Exergy analysis of renewable energy power plant with organic rankine cycle for regions outside Java Island

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Abstract. Considering the increase in national electricity demand by an average of 6% per year, especially for areas outside of Java that are far from the electricity grid, to meet the electricity needs generally use expensive Diesel Power Plants or small-scale steam power plants with low efficiency. On the other hand, outside of Java has the potential of abundant biomass and waste, which includes biomass from forest waste, plantations of more than 100,000,000 tons used as electrical energy will obtain greater than 1,000Mwe. The potential of this electrical energy will be able to support national energy supply especially in outside Java regions, while at present the performance of conventional steam power plant-small capacity below 5 Mw which has been installed. At this time the efficiency is still low at around 20%. So, we need an electric biomass fuel technology power plant that has better performance. In this analysis, it is proposed that an alternative solution is to use an Organic Rankine cycle-ORC power plant that uses organic working fluids that have lower evaporation temperatures than water. By using this ORC plant that uses n-Pentane as its organic working fluid, it is estimated that the efficiency can be greater than 25%, and environmentally more friendly.

1. Introduction
The performance of small-scale Biomass power plants using conventional steam power plant which is commonly used at this time, the performance is still around 20%. This is because to convert into electricity, especially utilizing high Enthalpy sources because it uses water working media, where the point of evaporation occurs at temperatures that are high. Besides that, a lot of heat is wasted out of the cycle, including in the form of steam that comes out of the turbine which is discharged into the condenser and then discharged into the environment or into the sea/river through the cooling water body [1].

On the other hand, an Organic Rankine cycle power plant using an organic fluid which has a much lower evaporation temperature than water. It can work by utilizing a lower enthalpy heat source or producing the same amount of megawatt capacity. Organic Rankine cycle generators require less heat energy. In this study, the performance improvement of the Organic Rankine cycle will be analyzed and compared to the small-scale conventional steam power cycle with exergy analysis as well as the Organic system will use n-Pentane organic working fluid. In this analysis, several simulations of exergy calculations are made in order to get the optimum cycle configuration using TU Delft software, Cycle tempo. 5.0.

2. Literature review and hypothesis development
2.1. Exergy and Energy
Energy is defined as movement or the ability to produce motion and always conserves in the process and follows the first law of thermodynamics. While exergy is defined as work or the ability to produce movement and is always immutable in a reversible process and obeys the second law of thermodynamics. Energy is measured as quantity while exergy is measured as quantity and quality. Every energy transfer, there is also a transfer of exergy [2, 3].

Exergy Analysis - Exergy balance.

One of the main uses of this concept is for exergy balance in the analysis of thermal systems. Exergy analysis is a tool for identifying the type, location, magnitude of thermal losses. Identifying and quantifying these losses which allows for evaluation and refinement of the thermodynamic system design. Mathematical equations of the Exergy equilibrium General Exergy Equation For a flow, the total flow exergy: $E_{total}$ (kJ), can be expressed as:

$$E_{total} = E_{KE} + E_{PE} + E_{PH} + E_{O}$$  \(1\)

Where,

- $E_{KE}$ = Kinetic exergy;
- $E_{PE}$ = Potential Exergy;
- $E_{PH}$ = Exergy physics;
- $E_{O}$ = Chemical exergy.

Both $E_{KE}$ and $E_{PE}$ are high energy and fully convertible into work, whereas $E_{PH}$ dan $E_{O}$ are low-level energy are related to physical and chemical processes that interact with the environment. For this study focused only on physical exergy and no chemical reactions were considered, further states if needed:

$$E_{total} = E_{PH} = m_i \left( h_i - h_o \right) - T_o \left( s_i - s_o \right)$$  \(2\)

Where :

- $i$ = State point reference;
- $0$ = Reference environmental conditions .
- $m$ = Mass flow rate (kg/s);
- $h$ = Entalpy (kJ/kg);
- $s$ = Entropy (kJ/kgK);
- $T$ = Temperature (K).

Exergy balance volume control

For volume control, an exergy equilibrium can be expressed as :

$$E_{input} = E_{destroyed} + E_{waste} + E_{destroyed}$$  \(3\)

Where:

- $E_{input}$ = The total exergy goes to the control volume;
- $E_{desired}$ = Total output exergy (net work output);
- $E_{waste}$ = amount of energy from systems other than above;
- $E_{destroyed}$ = The amount of exergy damaged or lost due to the process irreversible;

$E_{destroyed}$ is directly related to entropy with the equation:

$$E_{destroyed} = T_o s$$  \(4\)

2.2 Performance criteria

The performance criteria of exergy system depend on the rate of transfer of exergy in and out of the control volume, Kotas (1995)

2.3. Description of Organic Rankine cycle plant that will study in this analysis:
In this analysis, a typical Organic Rankine cycle with a capacity of less than 5 MW will be used, given the largest capacity currently produced organic turbines in the market. This Organic Rankine cycle plant, its electricity production can be fed into the national interconnection network. Figure 1 Schematic Biomass power plant with Organic Rankine cycle.

![Figure 1. Schematic of the Organic Rankine cycle power plant](image)

**Exergy analysis of ORCBP - Organic Rankine cycle Biomass power plant**

As shown in Figure 2 is a simplification of the Organic Rankine cycle flow diagram, where the heat of BCBPP is from 2 sources so that in this analysis the primary Exergy input is the total exergy from 2 sources, namely as follows:
1. Hot fluid supplied to evaporator 2 to vaporize pentane from hot source (Boiler)
2. Stage 2. The remaining warm liquid from the evaporator is distributing to the preheater for preheating of the fluid

Overall exergy output is the production of net electrical energy. Referring to the definition of exergy, the exergy from ORC-BPP is the maximum possible amount of work that can be extracted from the hot fluid that comes out of the boiler regarding the average environmental conditions at the plant location.

**Overall Exergy Flow Analysis**

Process description:

Figure 2 shows the flow chart for the exergy flow of ORC-BPP. The exergy flow process will simplify that consists of a hot fluid source from the boiler, warm fluid that comes out of the pentane evaporator to the pentane preheater as the Pantene preheater. Pentane turbine, pentane steam condensation system and cooling water system. Several exergies received from boiler, the heat source will distribute to the evaporator, many exergies in the form of output power or that comes out of ORC-BPP or out to the environmental system, which can supply electrical energy to the national transmission network [4].
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Figure 2. Flow diagram of the Organic Rankine Cycle-Biomass Power Plant (ORC-BBP)

**Exergy equilibrium equation:**

Exergy into the BCBPP system (Organic Cycle-Biomass Power Plant) consists of exergy from incoming fluid exergy (E7, E14), Exergy out of the system is SBBP overall output power is net electrical energy (Wnett) and exergy coming out of the pentane condenser (E5). Several damaged or lost exergy due to irreversible processes, regarding Figure 2, can be expressed by the following equation:

\[ \sum E_7 + \sum E_{14} = \sum E_{12} + \sum E_5 + \sum I_{\text{processes}} \]  

(5)

**Evaporator and Preheater - Pentane evaporation process**

**Description:**

The flow process in the steam generation process is presented in Fig.3. The warm pentane liquid leaves the preheater, then is fed into the pentane evaporator by hot water heated in the boiler using the results of biomass combustion. The pentane liquid will evaporate, then the pentane turbine is channelled.

Figure 3. Balance in the ORC-Biomass Power Plant (ORC-BP) Evaporator

**Exergy equilibrium equation:**

Exergy into the process is the amount of exergy from the pentane liquid and exergy from the hot fluid and exergy out of the pentane evaporator drain. Exergy out of the process is the amount of
exergy from pentane gas and exergy of warm fluid that leaves the evaporator [5]. Several exergy is
damaged or lost due to irreversible processes, in the form of the equation:
\[ \sum E_7 + \sum E_{10} = \sum E_1 + \sum E_{11} + \sum I_{\text{processes}} \] (6)

where:
- \( E_7 \) = Exergy from incoming hot fluid
- \( E_{10} \) = Exergy from pentane liquid enters the evaporator
- \( E_1 \) = Exergy from pentane gas leaving the evaporator
- \( E_{11} \) = Exergy warm fluid out of the evaporator
- \( I_{\text{process}} \) = Exergy damaged or lost due to irreversible processes,

Proses steady-state: \[ \sum E_7 + \sum E_{10} = \sum E_1 + \sum E_{11} \]

**Steam expansion in a pentane turbine**

Process description:
The flow process of pentane vapor expansion and energy conversion is presented in Figure 4. Pentane vapor from the evaporator – Boiler after passing through the steam separator, the main stop valve is inserted into the pentane turbine. The pentane vapor enters the turbine (1) with a predetermined input condition characteristic. The entry to the turbine is controlled first by the main stop valve, valve governor and enters through the pentane gas chest which balances the thrust power on the level 1 blades.

![Figure 4. Flow diagram of the Pentane Turbine expansion process](image)

Pentane vapour is directed to blade row 1 by the nozzle and expansion in the blade row 1, then expansion pentane vapour in the blades of the next level and after that the pentane vapour is released into the condenser which is kept at a low pressure of about 1 bar, for further enter the condensation process. This process is presented in the actual 1-2 process image in the P-S diagram of Figure 5.
As the pentane vapour expands as it passes through the row of blades, a significant portion of the energy is converted into mechanical energy in the form of a turbine rotor rotation. Most of the energy is converted by the stage 1 blades and pentane vapour exits from these blades at a lower pressure. The turbine and generator are coupled together and rotate together with 3000 rpm rotation. The generator rotor carries a magnetic field, with the rotation, mechanical energy is converted into electrical energy ($W_{\text{gross}}$). The amount of gross electrical energy generated depends on the efficiency of the turbine and generator.

Exergy equilibrium equation [6]

The exergy input is from pentane steam entering the turbine (1), the exergy that comes out consists of the work produced ($W_{\text{gross}}$) and the exergy from the Pentane vapour that leaves the turbine. Some exergy are damaged or lost due to irreversible processes,

Regarding Figure 3, it can be expressed by the following equation:

$$\sum E_1 = \sum E_{W_{\text{gross}}} + \sum E_2 + \sum I_{\text{Process}}$$

where;

- $E_{37}$ = Exergy rate from pentane vapor to the turbine;
- $E_{W_{\text{gross}}}$ = Exergy rate of generator-gross electrical energy
- $E_2$ = Pentane vapor exergy rate exits the turbine;
- $I_{\text{Process}}$ = Exergy damage in the exergy conversion process

In exergy terminology:

- $E_1 = m_1 [(h_1 - h_o) - T_o(s_1 - s_o)]$
- $E_2 = m_2 [(h_2 - h_o) - T_o(s_2 - s_o)]$
- $m_1 = m_2$
- $W_{\text{gross}} = MW_e$

where,

- $m_1$ = Mass flow rate from pentane vapor to turbine;
- $h_1, s_1$ = Enthalpy and Entropy of pentane vapor to the turbine
- $T_o$ = Reference ambient temperature (° K);
- $h_o, s_o$ = Enthalpy and entropy of pentane vapor under environmental conditions

**Performance - Criteria** -

The purpose of this process is to convert as much as possible the energy from the pentane vapour entering the turbine to electrical power. The measure of performance criteria is the ratio of the gross power output (electrical energy produced) to the energy from the pentane steam used to generate power. Regarding Figure 2, the exergy efficiency Of turbine-generator, can be expressed as;
Assumptions:
- Adiabatic process (no heat loss): $Q = 0$.
- No pentane vapor leakage.

Pentane Vapor Condensation Process

The flow process in pentane condensation illustrated in Figure 6, where the pentane vapour leaves the turbine and enters the condenser where the steam cooled by cooling water taken from the environment. From the results of this cooling, the pentane vapour will condense into pentane liquid which will accommodate in the pentane tank located at the bottom of the condenser. This pentane liquid is then pumped by the pentane pump to be reheated in the preheater and evaporated back into the pentane evaporator, so this becomes a closed cycle.

Figure 6. Fluid flow diagram in a pentane condenser,

Exergy equilibrium equation:

Exergy into the process is the amount of exergy from cooling water entering (14) and exergy from incoming pentane gas from pentane turbine(2). Exergy leaving the process is the amount of exergy of pentane liquid (6) and cooling water exergy that comes out of the condenser (6). Several exergy are damaged or lost due to irreversible processes, in the form of an equation:

$$\sum E_2 + \sum E_{14} = \sum E_5 + \sum E_6 + \sum I_{process}$$

Where:
- $E_2$ = Exergy from incoming pentane gas;
- $E_{14}$ = Exergy from cooling water enters the condenser;
- $E_5$ = Exergy from the pentane liquid exits the condenser;
- $E_{32}$ = Exergy cooling water coming out of the condenser
- $I_{process}$ = Exergy that is damaged or lost due to irreversible processes,

Steady-state process:
$$\sum E_2 + \sum E_{14} = \sum E_5 + \sum E_6$$

Performance criteria:

The expected function of this process is to condense pentane vapour by maximizing cooling water exergy. The performance criterion is the ratio of the exergy from cold water to the exergy lost by pentane gas output (effectiveness of the heat transfer unit) Stated as;

$$\eta_{condenser} = \frac{m_{14}(\varepsilon_2 - \varepsilon_6)}{m_2(\varepsilon_5 - \varepsilon_{14})}$$

Assumptions:
- Steady state process (constant mass flow):.
- Adiabatic process (no heat loss): $Q = 0$. 
3. Results and Discussion

The exergy analysis simulation is developed and analyzed with the calculation of calculations performed with the TU Delf Tempo cycle software. Summary of the results of the Energy & Exergy analysis of the ORC Plant is presented in Figure 7 and Table 1.

![Figure 7 Heat balance diagram of the OrganicRankine cycle -Biomass Power Plant (ORC-BP)](image)

The simulation results show that the total exergy that comes out of the boiler/heat source is 5.302 MW, the total exergy received by the pentane turbine is 2.552MW, the decrease in the turbine is 128 kW against gross work, the work produced by the turbine is 2.424 MW. The overall exergy of BCBPP was 44.6%. While as a comparison the overall energy efficiency is 45.7% and the overall exergy efficiency is 44.6% also as a comparative study. The simulation results show that compared to conventional steam power plant has better exergy performance, including higher output power, increased generating efficiency, and exergy efficiency, and generator went up [7-9].

| Remarks       | No | Apparatus | Type | Energy (Kw) | Totals (Kw) | Energy (Kw) | Totals (Kw) |
|---------------|----|-----------|------|-------------|-------------|-------------|-------------|
| Absorbed      | 9  | Boiler    | 1    | 5302.50     | 5434        |             |             |
| Power         |    |           |      |             |             |             |             |
| Delivered     | 1  | Generator | G    | 2424.47     | 2424.47     |             |             |
| Gross Power   |    |           |      |             |             |             |             |
| Aux Power     | 7  | Pump      | 8    | 185.35      | 185.35      |             |             |
| Consumption   | 2  | Pump      | 8    | 373.41      | 373.41      |             |             |
|               | 19 | Pump      | 8    | 42.93       | 42.93       |             |             |
| Delivered     |    |           |      |             |             |             |             |
| Net Power     |    |           |      |             |             |             | 1822.77     |
| Efficiencies  |    | Gross     |      | 45.7%       | 44.6%       |             |             |
4. Discussion of simulation results

Based on the main objective of this exergy analysis for ORC -BP has proved that this plant will increase the power plant performance compared to the small-scale conventional Steam Power Plant (SPP), including improving plant efficiency more than 10% and will be environmentally more friendly.

5. Conclusion

Analysis of performance improvement of the Organic Rankine cycle have been done. It was compared to the small-scale conventional steam power cycle with exergy analysis as well as the Organic system will use n-Pentane organic working fluid. In this analysis, several simulations of exergy calculations were made to get the optimum cycle configuration using TU Delft software, Cycle tempo. 5.0. The simulation results show that compared to conventional steam power plant has better exergy performance, including higher output power, increased generating efficiency, and exergy efficiency, and generator went up. It was also proved that the plant was able to increase the power plant performance compared to the small-scale conventional Steam Power Plant (SPP) by maintaining the environmental friendly process.

NOMENCLATURE

| General | Greek symbols | Abbreviation |
|---------|---------------|--------------|
| E = Exergy (kJ) | $\eta = \text{Efficiency (\%)}$ | CD = Condensate |
| $g =$ Gravitational force (m/s$^2$) | $\varepsilon = \text{Speciﬁc exergi (kJ/kg)}$ | CWP = Circulating water |
| $h =$ Speciﬁc enthalpy (kJ/kg) | | COP = Coefﬁcient of performance |
| $I =$ Irreversibility | | BFP = Boiler feed pump |
| $m =$ Mass ﬂow (kg/s) | $a = \text{Air}$ | |
| $s =$ Speciﬁc entropy (kJ/kg-K) | $s = \text{Vapors}$ | |
| $T =$ Temperature ($^\circ$C) | $t = \text{Total}$ | |
| $X =$ Quality | $w = \text{Water}$ | |
| $W =$ Power (W) | | |

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