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Economic Sensitivity Analysis of Waste Heat Recovery System in PME Biodiesel-Fueled Industrial Diesel Generators

Erwin Budi Sulistyo
Institut Teknologi Sepuluh Nopember, Indonesia
Email: erwinbudisulistyo@gmail.com

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Sensitivity Analysis; Investment Feasibility; Waste Heat Utilization; PME Biodiesel; Industrial Diesel Generator

Abstract

This study analyzes the economic sensitivity of an exhaust gas waste heat utilization system in a PME biodiesel-fueled industrial diesel generator to replace electrical heating energy in the biodiesel preheater system. Investment feasibility was evaluated using Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PBP) under variations in electricity tariffs, annual operating hours, capital expenditure (CAPEX), and discount rates. The baseline analysis indicates strong financial feasibility, yielding an NPV of IDR 2,229,466,230, an IRR of 93.7%, and a payback period of 1.07 years. Sensitivity analysis shows that the electricity tariff is the most dominant parameter affecting investment viability. Based on a linear interpolation approach, the investment reaches its break-even point at an electricity tariff of approximately IDR 435/kWh. Overall, the system demonstrates robust economic resilience and strong potential for energy conservation and industrial decarbonization under the framework of Economic Sensitivity Analysis of Waste Heat Recovery System in PME Biodiesel-Fueled Industrial Diesel Generators.

INTRODUCTION

Several previous studies have investigated exhaust gas waste heat recovery systems in diesel generators using waste heat recovery technology (Saidur et al., 2012; Vakkilainen, 2017). However, most existing studies primarily focus on thermal performance, heat exchanger design, and technical system analysis. Research concerning the economic sensitivity of WHR investment systems specifically applied to PME biodiesel-fueled generators remains very limited (Farhat et al., 2022; Ibnu Hakim, 2026).

This issue becomes critical because PME biodiesel-fueled generators exhibit operational characteristics significantly different from those of conventional diesel generators (Chand et al., 2024). The high viscosity of PME biodiesel requires a continuous preheating process at temperatures ranging from 50–70 °C before entering the combustion chamber. This constant thermal energy demand creates a strong dependence on heating system stability. From an economic perspective, waste heat recovery (WHR) system investments in this application face higher uncertainty in maintenance costs due to the increased potential for fouling and carbon deposition in heat exchanger components, resulting from the corrosive characteristics and high viscosity of biodiesel blends (Shu et al., 2013; Vahvanen, 2020). In addition, fluctuations in industrial electricity tariffs and variations in generator operating hours may directly shift the break-even point of cost savings generated through the elimination of electric heaters. Therefore, evaluating the economic resilience of the investment through sensitivity analysis is essential to mitigate potential financial risks over the project lifetime (Brückner et al., 2015; Jouhara et al., 2018).

This study aims to analyze the economic sensitivity of a waste heat recovery system applied to an industrial diesel generator fueled by PME biodiesel (Kumar et al., 2022; Pili et al., 2020). The novelty of this research lies in the integration of an economic sensitivity model that specifically considers electricity savings from biodiesel preheater substitution in the MTU 12V4000G23 generator, as well as the determination of the minimum investment feasibility threshold (break-even point) under external parameter fluctuations. For scientific transparency, all primary data and generator operational parameters used in this study were derived from the author's thesis research conducted at Institut Teknologi Sepuluh Nopember (ITS). The analysis was performed using Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PBP), under variations in electricity tariffs, annual operating hours, initial investment costs (Capital Expenditure/CAPEX), and discount rates.

METHOD

Waste Heat Recovery System

This study used operational data from a waste heat recovery system applied to an MTU 12V4000G23 industrial diesel generator fueled by PME biodiesel. The system utilized exhaust gas thermal energy to replace electrical heating demand in the biodiesel preheater system, thereby reducing energy consumption from electric heaters. System data were obtained from technical and economic evaluations conducted in the author's thesis research.

The diesel generator had a continuous power output of 1430 kW with an exhaust gas temperature of approximately 430 °C. The proposed system achieved annual electrical energy savings of 221,628 kWh/year through the elimination of electric heater usage.

The waste heat recovery system demonstrated the application of waste heat utilization in industrial diesel power generation to improve energy efficiency and reduce auxiliary electricity consumption.

Economic Feasibility Parameters

The basic parameters used in the economic feasibility analysis are presented in Table 1.

Table 1. Basic Parameters for Economic Feasibility Analysis

Parameter	Electric Heater	Waste Heat Recovery
Heating power	25.3 kW	0 kW
Annual electricity consumption	221,628 kWh	0 kWh
Annual energy cost	IDR 438,738,016	IDR 0
Energy source	Electricity	Exhaust gas waste heat

Electrical Energy Savings Estimation

The estimation of annual electrical energy savings was obtained based on an evaluation of the energy consumption of the existing electric heater system used in the PME biodiesel preheater. The waste heat recovery system was designed to replace the electrical heating demand, thereby eliminating electricity consumption in the biodiesel preheating system. Based on the system evaluation results from the thesis research, the implementation of the waste heat recovery system was able to reduce electrical energy consumption by 221,628 kWh/year, resulting in annual operational cost savings of IDR 438,738,016. These energy savings values were used as the basis for the economic sensitivity analysis and investment feasibility evaluation of the system.

Economic Feasibility Analysis Formulation

The economic feasibility analysis was conducted using the Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PBP) parameters to evaluate the investment feasibility of the waste heat recovery system (Orynkanova & Stepanova, 2020).

NPV equation:

$$NPV = \sum_{t-1}^{n} \frac{CF_t}{(1+i)^t} - CAPEX \quad (1)$$

where:

1. NPV= Net Present Value
2. CF_t= net cash flow in year-t
3. i= discount rate
4. t= time period or year-t
5. n= project lifetime
6. CAPEX= initial investment cost (Capital Expenditure)

In this study, the CF_tvalue was obtained from annual operational cost savings resulting from the elimination of electric heater usage in the biodiesel preheater system. The annual cash flow was then discounted using a 10% discount rate to determine the present economic value of the waste heat recovery system investment.

The interpretation of the NPV values is as follows:

1. $NPV > 0$: the investment is financially feasible
2. $NPV = 0$: break-even condition
3. $NPV < 0$: the investment is not financially feasible

Payback Period Equation

$$PBP = \frac{CAPEX}{CF_t} \quad (2)$$

where:

- PBP= Payback Period
- CAPEX= initial investment cost (Capital Expenditure)
- CF_t= annual net cash flow

Note: The analysis was conducted using a project lifetime of 10 years and a discount rate of 10%.

Sensitivity Analysis Method

Sensitivity analysis was conducted to evaluate the effect of changes in economic parameters on the investment feasibility of the system (Paramita et al., 2025). The analyzed economic parameters included electricity tariffs, annual operating hours, Capital Expenditure (CAPEX), and discount rates. Parameter variations were applied within a range of −30% to +30% from the baseline condition to determine the sensitivity level of each parameter toward the Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PBP) values.

RESULT AND DISCUSSION

System Energy Consumption Comparison

The waste heat recovery system was able to replace the electrical energy demand in the biodiesel preheater system, thereby eliminating the energy consumption of the electric heater. The comparison of system energy consumption is presented in Table 2.

Table 2. System Energy Consumption Comparison

Parameter	Electric Heater	Waste Heat Recovery
Heating power	25.3 kW	0 kW
Annual electricity consumption	221,628 kWh	0 kWh
Annual energy cost	IDR 438,738,016	IDR 0
Energy source	Electricity	Exhaust gas waste heat

Based on Table 2, the waste heat recovery system was able to eliminate electrical energy consumption by 221,628 kWh/year and generate annual operational cost savings of IDR 438,738,016. These results indicate that the utilization of exhaust gas waste heat can improve the energy efficiency of diesel generators while reducing dependence on external electrical energy sources.

In addition to providing energy savings, the system also recovers thermal energy that would otherwise be released into the environment, thereby supporting the implementation of energy conservation in biodiesel-fueled diesel power generation systems.

Baseline Economic Performance

The results of the baseline economic evaluation are presented in Table 3.

Table 3. Baseline Economic Analysis Results

Parameter	Value
CAPEX	IDR 468,000,000
Annual savings	IDR 438,738,016
NPV	IDR 2,229,466,230
IRR	93.70%
Payback Period	1.07 years

The waste heat recovery system demonstrated strong investment feasibility with a Net Present Value (NPV) of IDR 2,229,466,230 and an Internal Rate of Return (IRR) of 93.7%. The IRR value, which is significantly higher than the 10% discount rate, indicates that the system provides a high rate of investment return.

Furthermore, the payback period of 1.07 years indicates that the investment can be recovered within a relatively short period. These results suggest that the utilization of exhaust gas waste heat has strong potential to be implemented as an energy efficiency solution in biodiesel-fueled industrial diesel generators.

Sensitivity to Electricity Tariff

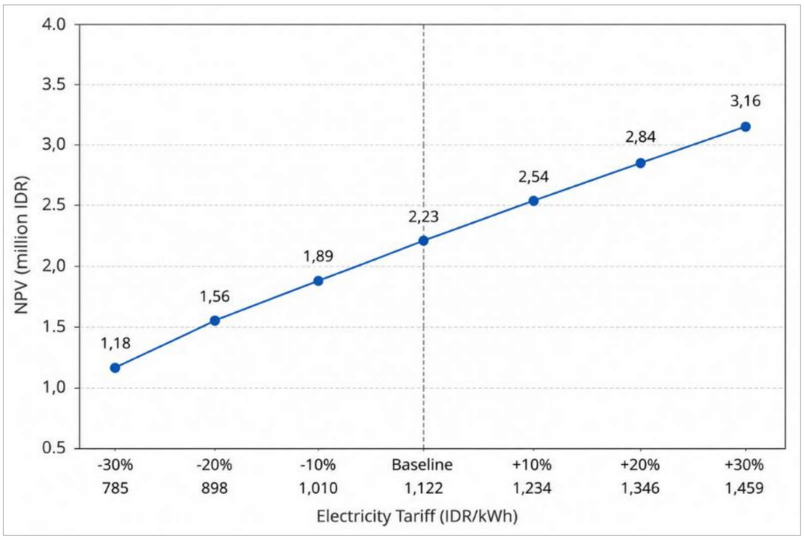
Electricity tariff is the dominant parameter affecting the operational cost savings of the system. Changes in electricity tariffs directly influence the annual cash flow due to the reduction in electrical energy consumption from the electric heater (Vilas Bôas et al., 2022).

The results of the sensitivity analysis on electricity tariff variations are presented in Table 4.

Table 4. NPV Sensitivity to Electricity Tariff Variations

Electricity Tariff Variation	Electricity Tariff (IDR/kWh)	NPV
-30%	785	IDR 1.18 billion
-20%	898	IDR 1.56 billion
-10%	1,012	IDR 1.89 billion
Baseline condition	1,122	IDR 2.23 billion
10%	1,234	IDR 2.54 billion
20%	1,346	IDR 2.84 billion
30%	1,459	IDR 3.16 billion

Based on Table 4 and Figure 1, an increase in electricity tariff directly increases the Net Present Value (NPV) of the system. Conversely, a decrease in electricity tariff reduces the NPV value due to lower annual operational cost savings. Nevertheless, the system still maintains a positive NPV even under a 30% reduction in electricity tariff. This condition indicates that the waste heat recovery system possesses relatively strong economic resilience against fluctuations in industrial electricity tariffs.



Picture 1. NPV Sensitivity to Electricity Tariff Variations

Investment Feasibility Threshold Analysis

Additional analysis was conducted to determine the minimum electricity tariff at which the system still maintains a positive NPV value. The estimation was performed using a linear interpolation approach based on the electricity tariff sensitivity results presented in Table 4.

The interpolation analysis was carried out using the two lowest sensitivity points, namely:

1. Electricity tariff of 785 IDR/kWh (X_1) with an NPV of IDR 1.18 billion (NPV_1),
2. Electricity tariff of 898 IDR/kWh (X_2) with an NPV of IDR 1.56 billion (NPV_2).

The linear interpolation equation is expressed as follows:

$$NPV = mX + b \tag{3}$$

where:

1. X= electricity tariff (IDR/kWh)
2. m= gradient of NPV change with respect to electricity tariff
3. b= constant coefficient

The gradient mwas calculated by expressing the NPV values in billion IDR using the following equation:

$$m = \frac{NPV_2 - NPV_1}{X_2 - X_1} \tag{4}$$

Substituting the sensitivity data yields:

$$m = \frac{1.56 - 1.18}{898 - 785} = 0{,}00336$$

The constant value was obtained by substituting one of the sensitivity points into the linear equation:

$$NPV_1 = mX_1 + b \tag{5}$$

$$1.18 = (0.00336)(785) + b$$

$$1.18 = 2.64 + b$$

$$b = 1.18 - 2.64$$

$$b = -1.46$$

Thus, the linear approximation equation can be expressed as:

$$NPV = 0.00336X - 1.46$$

The electricity tariff at the break-even condition was determined when:

$$NPV = 0$$

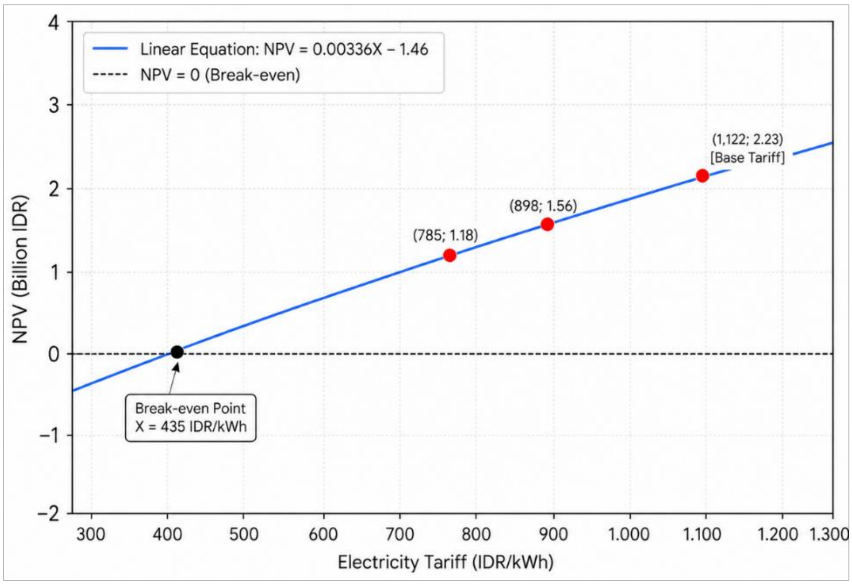
$$0 = 0.00336X - 1.46$$

$$0.00336X = 1.46$$

$$X = \frac{1.46}{0.00336}$$

$$X \approx 435 \text{ IDR/kWh}$$

The estimation results indicate that the investment break-even point occurs at an electricity tariff of approximately 435 IDR/kWh. This value is significantly lower than the baseline electricity tariff used in this study, which is 1,122 IDR/kWh. Therefore, the system still possesses a considerable economic resilience margin against fluctuations in electricity energy tariffs.



Picture 2. Linear Interpolation Graph of Electricity Tariff Sensitivity to NPV

Implications and Investment Resilience of the System

The sensitivity analysis results indicate that electricity tariff is the most dominant parameter affecting the economic feasibility of the waste heat recovery system. An increase in electricity tariff enhances annual operational cost savings, thereby increasing the system's Net Present Value (NPV).

Furthermore, the investment feasibility threshold analysis demonstrates that the system still possesses a considerable economic resilience margin against reductions in electricity energy tariffs. This condition indicates that waste heat recovery has strong long-term implementation potential as an energy conservation solution for biodiesel-fueled industrial diesel generators. The implementation of the system also has the potential to support reductions in electricity consumption and improvements in industrial energy efficiency in accordance with energy conservation and industrial decarbonization principles (Turek et al., 2024).

Research Limitations

This study still employs an economic analysis approach based on operational data and linear sensitivity estimation without considering real-time thermal performance dynamics or long-term heat exchanger performance degradation caused by fouling. In addition, the analysis has not yet considered fluctuations in biodiesel prices and detailed annual maintenance costs. Therefore, future studies may be further developed using integrated thermodynamic simulations and more comprehensive uncertainty analysis methods.

CONCLUSION

The implementation of waste heat recovery in the MTU 12V4000G23 industrial diesel generator fueled by PME biodiesel improved system energy efficiency by eliminating the electrical demand of the biodiesel preheater. The system achieved annual electricity savings of 221,628 kWh and operational cost savings of IDR 438,738,016 per year.

The economic analysis indicates strong investment feasibility, with a Net Present Value (NPV) of IDR 2,229,466,230, an Internal Rate of Return (IRR) of 93.7%, and a payback period of 1.07 years. These results suggest that the waste heat recovery system has strong potential as an energy conservation solution for PME biodiesel-fueled industrial diesel generators.

The sensitivity analysis shows that the electricity tariff is the dominant parameter affecting economic feasibility. An increase in electricity tariffs leads to higher NPV due to increased annual cost savings. Based on the investment feasibility threshold analysis using a linear interpolation approach, the break-even point occurs at an electricity tariff of approximately IDR 435/kWh. This value is significantly lower than the baseline electricity tariff used in this study (IDR 1,122/kWh), indicating a strong economic resilience margin against fluctuations in electricity prices.

REFERENCES

Brückner, S., Liu, S., Miró, L., Radspieler, M., Cabeza, L. F., & Lävemann, E. (2015). Industrial waste heat recovery technologies: An economic analysis of heat transformation technologies. *Applied Energy*, *151*, 157–167. https://doi.org/10.1016/j.apenergy.2015.01.147

Chand, S. M., Prakash, J. O., & Rohit, K. (2024). Impact of biodiesel blends on performance, emissions and waste heat recovery of diesel engine driven cogeneration system. *Journal of Thermal Engineering*, *10*(3), 680–696. https://doi.org/10.14744/thermal.0000819

Farhat, O., Faraj, J., Hachem, F., Castelain, C., & Khaled, M. (2022). A recent review on waste heat recovery methodologies and applications: Comprehensive review, critical analysis and potential recommendations. *Cleaner Engineering and Technology*. https://doi.org/10.1016/j.clet.2021.100387

Ibnu Hakim, I. (2026). Techno-economic analysis of waste heat recovery on the organic Rankine cycle: A case study at Gunungsitoli gas engine power plant. *Proceeding SNTTM BKS-TM Indonesia*, *23*(1), 320–323. https://doi.org/10.71452/t6ewq657

Jouhara, H., Khordehgah, N., Almahmoud, S., Delpech, B., Chauhan, A., & Tassou, S. A. (2018). Waste heat recovery technologies and applications. *Thermal Science and Engineering Progress*. https://doi.org/10.1016/j.tsep.2018.04.017

Kumar, S., Thakur, J., & Gardumi, F. (2022). Techno-economic modelling and optimisation of excess heat and cold recovery for industries: A review. *Renewable and Sustainable Energy Reviews*, *168*, 112811. https://doi.org/10.1016/j.rser.2022.112811

Orynkanova, Z. M., & Stepanova, D. I. (2020). Evaluation of the economic efficiency of heat recovery from exhaust gas of diesel power plants in Kazakhstan. *International Journal of Energy Economics and Policy*, *10*(4), 399–404. https://doi.org/10.32479/ijeep.9360

Paramita, P. D. P., Daniarta, S., Imre, A. R., & Kolasiński, P. (2025). Techno-Economic Analysis of Waste Heat Recovery in Automotive Manufacturing Plants. *Applied Sciences (Switzerland)*, *15*(2). https://doi.org/10.3390/app15020569

Pili, R., García Martínez, L., Wieland, C., & Spliethoff, H. (2020). Techno-economic potential of waste heat recovery from German energy-intensive industry with Organic Rankine Cycle technology. *Renewable and Sustainable Energy Reviews*, *134*, 110324. https://doi.org/10.1016/j.rser.2020.110324

Saidur, R., Rezaei, M., Muzammil, W. K., Hassan, M. H., Paria, S., & Hasanuzzaman, M. (2012). Technologies to recover exhaust heat from internal combustion engines. *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2012.05.018

Shu, G., Liang, Y., Wei, H., Tian, H., Zhao, J., & Liu, L. (2013). A review of waste heat recovery on two-stroke IC engine aboard ships. *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2012.11.034

Turek, V., Kilkovský, B., Daxner, J., Babička Fialová, D., & Jegla, Z. (2024). Industrial Waste Heat Utilization in the European Union—An Engineering-Centric Review. *Energies*. https://doi.org/10.3390/en17092084

Vahvanen, J. (2020). *Waste heat electricity recovery techniques on large ships*.

Vakkilainen, E. (2017). *Steam generation from biomass: construction and design of large boilers*. Butterworth-Heinemann.

Vilas Bôas, R., de Almeida, L. de A., & Mendes, M. F. (2022). Techno-economic evaluation of biodiesel production using by-product as raw material and hydrotalcite-hydroxyapatite as catalyst. *Research, Society and Development*, *11*(4), e0511426977. https://doi.org/10.33448/rsd-v11i4.26977