from the condenser of 18,664 kW. From the results of these calculations, the network rate that can be produced at PLTMG by utilizing flue gas using this organic rankine cycle is 4,556 kW with a compound efficiency that can be produced of 19.97%.

From the combination of the Otto Energy cycle and the organic Rankine cycle, the combined efficiency produced using equation (16) of 50.56% can be calculated

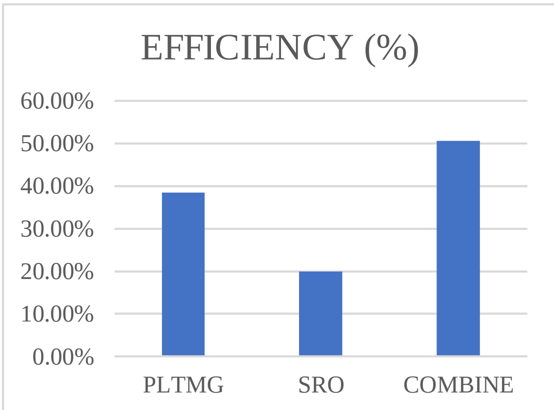

Figure 3. Efficiency comparison (%)

In the graph above, it can be analyzed that the efficiency value generated from the combination of the Otto Energy cycle in PLTMG and the organic Rankine cycle has a higher efficiency level with a value of 50.56%. In this result, there was an increase in efficiency of 12.07% from the original efficiency of PLTMG Balai Pungut-Duri.

Figure 4. Comparison of Power Generated

The power generated from the combined Otto energy cycle at the Balai Pungut PLTMG and the organic Rankine cycle showed an increase in the power value produced by 19,086 kW. There was an increase from the previous one when it had not utilized the heat generated from flue gas using ORC where the power generated was 14,530 kW. After utilizing flue gas using ORC there was an increase of 4556 kW.

The utilization of Flue Gas using ORC can increase the power and efficiency of PLTMG. Flue Gas that comes out of gas turbines has a high temperature. In the ORC system, the wasted heat can be used to heat the organic work fluid in the ORC. Utilizing this wasted heat, previously wasted energy can be converted into additional power, thereby increasing the total power output of the PLTMG.

The organic working fluid in ORC has a lower boiling point than water in the conventional Rankine cycle, which allows the utilization of wasted heat at low temperatures to produce steam in the ORC. At lower temperatures, the energy conversion efficiency can be higher, because the temperature difference between the heat source and the coolant is greater.

Utilization of Flue Gas through ORC can also help reduce exhaust gas emissions from PLTMG. Harnessing exhaust heat to generate additional power, and can reduce emissions of greenhouse gases and other pollutants resulting from burning fossil fuels.

IV. CONCLUSION

In this study, the flue gas produced from PLTMG Balai Pungut-Duri has enough heat to be utilized in electrical energy using the organic Rankine cycle method. The working fluid used in the use of this organic rankine cycle is R11, with a gas flue temperature of 494 0C capable of producing electrical power of 19,086 kW with an increase in efficiency of 12.06% from the original efficiency value of PLTMG Balai Pungut by 38.49% to 50.56%. The power generated from the utilization of heat from the flue gas of the Balai Pungut PLTMG certainly also increased by 4556 kW. This is because the utilization of heat from flue gas is one way to reduce fuel consumption at the Balai Pungut PLTMG after all the heat will be flowed to the evaporator to increase the heat.

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