



Harnessing Oil Refinery Exhaust Heat via Organic Rankine Cycle for Green Hydrogen Production Toward Net-Zero Emission

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Abstract

The increasing CO₂ emissions and the complexity of human activities have driven the Indonesian government to enact Law Number 16 of 2016 to achieve greenhouse gas emission reduction targets by 2030. Oil refineries, which previously only disposed of waste heat without being utilized, have now become potential sources of sustainable energy. Through the development of Organic Rankine Cycle (ORC) technology, this waste heat can be converted into electricity. This research focuses on four types of working fluids, namely Propane, Isopentane, Isobutane, and R245fa. The results showed that the electricity generated from each ORC system was 18.34 MWh (Propane), 52.77 MWh (Isopentane), 32.17 MWh (Isobutane), and 21.23 MWh (R245fa), respectively. This electricity can be used to produce green hydrogen through electrolysis methods, resulting in 366.83 kg (Propane), 1055.42 kg (Isopentane), 643.33 kg (Isobutane), and 424.67 kg (R245fa) of green hydrogen. Compared to hydrogen production through fuel technology, ORC implementation can reduce CO₂ emissions by 12.64 t.CO₂ (Propane), 36.36 t.CO₂ (Isopentane), 22.16 t.CO₂ (Isobutane), and 14.63 t.CO₂ (R245fa). All calculations were based on 24-hour operation. Isopentane produces the highest power among the four other organic working fluids and generates the largest profit from green hydrogen production through electrolysis processes, amounting to Rp. 55,069,944.78 per day. The innovation of applying ORC systems in oil refineries is an effective step in reducing carbon emissions to support sustainable energy production.

Keywords:

Organic Rankine Cycle (ORC); Working Fluid; Hydrogen; CO₂ Emissions; Electrolysis.

1 Introduction

CO₂ emissions continue to increase with the complexity of human activities, including the transportation, household, and industrial sectors. The Indonesian government passed Law No. 16 of 2016 to support the Paris agreement to achieve greenhouse gas emission reductions by 2030 [23]. Reduced CO₂ emissions, exhaust gas and energy savings can result from an effective system. One approach that can be taken is to focus on energy sources that are non-conventional or renewable resources, such as solar thermal energy, wind, water (either through hydroelectricity, ocean heat, tides, or ocean waves), biomass, waste heat and so on.

Exhaust heat is an alternative energy source of heat generated through the process of fuel combustion or chemical reactions, then released into the environment without being utilized, although it still has the potential to be used [24]. Utilizing exhaust heat not only has benefits in reducing pollution but also reduces the energy

consumption required for auxiliary equipment such as fans, pumps, and others. In Indonesia, most power plants use steam power [25], and the exhaust heat generated by steam power plants has the potential to be reused. The average flue gas temperature of 150°C in steam power plants can be utilized [26]. However, exhaust heat does not only come from steam power plants, but also from processing units of the oil and gas industry. Exhaust heat from these industries can also be utilized through Organic Rankine Cycle (ORC) technology.

ORC technology is currently undergoing significant development. As a result, waste heat that was previously just thrown away without being utilized, is now an opportunity to generate electricity through ORC. The working principle of ORC is similar to Rankine Cycle: The difference lies in the type of fluid used. ORC has the ability to use heat sources with temperatures around 80°C, as the organic fluid used has a low boiling point. The ORC cycle has the advantage of operating at lower temperatures. The ORC system can also be utilized to produce green hydrogen, which is an environmentally friendly alternative fuel. Utilization of this waste heat can generate additional electrical energy, which can improve efficiency and reduce the waste of heat released to the environment, as well as reduce fuel consumption [29].

Hydrogen is the third most abundant element on the Earth's surface, generally not found in its pure form because it reacts easily with other elements. Hydrogen production is generally done artificially by breaking down hydrogen-containing compounds. The current leading commercial production methods are fossil fuel and water-based [28]. Electrical energy generated from the design of ORC systems in oil refineries acts as a major component in the production of green hydrogen, along with the need for water. Green hydrogen is considered as a potential green energy for the future.

The benefits of waste heat in waste heat recovery can be classified into two categories: 1. Direct Benefits: The direct effect of utilizing waste heat is that it can improve the efficiency of the combustion process. This is reflected in reduced fuel consumption. 2. Indirect Benefits: The combustion of exhaust gases from Internal Combustion Engines largely produces various emissions and greenhouse gases such as: unburned hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), smoke opacity, carbon dioxide (CO₂), particulate matter (PM) [5]

Research into the utilization of flue gas heat in industries with SRO applications has been carried out in the last decade. Whether it is research in comparison in the selection of suitable working fluids or components, or in economic and energy analysis. [16]

In the preparation of this research, problems were formulated based on existing problems in the field, including:

- 1) How can the application of the ORC system in oil refineries be optimized for green hydrogen production as part of efforts to support the net-zero emission target?
- 2) How much power, hydrogen production, profit, and emission reduction from each fluid?
- 3) How can this research contribute to emission reduction to achieve Net Zero Emission?

In writing this research, it aims to:

- 1) Evaluate the impact of ORC technology on green hydrogen production in oil refineries towards achieving net-zero emission targets in the oil and gas industry.
- 2) Identify the environment impact of ORC technology on green hydrogen production in oil refineries towards achieving net-zero emission targets in the oil and gas industry.
- 3) Provide practical recommendations for the oil and gas industry in selecting and implementing ORC systems for green hydrogen production, supporting sustainability and achieving net-zero emission targets.

From the research carried out, there are benefits obtained, including:

- 1) Identify opportunities in the implementation of ORC technology to produce green hydrogen in oil refineries.

- 2) Providing valuable guidance in considering the effect of working fluid type on system efficiency, green hydrogen production, economic benefits, and emission reduction.
- 3) Introducing the concept of green hydrogen production as a strategic step in supporting efforts towards net zero emissions.

2 Research methods/ materials and methods

2.1 Working Fluid Criteria

The selection of working fluid is a crucial factor in ORC systems, the working fluid has a significant impact on the overall cycle performance [12]. In addition, the working fluid also affects turbine design, system safety, the type of materials used for system components, operational conditions, environmental impact, as well as the economic evaluation of the system as a whole.

Table 1. Characteristic of the working fluid used in the Research.[1]

| Working Fluida | Pc (Bar) | Tc (°C) | Density (kg/m ³) | Toxicity | Flammability | ODP | GWP | Safety Group |
|----------------|----------|---------|------------------------------|-----------|--------------|-----|-----|--------------|
| Isopentane | 33,3 | 187,8 | 616 | Low | Very high | 0 | 3 | A3 |
| N-Pentane | 33,64 | 196,5 | 620,8 | Low | Very high | 0 | 3 | A3 |
| R245fa | 36,51 | 154,2 | 134,05 | Very high | Low | 0 | 3 | B1 |
| Isobutane | 36,29 | 134,66 | 225,5 | Low | Very high | 0 | 3 | A3 |
| N-butane | 37,96 | 151,98 | 227,94 | Low | Very high | 0 | 3 | A3 |

*ODP adalah Ozone Depletion Potensial

*GWP adalah Global Warming Potential

1. Global Warming Potential (GWP) ≤ 1430 , as is the case for R134a.
2. Ozone Depletion Potential (ODP) ≤ 0.01 .
3. Health, where the health risk value in accordance with the National Fire Protection Association (NFPA) must be at least equal to the moderate hazard level.
4. Instability, which also uses the NFPA scale, with the instability value having to be at least equivalent to a low hazard level.

The determination of organic working fluids suitable for application in the ORC scheme is based on five main criteria, namely thermophysical properties, environmental aspects, safety aspects, operational performance, and availability in Indonesia. Each criterion is evaluated based on the parameters shown in Table 2.

Table 2. ORC Working Fluid Criteria

| Criteria | Parameter |
|----------------------------|---|
| Thermophysical Properties | Density, Heat of Vaporization, Heat Capacity, Viscosity, Heat Conductivity, Melting Point, Critical Temperature, and Critical Pressure. |
| Environmental Aspects | Ozone Depletion Potential (ODP), Global Warming Potential (GWP), Atmosfer Life Time. |
| Safety Aspects | Toxicity, Flammability. |
| Performance (Operation) | Efficiency, Maximum Working Pressure, Minimum Pressure, Mass Flow Rate, Pinch Point, Capacity. |
| Availability in the Market | Types of Refrigerant in the Indonesian Market |

(Bachtiar, C., & Ambarita, H. 2010).

2.2 Energy analysis

The first law of thermodynamics states that energy can neither be created nor destroyed but can only change from one form to another. Based on this concept, the efficiency of a system is defined as the ratio of the output work produced to the input energy provided. An increase in exhaust temperature enhances both the thermal efficiency and energy efficiency of the cycle while reducing total energy losses [6]. Modifying the ORC configuration is an effective approach to improving energy conversion efficiency, as demonstrated by [11], who showed that incorporating regeneration in ORC results in higher efficiency compared to the standard ORC.

In the preliminary stage of this research, thermodynamic analysis was performed using a modeling approach, considering five different working fluids: Isopentane, N-pentane, R245fa, Isobutane, and N-butane. The characteristics of the working fluid are listed in Table 1. The properties of the working fluid have a significant influence on the thermal efficiency of the ORC system [6]. Based on the saturated vapor curve in the temperature-entropy diagram, the working fluid in ORC can be grouped into three categories: dry fluid, isentropic fluid, and wet fluid.

One factor that affects the relationship between the working fluid and the thermodynamic performance of the ORC cycle is the critical temperature (Tc). This critical temperature plays a role in determining the thermal stability during the heat transfer process inside the evaporator.

Given the many options of working fluid types, several criteria have been proposed to guide the selection of working fluid types. These criteria include:

2.3 Thermal energy efficiency

In designing this cycle, factors such as heat source, environmental impact, and thermodynamic properties were taken into account. The design of this ORC involves the use of four types of organic working fluids that have different properties. To analyze the feeding system, calculations for each component were used eqs.(1) - (8):

1. Pump power

$$W_{pump} = m(h_4 - h_3)\eta_{pump} \quad (1)$$

Where: W_{pump} = Pump power (kW), m = Mass flow rate working fluid (kg/s), h_4 = Enthalpy at condition 4 (kJ/kg), h_3 = Enthalpy at condition 3 (kJ/kg), η_{pump} = Pump efficiency [22].

2. Pre-heater heat

$$Q_{pre\ heater} = \frac{m(h_5 - h_4)}{\eta_{pre\ heater}} \quad (2)$$

Where: $Q_{pre\ heater}$ = Pre heater heat (kW), m = Mass flow rate working fluid (kg/s), h_4 = Enthalpy at condition 4 (kJ/kg), h_5 = Enthalpy at condition 5 (kJ/kg), $\eta_{pre\ heater}$ = Pre heater efficiency [22].

3. Evaporator heat

$$Q_{evaporator} = \frac{m(h_1 - h_5)}{\eta_{evaporator}} \quad (3)$$

Where: $Q_{evaporator}$ = Evaporator heat (kW), m = Mass flow rate working fluid (kg/s), h_1 = Enthalpy at condition 1 (kJ/kg), h_5 = Enthalpy at condition 5 (kJ/kg), $\eta_{evaporator}$ = Evaporator efficiency [22].

4. Turbin power

$$W_{turbine} = m(h_1 - h_2)\eta_{turbine} \quad (4)$$

Where: $W_{turbine}$ = Turbine power (kW), m = Mass flow rate working fluid (kg/s), h_1 = Enthalpy at condition 1 (kJ/kg), h_2 = Enthalpy at condition 2 (kJ/kg), $\eta_{turbine}$ = Turbine efficiency [22].

5. Generator power

$$W_{generator} = W_{turbine} \times \eta_{generator} \quad (5)$$

Where: $W_{generator}$ = Generator power (kW), $W_{turbine}$ = Turbine power (kW), $\eta_{generator}$ = Generator efficiency [22].

6. Condenser heat

$$Q_{condensor} = m(h_4 - h_3) \quad (6)$$

Where: $Q_{condensor}$ = Condenser heat (kW), m = Mass flow rate working fluid (kg/s), h_2 = Enthalpy at condition 2 (kJ/kg), h_3 = Enthalpy at condition 3 (kJ/kg), $\eta_{evaporator}$ = Evaporator efficiency [22].

7. Air cooled fan power

$$W_f = \frac{m_{air}(h_{aout} - h_{ain})}{\eta_{fan}} \quad (7)$$

Where: W_f = Air cooled fan power (kW), m_{air} = Mass flow rate air (kg/s), h_{aout} = enthalpy of air out, h_{ain} = enthalpy of air in, η_{fan} = Fan efficiency [22].

8. Efficiency thermal

$$\eta_{thermal} = \frac{W_{generator} - W_{pump} - W_{fan}}{Q_{evaporator} + Q_{pre\ heater}} \quad (8)$$

Where: $\eta_{thermal}$ = efficiency thermal, $W_{generator}$ = Generator power (kW), W_{pump} = Pump power (kW), W_{fan} = Air cooled fan power (kW), $Q_{evaporator}$ = Evaporator heat (kW), $Q_{pre\ heater}$ = Pre heater heat (kW) [22].

2.4 CO₂ emissions in hydrogen production

This study analyzes the utilization of waste heat from oil refineries using the Organic Rankine Cycle (ORC) for hydrogen production through electrolysis. The data used include the waste heat source, ORC system efficiency, and CO₂ emission factors of various electricity generation technologies Table 3. In this study, we specifically compared CO₂ emissions from hydrogen production using an ORC with hydrogen production using fuel-based power generation, which has an emission factor of 0.689 tCO₂/MWh. This comparison aims to evaluate the potential of ORC in reducing CO₂ emissions and supporting Net Zero Emissions in the oil and gas industry.

Table 3. CO₂ Emissions from Power Generation Technologies [16]

| Technology | Emission CO ₂ Factors | |
|---------------------------------------|---|--|
| | Central Terminals (tCO ₂ /MWh) | Point of Consumption (tCO ₂ /MWh) |
| Coal and hard coal | 0,993 | 1,098 |
| Brown coal | 0,896 | 0,991 |
| Black coal | 0,965 | 1,067 |
| Imported coal | 0,905 | 1,001 |
| Nuclear | 0 | 0 |
| Hydroelectric, wind, photovoltaic | 0 | 0 |
| Biomass | 0 | 0 |
| Combined cycle | 0,353 | 0,390 |
| Natural Gas | 0,504 | 0,557 |
| Otto engine cogeneration (60% REE) | 0,336 | 0,356 |
| Gas turbine cogeneration (62% REE) | 0,325 | 0,344 |
| Combined cycle cogeneration (67% REE) | 0,301 | 0,318 |
| Fuel | 0,689 | 0,762 |
| Marine auxiliary power system | 0,626 | 0,699 |

2.5 Research location

The location of our research is at the Oil and Gas Human Resources Development Center (PPSDM Migas) Cepu. 2.6 Research Methods. This research process starts with data collection which is directly carried out at PPSDM Migas Cepu. Furthermore, the system is designed according to the desired parameters. REFPROP software is used to obtain the thermodynamic properties of the organic working fluid to be used. In this process, several kinds of organic fluids are selected to compare the highest efficiency value. The flowchart of this process can be seen in Fig. 1.

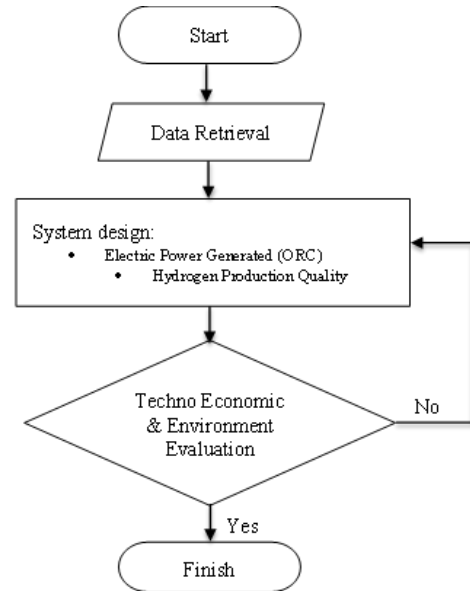


Fig. 1. Flowchart of organic rankine cycle (ORC) system

To illustrate the initial sketch of waste heat extraction from the boiler, a visual representation is provided, as shown in Fig. 2. This figure depicts the flow of waste heat extracted after exiting the boiler for further utilization.

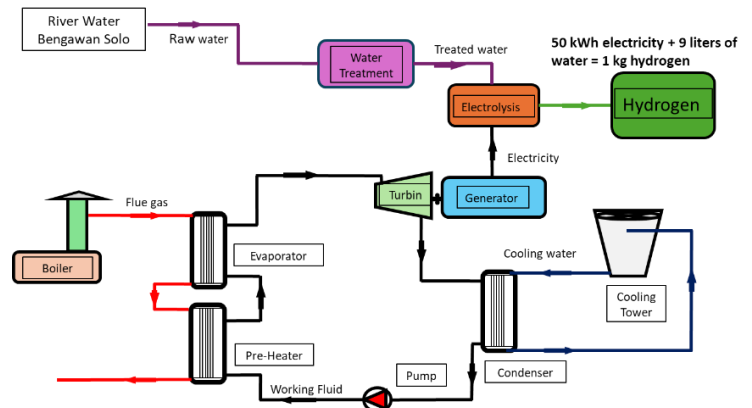


Fig. 2. Proses Flow Diagram (PFD) design

Fig. 2. The Process Flow Diagram (PFD) design illustrates the process flow of the ORC system developed in this study. The system's performance was evaluated sequentially using the equations provided in Section 2.3. The pump power was first calculated from the enthalpy difference between points 4 and 3 using Eq. (1). The heat absorbed by the preheater and evaporator was then determined using Eqs. (2) and (3), respectively. Turbine power was obtained from the enthalpy difference between points 1 and 2 in Eq. (4) and subsequently converted into generator output power through Eq. (5). The condenser heat duty was calculated using Eq. (6), while the cooling tower fan power consumption was evaluated using Eq. (7) based on the air mass flow rate and the change in air enthalpy. Finally, the net thermal efficiency was determined using Eq. (8), considering the net electrical output and the total heat input from both the evaporator and the preheater.

2.6 Research data

From the research conducted at PPSDM Migas Cepu, data was obtained to calculate the ORC system. As follows

Table 4. ORC Design Field Data at PPSDM Migas Cepu

| Indicator | Data Field | Unit |
|-----------------------|------------|-----------------------|
| Temperature | 303,7 | °C |
| Pressure | 0,2 | kg/cm ² |
| Flue gas flow rate | 152,6 | m ³ /menit |
| Flue gas mass | 1.558 | Kg/s |
| Mass of Organic Fluid | 45 | Kg/s |

3 Results and discussion.

At present, Organic Rankine Cycle (ORC) technology is experiencing a very significant development. As a result, waste heat that was previously only disposed of without being utilized, is now an opportunity to generate electricity through ORC. The design process begins with data collection at PPSDM Migas Cepu and setting design parameters based on data obtained from literature sources and field research. Next, the system is designed in accordance with the desired parameters. The use of REFPROP software is carried out to obtain the thermodynamic properties of organic working fluids. At this stage, only four types of organic fluids are used, namely Isopentane, Isobutane, Propane and R245fa. The system design will be explained sequentially. The overall system has the following scheme.

The combustion gases are utilized to heat the air through the process in the air preheater component. After this stage, the heat from the flue gas is no longer utilized, and the flue gas is vented to the environment through the stack. Although at this point the flue gas has lost most of its heat, the flue gas temperature of 120°C-150°C still has potential heat that can be utilized. One way to utilize it is through an Organic Rankine Cycle (ORC). ORC is used to take advantage of the heat at low temperatures to vaporize organic working fluids with low boiling points. In the utilization of organic working fluids, several organics must be considered, including heat source, environmental impact, and thermodynamic properties. In this ORC design, there are 4 types of organic fluids that have different characteristics, namely Isopentane, Isobutane, Propane and R245fa. As shown below, an example of the use of REFPROP software is used to find the properties of the organic working fluid that will be used in this ORC innovation.

From the calculation results, the ORC design for oil refineries uses heat from flue gas which has a temperature of about 150°C. The heat from the exhaust gas is used to vaporize the organic working fluid which has a low boiling point. Based on the results of the ORC system design, the power generated reached 52.77123 kWh (Isopentane), 32.16672 kWh (Isobutane), 18.34265 kWh (Propane), .23334 kWh (R245fa), with efficiencies of about 14.7%, 10.92%, 6.77% and 12.69%.

Table 5. Calculation Results of 4 Organic Working Fluids

| Parameters | Unit | Isopentane | Isobutane | Propane | R245fa |
|--------------------|------|------------|-----------|---------|---------|
| Mass of Flue gas | Kg/s | 1.558 | 1.558 | 1.558 | 1.558 |
| Organic Fluid Mass | Kg/s | 25 | 25 | 25 | 25 |
| Turbine Power | MW | 2,44311 | 1,4892 | 0,84915 | 0,98303 |
| Pump Power | MW | 0,16159 | 0,1675 | 0,19375 | 0,07562 |
| QEvaporator | MW | 17,0125 | 24,295 | 14,4925 | 12,325 |
| QCondenser | MW | 10,1083 | 8,11725 | 6,31525 | 4,7695 |
| Thermal Efficiency | % | 14,79 | 10,92 | 6,77 | 12,69 |

The results in Table 5 were obtained through sequential calculations using eqs (1) to (8). First, the pump power was

calculated from the enthalpy difference between pump outlet and inlet, followed by the heat absorbed in the preheater and evaporator. Turbine power was then determined from the enthalpy drop across the turbine, and converted to generator output by accounting for generator efficiency. Finally, condenser heat duty was computed. These values were then used to obtain the net power (turbine power minus pump power) and thermal efficiency (ratio of net power to total heat input).

Isopentane achieved the highest net power due to its thermophysical properties—particularly its boiling point and latent heat—which match the heat source temperature. This allows for effective heat absorption and efficient expansion in the turbine, resulting in higher cycle efficiency.

Based on the electrical power generated by the ORC system, to produce 1 kg of hydrogen through the electrolysis process requires 50 kWh of electrical power. The estimated cost of producing 1 kg of hydrogen is IDR 41,809 [30]. While the estimated selling price of 1 kg of hydrogen is Rp. 93,987, and it is assumed that the ORC works 24 hours.

Through a trial introduction of this innovation at the PPSDM Migas Cepu Refinery Unit, we compared four organic working fluids to produce electricity, as illustrated in the attached figure. The emission factors for producing hydrogen by fuel method are illustrated in the Fig. 3 and to see the comparison between hydrogen production and the benefits that can be obtained, can be seen from Fig. 4.

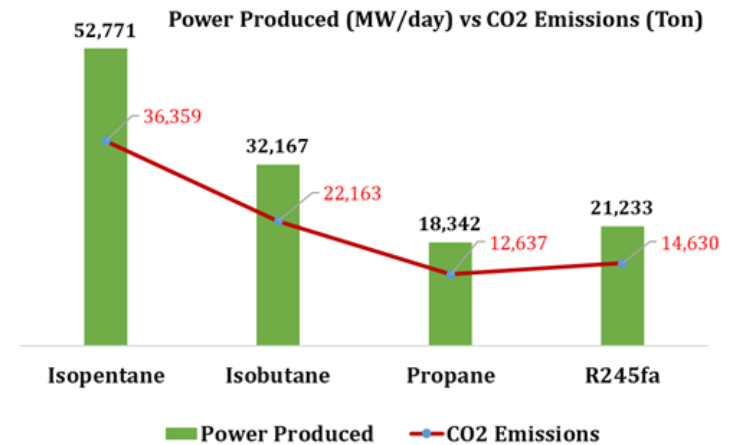


Fig. 3. Graph between Power Generated vs CO₂ Emissions

Higher net power leads directly to greater hydrogen production potential and larger CO₂ emission reductions. For example, Isopentane, with the highest net power, can produce 1,055.42 kg/day of hydrogen and reduce CO₂ emissions by 36.36 tCO₂/day. In contrast, propane, with the lowest net power, produces only 366.83 kg/day of hydrogen and reduces CO₂ emissions by 12.64 tCO₂/day.

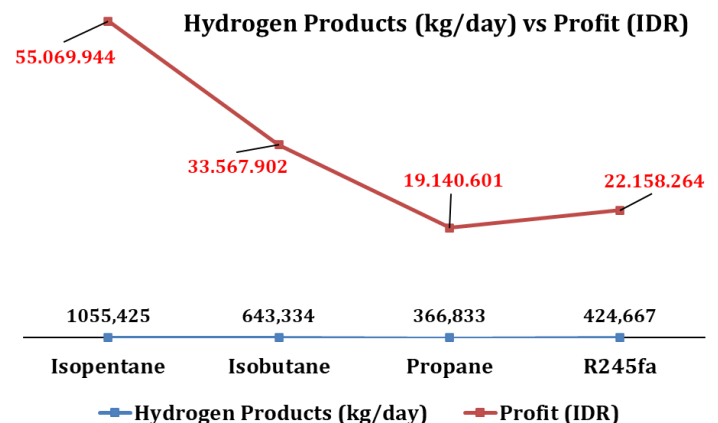


Fig. 4. Graph between Energy Produced vs Profit

A similar pattern is observed in Figure 4, where higher net power results in greater daily revenue from hydrogen sales. Isopentane provides the highest economic benefit at IDR 55,069,944.78/day, followed by Isobutane, R245fa, and Propane. The superiority of Isopentane not only from an energy standpoint but also from environmental and economic perspectives, making it the most optimal working fluid for the heat source conditions in this study.

4 Conclusion

This research investigated the utilization of exhaust heat from oil refineries through the application of Organic Rankine Cycle (ORC) technology to support green hydrogen production and reduce carbon emissions. The study confirms that ORC systems can effectively convert otherwise wasted thermal energy into electricity, which is then used to drive water electrolysis for hydrogen generation without direct CO₂ emissions. The comparative analysis of four organic working fluids (Propane, Isopentane, Isobutane, and R245fa) demonstrates clear differences in performance. Among them, Isopentane achieved the highest efficiency, producing 52.77 MWh of electricity and 1055.42 kg of hydrogen per day. This hydrogen output corresponds to daily profits of Rp. 55,069,944.78, showing the strong economic feasibility of ORC-based hydrogen production. By contrast, conventional fuel-based electricity generation producing similar power would emit approximately 36.359 CO₂ per day, highlighting the significant environmental advantage of the ORC approach. The other working fluids also exhibited promising results: Isobutane produced 32.17 MWh of electricity and 643.33 kg of hydrogen, while R245fa generated 21.23 MWh and 424.67 kg, and Propane produced 18.34 MWh and 366.83 kg. In all cases, the ORC system successfully avoided substantial CO₂ emissions while creating additional economic value. Overall, the study demonstrates that ORC integration in refinery operations is both technically and economically viable. The system leverages waste heat that would otherwise be lost, enhances refinery sustainability, and contributes directly to reducing the carbon footprint of the oil and gas sector. With proper infrastructure support, particularly continuous 24-hour operation and an adequate water supply for electrolysis, the ORC system can serve as a cornerstone technology for clean hydrogen production. In conclusion, the application of ORC technology represents not only an innovative pathway to sustainable energy production but also a critical step toward achieving Indonesia's broader net-zero emission goals.

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