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Article

Performance Analysis of a Waste Heat Recovery System for a Biogas Engine Using Waste Resources in an Industrial Complex

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Abstract: To achieve carbon neutrality and address global energy supply issues by 2050, there is active progress in the industrial sector for waste energy recovery and commercialization projects. It is necessary to consider both the energy recovery efficiency and economic feasibility based on the production volume for the resource utilization of waste energy, along with eco-friendly processing methods. In this study, a waste heat recovery system was designed to recover a large amount of thermal energy from high-temperature exhaust gases of gas engines for power generation by using biogas produced from organic waste in industrial complexes. Types and sizes of components for a waste heat recovery system that were suitable for various engine sizes depending on biogas production were designed, and the energy recovery efficiency was analyzed. The waste heat recovery system consisted of a smoke tube boiler that generated superheated steam at 161 °C under 490 kPa of pressure from the exhaust gas as the heat source, along with two economizers for heating both supply water and hot water. Heat exchangers that were suitable for three different engine sizes were configured, and their performance and energy flow were calculated. In particular, when operating two engines with a power output of 100 kW, the boiler showed the highest steam production efficiency, and the superheated steam production from high-temperature exhaust gas at 600 °C was designed to be 191 kg/h, while hot water at 58 °C was designed to be produced at 1000 kg/h. In addition, further research on the heat exchanger capacity ratio confirmed that it was within a certain range despite the difference in heat exchanger capacity and efficiency depending on the engine size. It was confirmed that the heat exchange capacity ratio of the boiler was important as an optimal-capacity design value for the entire system, as it ranged from 46% to 47% of the total heat exchanger size.

Keywords: waste heat recovery system; biogas engine; heat exchanger; efficiency; energy flow; optimum design

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1. Introduction

Waste heat recovery systems (WHRSs) have recently attracted considerable attention for the achievement of the NetZero target for industrial complexes due to their potential to improve energy efficiency in engines and industrial processes. The potential for WHR can be classified according to the temperature range. Based on the temperature range of heat wasted by industries, Forman et al. [1] presented estimates by dividing the range into low temperatures (LT < 100 °C), medium temperatures (MT, 100–400 °C), and high temperatures (HT > 400 °C). Papapetrou et al. [2] presented a methodology for estimating the potential for WHR by industries and quantified the potential in European countries. Their results were similar to the estimates presented by Forman [1]. Bianchi et al. [3] identified and quantified the primary energy consumption in major industrial sectors along with the relevant waste streams and temperature levels to outline the prospects for industrial WHR in the EU. They confirmed that the potential was of the high order of 279 TWh/year, even when a conservative estimate was used, unlike when other methods were used.

Recent research has focused on developing and optimizing WHRSs to improve their performance and efficiency. For example, there have been advances in thermoelectric generators, organic Rankine cycles (ORCs), and heat exchangers, among other technologies. Burnete et al. [4] reviewed thermoelectric generation for internal combustion engines for waste heat recovery. The authors explained the efficiency, reliability, and cost-effectiveness of different types of thermoelectric generators (TERs) and provided various application cases in internal combustion engines (ICEs). TEGs are expected to have a simple structure and compact layout. However, limited by current TEG materials, the conversion efficiency of TEGs measured in existing test benches is still low. Tian et al. [5] reviewed, summarized, and discussed recent advances in Rankine cycles for ICEs and WHR. Based on the ideal thermodynamic cycle and the heat source, the effects of three major factors (cycle configuration, working fluid, and key components) on the performance of the Rankine cycle were investigated. Zhang et al. [6] conducted experiments on a single-screw expander ORC system under different operating conditions to evaluate the performance of the system and the exergy destruction that occurred. They found that the exergy destruction in the system was mainly due to the pressure drops in the expander and evaporator, as well as the heat transfer in the evaporator and condenser. Keawkarmorop et al. [7] compared the heat transfer performance of heat exchangers for waste heat recovery with two different fin shapes and confirmed that the serrated and welded spiral fin-and-tube heat exchanger had a heat transfer performance improvement of up to 52%. Bari et al. [8] designed a desalination plant operated with exhaust heat from a large generator with a capacity of 1.1 MW and performed a simulation to minimize the cost by minimizing the weight of the heat exchanger. Saryazdi et al. [9] proposed the configuration of an economically advantageous waste heat recovery system for the optimal design of a preheating system.

WHR systems can recover waste heat from various sources, including exhaust gases, process fluids, and waste streams. In addition to technological advances, there has been a growing emphasis on integrating WHR systems with other energy systems, such as combined heat and power (CHP) systems, to further improve their efficiency and reduce their environmental impacts. Several studies have shown that the implementation of WHR systems can significantly reduce greenhouse gas emissions and improve the sustainability of industrial processes. For example, a study by the International Energy Agency (IEA) found that implementing WHR systems in the cement, iron, steel, and chemical industries could reduce their CO_2 emissions by up to 10%. To achieve the NetZero target for industrial complexes, a combination of measures will be needed, including the adoption of renewable energy sources, energy-efficient technologies, and carbon capture and storage (CCS) technologies. WHR systems can play a key role in this mix by providing a cost-effective and sustainable solution for recovering waste heat and reducing the carbon footprint of industrial processes.

One of the key challenges in WHRSs is the optimization of a system's design and integration with an engine, which requires a multidisciplinary approach involving thermodynamics, materials science, and control engineering. Another challenge is the cost-effectiveness of the system, which depends on the specific application and the available waste heat source. It is necessary to optimize the performance and efficiency of waste heat recovery systems (WHRSs) for various applications. Although significant progress has been made in the design and implementation of WHRSs, there is still much room for improvement in terms of maximizing waste heat recovery and switching to useful energy. One of the key challenges is to overcome the limitations of existing technologies, such as organic Rankine cycles, and to develop new and more efficient methods for waste heat recovery. Additionally, it is necessary to address the economic and environmental sustainability of WHRSs, particularly in industries where energy costs are high and there is a significant carbon footprint. Another important issue is the integration of WHRSs with other energy systems, such as combined heat and power (CHP) systems, and the optimization of these integrated systems. For the future, it is necessary to continue to develop new technologies and strategies that can optimize the recovery of waste heat and its conversion into useful energy while minimizing the economic and environmental costs of such systems. In order to improve the energy efficiency of industrial complexes, this study aimed to establish and operate a self-generation and waste heat recovery system by reprocessing organic waste in a complex and producing biogas. The results of the research show that WHRSs have great potential to improve energy efficiency in engines and industrial processes, and implementing them can greatly contribute to reductions in greenhouse gas emissions and an increase in sustainability.

2. WHRS Design Process

This study aimed to optimize heat exchangers with respect to the engine size of a waste heat recovery system and to recover exhaust gas heat energy as much as possible from a CHP engine which is using biogas produced by reprocessing organic waste from industrial complexes. The analysis technique for the components of the WHRS was based on the analysis of the thermodynamic cycle through the energy conservation law, and the individual performance was determined according to the type and size of the heat exchanger and the operating characteristics of the working fluid. The analysis of the waste heat recovery system was calculated by using the energy conservation equation based on the first law of thermodynamics. An energy flow analysis was performed based on the thermodynamic properties of the supplied water and superheated steam with engine exhaust gas and recovery energy, which were working fluids serving as waste heat sources. It was also necessary to determine the type and optimal size of the heat exchanger through the calculation of the recoverable heat of the system. Although an analysis case provided by an MAN engine was used to describe the heat recovery system of a typical internal combustion engine generator of a distributed power source [10], characteristics such as exhaust gas components and outlet temperatures vary depending on the composition of the biogas used. The production of biogas generated from waste in industrial complexes subject to empirical research is 100–150 m^3/h (hereinafter, under normal conditions), which is suitable for small engines. In this study, essential components that were applicable to a heat recovery system using exhaust gas were selected, and the capacity of each element—particularly the heat exchanger—was designed to obtain the optimal performance.

In addition, the heat of the heat exchanger when recovering exhaust heat energy with various capacities of the biogas engine was calculated, the heat recovery efficiency was analyzed, and the optimal engine and heat exchanger capacities for the target industrial complex were derived.

2.1. Configuration of the WHRS

The components of the WHR system were designed to generate biogas from waste resources generated in industrial complexes, recover waste heat from exhaust gases emitted from gas engines for distributed power generation, and remove harmful substances contained in the exhaust gases. For each component of the waste heat recovery system, a system flow chart of the working fluid (exhaust gas, supply feed water, steam) for performing the operation in a normal steady state was prepared. Figure 1 shows the system flow diagram of the components of the biogas engine waste heat recovery system. The arrows in Figure 1 represent the flow of liquid and gaseous working fluids in different colors and thicknesses depending on the changes in temperature. The water supply system was an open loop.

A large amount of organic waste generated in industrial complexes is reprocessed to produce biogas, and this biogas is used as fuel for gas engines and for the generation of electricity by driving generators. The produced electricity is directly used by factories in nearby industrial complexes, and the heat energy of the combustion gas emitted from engines is recovered as much as possible through heat exchangers, such as boilers and economizers, to produce hot water and superheated steam. In addition, nitrogen oxides, carbon dioxide, and dust contained in the exhaust gas are purified through selective catalytic reduction (SCR), CO_2 capture by using dry calcium hydroxide ($Ca(OH)_2$), and dust collection processes; then, they are released into the atmosphere. The core device of the exhaust gas waste heat recovery system of the biogas engine consisted of a heat recovery device consisting of a boiler and an economizer, as well as a purification device that used SCR, carbon capture, and a dust collector; Figure 2 shows a system design diagram of each component in the assembly.

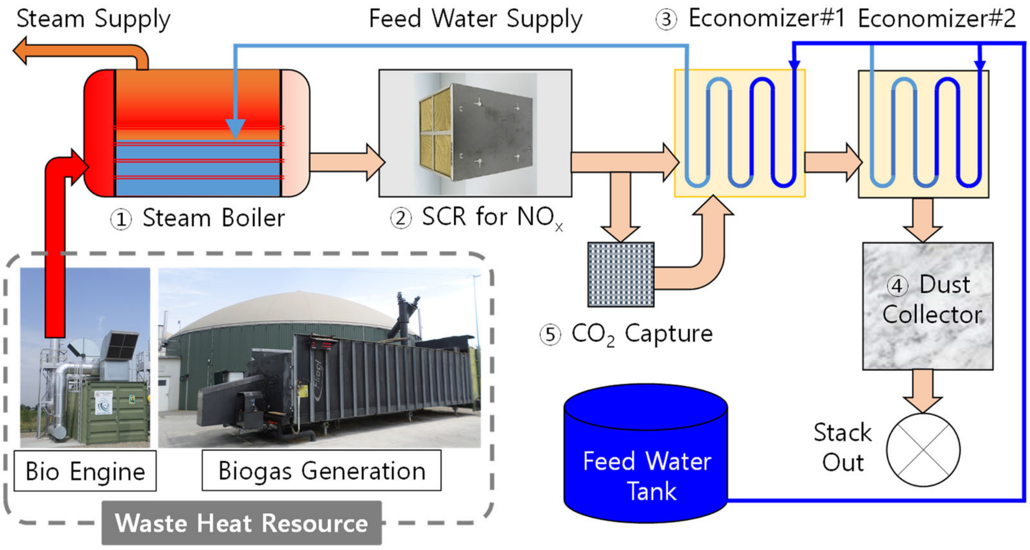


Figure 1. System flow diagram of the biogas engine WHRS (red color arrow means high temperature and blue color means low temperature).

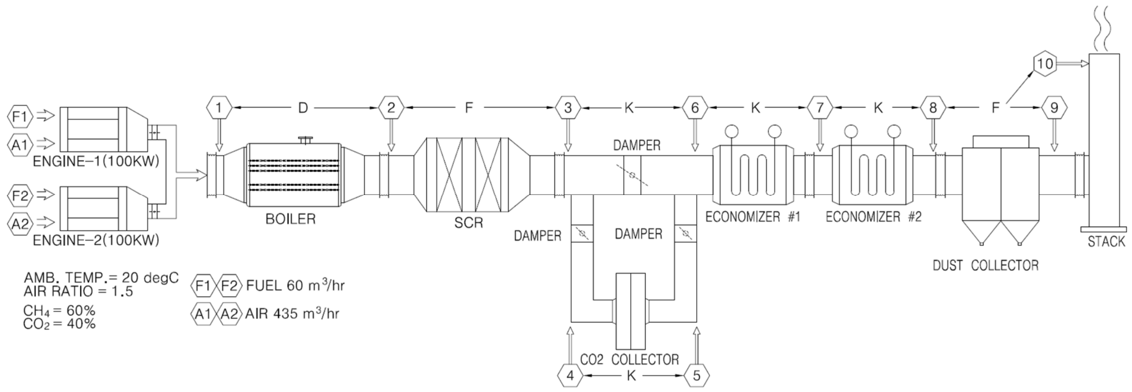


Figure 2. Schematic diagram of the biogas engine WHRS: (1) steam boiler, (2) SCR, (3) bypass duct, (4) carbon capture, (5) damper, (6) first economizer, (7) second economizer, (8) dust collector, (9) duct, and (10) stack.

2.2. Heat Exchanger Design

This section describes the design of heat exchangers for waste heat recovery from exhaust gases and the process of analyzing the performance for an optimal capacity. The function of heat energy recovery from exhaust gas was performed by a steam boiler and two economizers; in particular, the operating temperature of the boiler was designed to meet the operating temperature range for SCR and the conditions of use of steam and hot water (temperature and pressure) required in the production process.

For the steam boiler, a smoke tube that used high-temperature gas as a heat source was selected. A smoke tube boiler is a type of boiler that consists of a shell (a container) containing water, with a series of tubes inside the shell through which hot gases produced through the combustion of fuel pass. The heat from these gases is transferred to water, which is then converted into steam. The economizer recovers the remaining heat from the combustion exhaust gas from the boiler, and hot water is produced or the water supply of the boiler is preheated. The economizer is a device that absorbs energy from the gas emitted from a boiler, and it delivers residual thermal energy to the piping network along a path through which cold water is supplied, thereby reducing the load of the steam boiler and increasing the energy recovery rate. The process of designing the heat exchanger's capacity and detailed calculations used for the steam boiler and economizer are as follows.

2.2.1. Detailed Design of the Steam Boiler

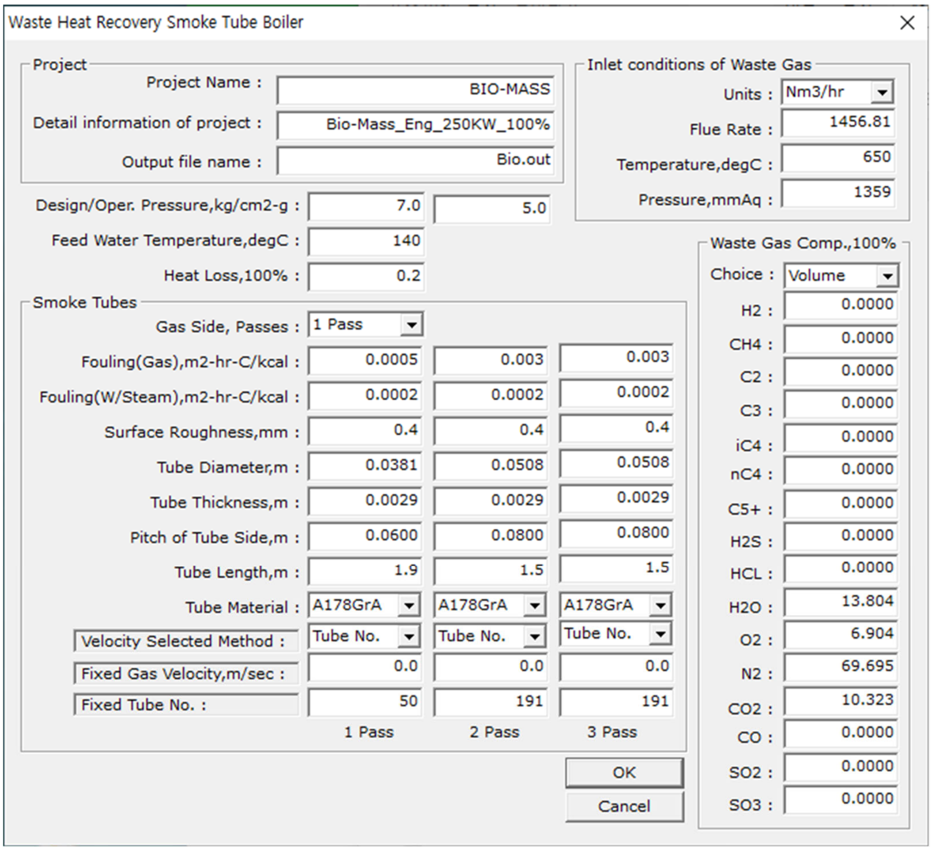
The exhaust pressure and temperature of the exhaust gas, which was the heat source of the waste heat recovery system, were designed to be 13.3 kPa (1359 mmAq gage pressure) and 650 °C, respectively. The dyeing industry, which is the target of this study, uses steam to heat a dye solution of 110 to 130 °C or requires hot water of 60 to 80 °C. First, we designed a steam boiler to produce superheated steam (10 °C of superheat degree) with a supply temperature of 161 °C at an operating pressure of 490 kPa (5 kg/cm^2) using high-temperature exhaust gas as a heat source. The feed water supplied to the boiler was preheated in two economizers. Figure 3 shows a summary of the results of the calculation by using the heat exchanger design program (HAD-WHRBT) [11] for the steam boiler, and the design process of the heat exchanger is described as follows:

1. The amount of heat was analyzed according to the components of the exhaust gas and the temperature conditions of the generator engine's exhaust port for each cases (100, 200, 250 kW of power generation).
2. The calculated exhaust heat of the biogas engine was used as an input for the design variables in the heat exchanger design program.
3. The detailed design of the steam boiler was carried out based on the values of the input design variables.
4. A calculation sheet was prepared for the heat transfer area of the associated waste heat boiler by using the heat exchanger design results.
5. Technical specifications and a strength statement were prepared for the approval of the waste heat boiler by the authorized institution.
6. The detailed design was completed by setting the positions of the boiler's peripheral equipment (pressure gauge, thermometer, water level meter, etc.).

2.2.2. Detailed Design of the Economizers

Heat may be slightly recovered from the exhaust gas emitted through the boiler through an additional heat exchange process, while residual heat remains. The heat exchanger used at this time is an economizer. During the design process, exhaust gas heat recovery was used for the production of steam and hot water, and it was necessary to find the optimal conditions for steam production and hot water production. As a result of the calculation, it was decided that two economizers were to be installed to separate the functions of preheating the cooling water supplied to the boiler and supplying hot water. Therefore, there was a first economizer (with a gas temperature of 243 °C or higher) for preheating the boiler and a second economizer (with an exhaust gas temperature of 150 °C) that could produce hot water in a low-temperature region.

A heat exchanger design program, HAD-ECO [12] was used for the design of the economizer. The conditions of the waste heat gas and the inlet state of the coolant side were input into the design program; the variables related to the heat exchanger's flow pattern, heat exchanger's size, and the pin/tube shape were adjusted; and it was specified that 253 °C would be reached after the heat exchange of first economizer. In the second economizer, since the exhaust gas temperature was low, the temperature difference from the supplied coolant was not large, so a segmented pin shape with improved heat transfer performance was applied. According to previous studies [7], it was found that segmented fins had a higher heat transfer efficiency than that of plain fins. The design variables of the two economizers and the calculation results for each variable are shown in Table 1.



Project
Project Name : BIO-MASS
Detail information of project : Bio-Mass_Eng_250KW_100%
Output file name : Bio.out

Inlet conditions of Waste Gas
Units : Nm3/hr
Flue Rate : 1456.81
Temperature,degC : 650
Pressure,mmAq : 1359

Design/Oper. Pressure,kg/cm2-g : 7.0 5.0
Feed Water Temperature,degC : 140
Heat Loss,100% : 0.2

Smoke Tubes
Gas Side, Passes : 1 Pass

	1 Pass	2 Pass	3 Pass
Fouling(Gas),m2-hr-C/kcal :	0.0005	0.003	0.003
Fouling(W/Steam),m2-hr-C/kcal :	0.0002	0.0002	0.0002
Surface Roughness,mm :	0.4	0.4	0.4
Tube Diameter,m :	0.0381	0.0508	0.0508
Tube Thickness,m :	0.0029	0.0029	0.0029
Pitch of Tube Side,m :	0.0600	0.0800	0.0800
Tube Length,m :	1.9	1.5	1.5
Tube Material :	A178GrA	A178GrA	A178GrA
Velocity Selected Method :	Tube No.	Tube No.	Tube No.
Fixed Gas Velocity,m/sec :	0.0	0.0	0.0
Fixed Tube No. :	50	191	191

Waste Gas Comp.,100%
Choice : Volume
H2 : 0.0000
CH4 : 0.0000
C2 : 0.0000
C3 : 0.0000
iC4 : 0.0000
nC4 : 0.0000
C5+ : 0.0000
H2S : 0.0000
HCL : 0.0000
H2O : 13.804
O2 : 6.904
N2 : 69.695
CO2 : 10.323
CO : 0.0000
SO2 : 0.0000
SO3 : 0.0000

Figure 3. Results of the heat exchange calculations for the steam boiler of 250 kW WHRS.

Table 1. Design parameters of the economizers and calculation results.

Design Parameters	1st Economizer (1st ECO)	2nd Economizer (2nd ECO)
Heating surface (m^2)	10.1	17.3
Tube diameter (mm)	38.1	38.1
Minimum tube thickness (mm)	2.9	2.9
Tube length (mm)	500	500
Width of economizer (mm)	500	500
Transverse spacing (mm)	80	80
Longitudinal spacing (mm)	80	80
Tube arrang. (1 = stagg, 2 = inline)	2	2
Fin type (0 = no, 1 = solid, 2 = serr.)	1	1
Flow type (counter = 1, parallel = 2)	1	1
Fin height (mm)	15	15
Fin thickness (mm)	1.2	1.2
Fin pitch (mm)	11.6	5.8
Fin segment (mm)	-	4
Fin base height (mm)	-	5
Fin material	Carbon steel	Carbon steel

3. Evaluation of WHR Performance

It was also necessary to analyze the changes in waste heat recovery efficiency according to the operating conditions of the power generation system (time, capacity, etc.). The waste heat recovery capacity and efficiency under normal operating conditions were calculated by applying the thermal energy equation for exhaust gas, supply water, and steam based on the exhaust volume and gas characteristics of the generator engine based on the biogas supply, and the results are presented. The biogas generator engine was determined according to the organic waste emission and biogas production capacity of the demonstration complex. The design of the waste heat recovery system was performed based on the amount of biogas supplied. In this process, it was possible to design the size of the engine suitable for biogas supply and the size of the heat exchanger. The composition of exhaust gas emitted from the engine is shown in Table 2.

Table 2. Exhaust gas composition.

Gas	CO_2	H_2O	SO_2	O_2	N_2	HCl
VOL%	10.323	13.804	0	6.178	69.695	0

The design conditions of the waste heat recovery system using biogas with the components shown in Table 1 are as follows:

- Biogas supply: 150 m^3/h.
- 250 kW power generation engine exhaust gas flow rate: 1456.81 m^3/h:
  - Composition of biogas: CH_4 60 vol% + CO_2 40 vol%.
  - Excess air ratio of the internal combustion engine: 1.5.
  - Theoretical air–fuel ratio (A/F): 8.712 (volume ratio), 11.192 (weight ratio).
  - The mass flow rate of engine exhaust gas ($\dot{m}_{gas}$) was calculated by using a function of fuel consumption and the air supply rate (e.g., 150 + 150 × 8.712 = 1456.81 m^3/h = 1869.67 kg/h).
- Exhaust gas density: 1.2834 kg/m^3.
- Unit heat generation of biogas fuel: 5133.53 $kcal/m^3$.
- Total heat generation of biogas: $Q_{Biogas,fuel}$ =5133.53 $kcal/m^3$ × 150 m^3/h = 770,029.5 kcal/h = 894.9 kW.
- Exhaust gas emission temperature: 650 °C.

The following is a heat balance equation that calculates the recoverable capacity of waste heat held by exhaust gas:

Recoverable heat of exhaust gas:

$$Q_{gas} = \dot{m}_{gas} \times C_{P,gas} \times \Delta T_{gas} \tag{1}$$

- 2% for the heat loss rate assumption.

Exhaust gas heat was used to preheat the supplied water and produce steam, and this was calculated with the following heat settlement equation:

Supply water heating:

$$Q_{water} = \dot{m}_{water} \times C_{P,water} \times \Delta T_{water} \tag{2}$$

Heat generated by steam:

$$Q_{steam} = \dot{m}_{steam} \times h_{fg} \tag{3}$$

Overheating of steam generation:

$$Q_{superheat} = \dot{m}_{steam} \times \Delta h_{superheat} \tag{4}$$

These constraints for the optimal design were used:

- Supply water inlet temperature: $T_{water,in}$ =25 °C.
- Steam pressure and overheating: $\Delta h_{superheat} = 10$ °C.
- Hot water production (based on a 200 kW engine): $\dot{m}_{hotwater}$ = 1000 kg/h.

The following other assumptions were made:

- Efficiency of power generation of the bio-engine: $\eta_{power} = 34\%$.
- Heat loss of the boiler: $\eta_{loss,boiler} = 2\%$.
- Heat loss of the economizers: $\eta_{loss,ECO} = 10\%$.

The efficiency of the heat recovery system is defined as the sum of the heat recovered from the boiler and the two economizers divided by the total heat generation value of biogas fuel supplied to the engine:

Energy balance:

$$Q_{Biogas,fuel} = Q_{power} + Q_{steam} + Q_{superheat} + Q_{water} + \Sigma Q_{loss} \tag{5}$$

Energy conversion rate:

$$\eta_i = \frac{Q_i}{Q_{Biogas,fuel}}, i = power, water, steam, superheat \tag{6}$$

WHR efficiency:

$$\eta_{WHR} = \frac{Q_{water} + Q_{steam} + Q_{superheat}}{Q_{Biogas,fuel}} \tag{7}$$

Heat Balance between the Boiler and Economizers

The heat balance target of the waste heat recovery system consisted of a boiler that produced steam and two economizers that preheated the supplied water. One steam boiler performed the function of producing high-temperature superheated steam by heating hot supplied water that was preheated in the first economizer using the high-temperature exhaust gas. The two economizers, which consisted of a heat exchanger of liquid feed water and exhaust gas, were divided into the function of preheating the feed water (first ECO) to produce superheated steam and the function of supplying hot water (second ECO) to recover as much residual heat as possible before the final exhaust. Figure 4 shows the process through which the feed water (blue line) heated by the high-temperature engine exhaust gas (red line) and the phase changed. In the heat recovery process, the second economizer (second ECO) supplied hot water of 83 °C by preheating 25 °C feed water by using waste heat energy from the exhaust gas. In addition, the first economizer (first ECO) overheated the supply water to 120 °C, and then the boiler produced superheated steam of 161 °C by using the high-temperature exhaust gas.

Initially, the capacity of the engine planned for the demonstration complex was 250 kW, but in order to improve the efficiency through a distributed operation due to fluctuations in biogas production, it was also necessary to consider operating two 100 kW units. Therefore, it was necessary to calculate the waste heat recovery capacity and energy conversion efficiency by applying thermal equations for the exhaust gas, feed water, and steam for 250 kW and 100 kW power engines. In particular, in the case of two 100 kW power engines, it was necessary to establish an operation control strategy that depended on the production of biogas and to compare the optimal capacity of the heat exchangers in the steam boiler and economizers according to changes in the exhaust gas temperature and flow rate. The thermodynamic performance of the waste heat recovery system was compared for the same exhaust temperature conditions, as the amount of heat recovered for each biogas engine size under each condition was proportional to the temperature and flow rate of the exhaust gas. The engine exhaust temperature varied depending on the power capacity and operating conditions of the engine, and the boiler outlet temperature and the economizer outlet temperature were calculated differently depending on the supply water flow rate and the design conditions of the heat exchanger. The results of the performance analysis of the WHR system in terms of the engine size (generation power), efficiency, and recovery of heat based on the exhaust gas and feed water temperatures and the flow conditions at the inlet and outlet of each heat exchanger are summarized in Tables 3 and 4.

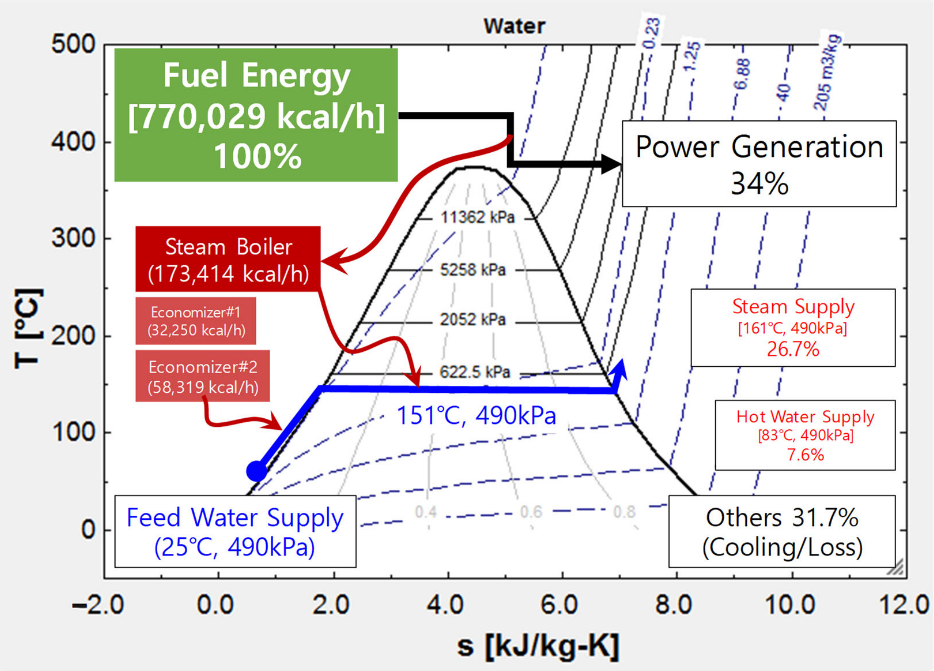


Figure 4. T-s diagram of the water-to-steam heat exchange process (EES).

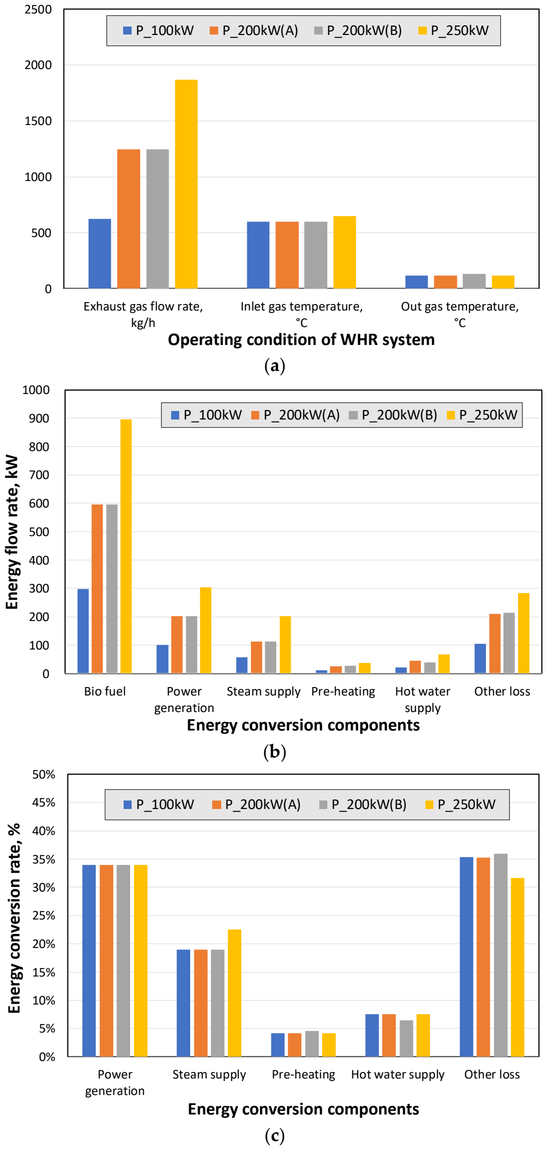
Table 3. Summary of the heat recovery performance according to the engine size.

Power Size (kW)	Gas Flow Rate (kg/h)	Boiler			First Economizer			Second Economizer			WHR Efficiency (%)
		T_{in} (°C)	T_{out} (°C)	$Q_{gas,B}$ (kW)	T_{in} (°C)	T_{out} (°C)	$Q_{gas,1ECO}$ (kW)	T_{in} (°C)	T_{out} (°C)	$Q_{gas,2ECO}$ (kW)	
250	1870	650	320	201.5	320	250	37.5	250	120	67.8	34.28
200B	1246	600	320	113.4	320	243	27.5	243	132	38.6	30.07
200A	1246	600	320	113.4	320	250	25.0	250	120	54.2	30.76
100	623	600	320	56.6	320	250	12.4	250	120	22.5	30.69

Table 4. Summary of the feed water conditions and production.

Power Size (kW)	Input Feed Water		Boiler		First Economizer		Second Economizer		Steam Production (kg/h)	Hot Water Production (kg/h)
	Flow Rate (kg/h)	$T_{water,in}$ (°C)	T_{steam} (°C)	$\dot{m}_{steam}$(kg/h)	T_{w1} (°C)	$\dot{m}_{preheat}$(kg/h)	T_{w2} (°C)	$\dot{m}_{hotwater}$ (kg/h)		
250	1320	25	161	320	120	320	83	1000	320	1000
200B	1191	25	161	191	151	191	58	1000	191	1000
200A	1187	25	161	187	140	187	64	1000	187	1000
100	592	25	161	92	133	92	64	500	92	500

The waste heat recovery efficiency is defined in Equation (7), and it is usually proportional to the engine size, but the optimal operating conditions involved maximizing the output of superheated steam and hot water at the same engine size under the given constraints. As shown in Tables 3 and 4, two cases (200A vs. 200B) using two 100 kW engines were compared. In the case of 200B, the temperature of the hot water supplied by the first economizer (first ECO) was increased to increase the production of superheated steam by the boiler, and in this case, the outlet temperature of the hot water produced by the second economizer (second ECO) in the final stage was lowered. In the repeated calculation process for various flow rates and temperature conditions, the WHR system's heat recovery efficiency in the case of 200A was found to be 30.76%. This result was optimal for a heat exchanger that maximized the production of superheated steam with 10 °C of superheating, and the flow rate and outlet temperature of the hot water and steam in the three heat exchangers were optimal. Based on the above results, the 200A case was selected as the optimal operating condition of the WHR system, and the capacity of the heat exchanger was determined. The waste heat recovery efficiency calculated according to each capacity of the engine and the production of steam and hot water using the recovered heat were compared with each other. Figure 5 shows the results of the comparison of the heat recovery in the waste heat recovery system and the energy recovery efficiency according to changes in engine power. Figure 5a,b confirms that as the engine's power capacity increased, the production of superheated steam (steam) naturally increased in proportion to it (100 < 200 < 250 kW). In addition, as shown in Figure 5c, the heat recovery efficiency was the largest at 250 kW, but as shown in Figure 5d, the production efficiency of steam was slightly higher at 200 kW. It can be seen that using two 100 kW power engines (P_200A case) provided the highest heat recovery efficiency and steam production. Based on the above calculation results, a detailed design of the heat exchangers of boilers and economizers for the production of feed water and steam was performed.

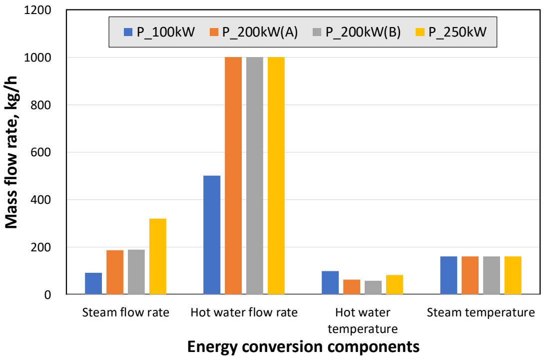


(**a**)

(**b**)

(**c**)

Figure 5. *Cont.*



(**d**)

Figure 5. Comparison of the heat balance calculations: (**a**) operating conditions of the WHR system; (**b**) gas energy flow rate in kW; (**c**) energy conversion rate; (**d**) mass flow rate of steam and hot water.

Sankey diagrams were used to analyze the energy flow and conversion efficiency of various waste heat recovery systems, power plants, and industrial processes. Figure 6 shows the energy flow of a WHRS with a Sankey diagram by quantifying the waste heat recovery at each stage. The comparison of the recovered heat for each engine size is intuitive, and the areas in the figure are proportional to the power, so this helps one understand the energy conversion and loss. These diagrams can visually represent energy flows and help identify areas for energy conservation and optimization.

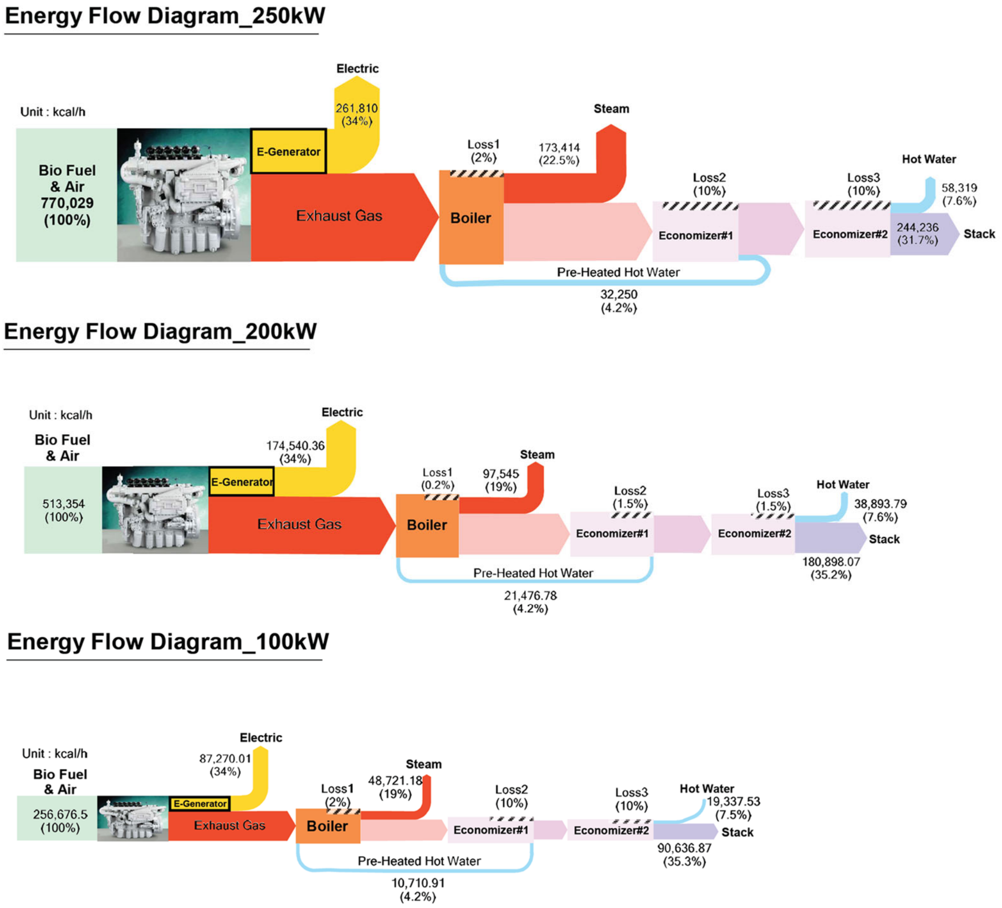


Figure 6. Comparison of energy flows in WHR according to engine sizes with a Sankey diagram.

4. Analysis of Heat Transfer Capacity

The multiplication of the heat transfer capacity (UA) by the heat transfer area of the heat exchanger and the total heat flow rate can be performed by using Equations (8) and (9) with the log mean temperature difference (LMTD).

$$\Delta T_{LMTD} = \frac{\Delta T_1 - \Delta T_2}{ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \tag{8}$$

$$UA_i = \frac{Q_i}{\Delta T_{LMTD}} \tag{9}$$

where ΔT_1 is the difference between the inlet temperature of the heat source and the outlet temperature of a cold fluid in a counterflow heat exchanger, and ΔT_2 is the difference between the outlet temperature of the heat source and the inlet temperature of the cooling water. The subscript i is used to indicate the heat exchanger consisting of a boiler and two economizers. The exhaust gas flows and is discharged in the order of the boiler, first economizer, and second economizer, and the cooling water is supplied to the counterflow heat exchanger through a utility line to produce hot water in the second economizer. Water is preheated in the first economizer, and superheated steam is produced in the boiler through a phase change. The amount of heat transferred from the exhaust gas to the boiler, first economizer, and second economizer is calculated in Equation (1), and the temperature of the cooling water at each heat exchanger's outlet is calculated by using Equations (2)–(4) with the calculated amount of heat recovered from the heat source. In this study, the optimal value from Equation (11) was calculated by using the heat transfer capacity ratio defined by Kim and Jung [13].

$$UA_{total} = UA_{boiler} + UA_{1st\ ECO} + UA_{2nd\ ECO} \tag{10}$$

$$u = \frac{UA_{boiler}}{UA_{total}} \tag{11}$$

where u is the heat transfer capacity ratio, UA_{boiler} is the heat transfer capacity of the boiler in the heat exchanger, and UA_{total} is the sum of the heat transfer capacity of the entire heat exchanger, as shown in Equation (10).

Optimal Design of the Boiler Capacity

In the process of designing the waste heat recovery system, when the temperature and flow conditions of the exhaust gas were determined, the conditions for maximizing the amount of waste heat recovered and the efficiency also needed to be determined. As an objective function, it was important to determine the supply temperature of hot water and steam produced by the waste heat recovery system. In addition, determining the appropriate size of the heat exchanger is an important design process when optimizing the performance of a heat exchanger that performs three different functions. Figures 7 and 8 compare the heat transfer capacity calculated in the heat exchanger design process and the results of the optimal design variables. Figure 7 shows the heat exchanger capacity calculated with Equations (8) and (9), which means the product of the heat transfer area (A) and the total heat flow rate (U). And Figure 8 shows the capacity of each heat exchanger in percentages for each capacity of the two engines. The value of UA_{total} was 728.5 W/K in the 200 kW power engine and 1139.1 W/K in the 250 kW power engine; the rate at which the capacity of the heat exchanger increased was 156.4%, while the rate at which the engine size increased was 125.0%. This meant that the larger the engine size, the greater the production of superheated steam, which improved the efficiency; therefore, the capacity of the heat exchanger also needed to increase.

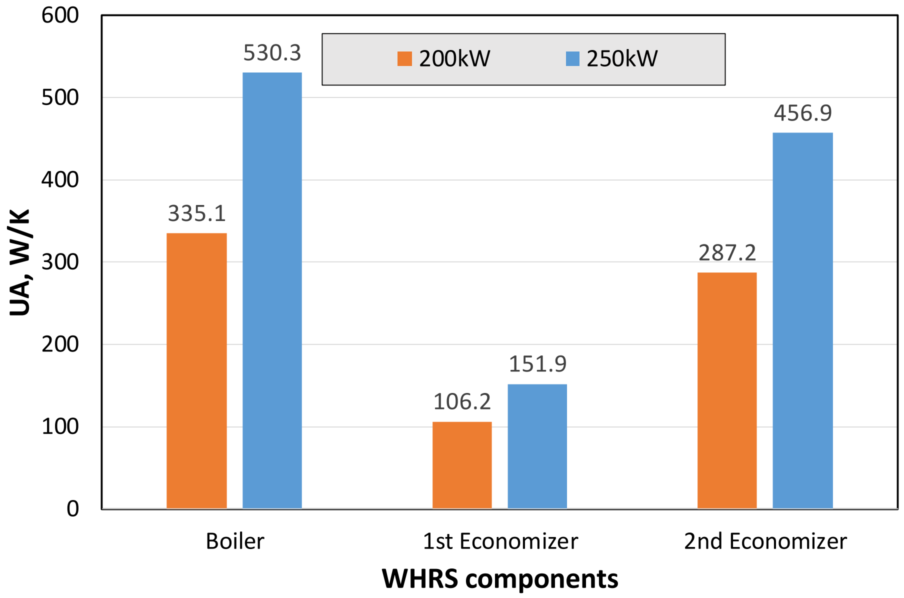


Figure 7. Heat exchanger capacity values (*UA*) when using two different engines.

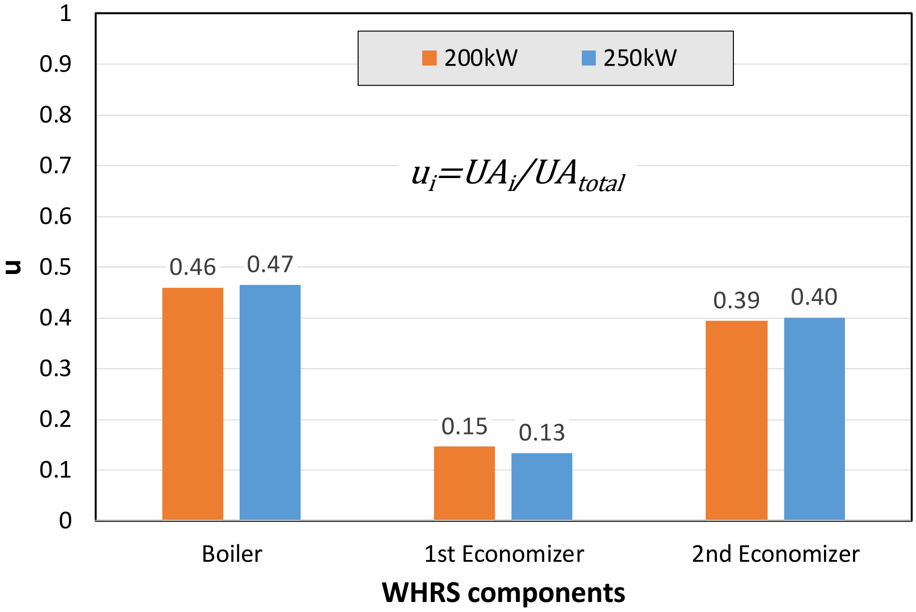


Figure 8. Comparison of the heat transfer ratios (u) and optimal values of the boiler.

In addition, determining the capacity of heat exchangers with three different functions is a very important design process that determines the performance and thermal efficiency of an entire waste heat recovery system. In this study, the heat exchange capacity of the boiler was defined in Equation (11) as the heat transfer capacity ratio (u) with respect to the total heat exchanger capacity of the waste heat recovery system. Figure 8 shows a comparison of the heat transfer capacity ratios (u) of the heat exchanger with the boiler when using two engines of different sizes. Despite the differences in engine size and heat exchanger efficiency, the capacity ratio of each heat exchanger was found to be from 46% to 47%. As a result, it was confirmed that despite the change in the size of the waste heat recovery system, the optimal value was around 46% for the boiler's heat exchange capacity and was an important reference value when designing the size of the entire system.

5. Conclusions

This study introduced the results of a design case of a WHR system for generating biogas from waste resources generated in industrial complexes, recovering waste heat from exhaust gases emitted from gas engines used for distributed power generation, and removing harmful substances contained in those exhaust gases. A system diagram of the working fluid (exhaust gas, supply water, steam) was designed to show the normal operation of each component of the waste heat recovery system, and the waste heat recovery efficiency was analyzed according to the engine size of the power generation. The engine size for the generator was determined based on the production of biogas, and the waste heat recovery capacity was calculated by applying the heat balance equation for supply water and steam according to the exhaust gas components. According to the analysis of the heat recovery system under the exhaust gas output conditions of a 250 kW power engine, the maximum recovery efficiency was found to be 34.0% of the power generation, 26.7% of the water preheating and superheated steam production, and 7.6% of the hot water production. In the analysis of the waste heat recovery system's performance with changes in the engine size, two 100 kW power engines were used to compare waste heat recovery and heat recovery efficiency according to the power output.

A summary of the results of the comparison of the engine sizes is provided as follows:

- In the performance analysis, the heat recovery efficiency was the greatest at 250 kW, and it was confirmed that the production of superheated steam increased as the power capacity increased;
- The engine exhaust temperature varied depending on the power capacity and operating conditions of the engine, and the boiler outlet temperature and the economizer outlet temperature were calculated differently depending on the supply water flow rate and the design conditions of the heat exchanger;
- In the case of using two 100 kW engines (200A case), it was confirmed that the heat recovery efficiency under the optimal operating conditions was 30.76% as a maximum value;
- Despite the change in engine size, it was confirmed that the heat exchanger capacity ratio (u) of the boiler was optimal in the range of 46% to 47%.

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