International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 12 Issue 11 ǁ November 2024 ǁ PP. 57-73

Comprehensive analysis of a combined Rankine and organic cycle for waste heat recovery: a strategy to maximize thermal efficiency

Amin Soltani[1], Gholamreza Nabi Bidhendi[2*], Nasser Mehrdadi[2]
[1]Department of Environmental Engineering, Aras International Campus, Jolfa, Iran
*[*2]Faculty of Environment, University of Tehran, Tehran, Iran*

Abstract
In this paper, a comprehensive analysis of a combined Rankine (water) cycle and an organic Rankine cycle (two-stage organic Rankine cycle) is presented, in which the low-temperature exhaust gas heat of a 123.5 MW combined cycle power plant unit can be effectively recovered and utilized along with the refrigeration energy of liquefied natural gas. A two-stage organic Rankine cycle is proposed to recover the low-temperature waste heat of the exhaust gas from the stack of a combined cycle power plant. The proposed combined cycle simultaneously produces output power and evaporates liquefied gas. The aim of this research is to perform parametric analysis and thermoeconomic optimization of the proposed system. Based on thermodynamic mathematical models, the effects of key thermodynamic design parameters on the system performance are tested from both thermodynamic and economic perspectives. The two-stage system under consideration shows a significant power output of 49.6 MW from the Rankine cycle and 3.8 MW from the organic Rankine cycle. A detailed exergy analysis shows that the condenser is the main site of exergy destruction, accounting for 3254 kW in the Rankine cycle and 714 kW in the organic Rankine cycle, raising concerns about operating costs, estimated at \$0.8 and \$0.25 per hour, respectively. The highest exergy efficiencies recorded are 86% for the Rankine cycle superheater and 85% for the organic Rankine cycle reheater, contributing to an overall cycle efficiency of approximately 80% and an exergy efficiency of 72%.

Keywords: *Rankine cycle, energy analysis, exergy analysis, thermodynamic cycle, thermal efficiency.*

Date of Submission: 08-11-2024 Date of acceptance: 20-11-2024

I. INTRODUCTION

Linear Increasing concerns about energy consumption and environmental sustainability have intensified the pursuit of innovative solutions for waste heat recovery. In industrial processes and power generation systems, significant amounts of heat are often wasted, which not only leads to energy inefficiency but also increases greenhouse gas emissions. Recovering this waste heat represents a unique opportunity to improve the overall performance of the system and contribute to the transition to a circular economy. Among the various technologies used for waste heat recovery, combined cycles that integrate organic and inorganic Rankine cycles have emerged as promising candidates due to their potential to improve thermal efficiency and optimize energy use. For example, Farrokh Bakht and Hebtollah Pour [7] studied the economic load dispatching of a power grid consisting of thermal units, electrical units, and combined heat and power units. For this purpose, a hybrid optimization algorithm derived from two ant colony and honey bee algorithms has been used to find the optimal solution. The proposed method has been simulated using Matlab software and implemented on two sample networks. Their results show that the proposed optimization method has a greater ability to find optimal solutions and has resulted in a lower total cost. Taghi Nasab and Barati [8] conducted a study aimed at the optimal use of combined heat and power plants to minimize environmental emissions. They used the crow search optimization algorithm to solve the economic load distribution problem and the economic load distribution/pollution problem. The results obtained from the crow search optimization approach for optimization are valid based on comparison with the results of the ant colony algorithm as well as other algorithms examined in other studies. When combined heat and power units are integrated with an integrated heat generation system, the results obtained from implementing the proposed crow search optimization approach are very promising. Arandian and Mohammadi Ardhali [9] conducted a study to optimize the size, location, and utilization of different technologies of cogeneration systems in thermal and electrical energy networks in order to increase the network operator's profit, taking into account technical, economic, and environmental constraints. The simulation results, while confirming the proposed method, show that the combined use of renewable and non-renewable technologies in cogeneration systems increases the annual profit of the network operator by \$134,937.09. Also, considering environmental constraints, the internal combustion engine-based cogeneration system does not play a role in the optimal combination of technologies.

Shahjoui and Taghipour Rezvan [10] presented a hybrid model using the fuzzy TOPSIS method and the modified digital logic method in a study and used it to select and evaluate various common primary drivers. To select the optimal system, the decision-making model presented using the fuzzy TOPSIS method and the modified digital logic method has been analyzed in Taleghani Hospital, Tehran, from the technical, economic, environmental and social aspects of its implementation and effectiveness. The results show that the gas-fired piston engine is the best choice among the options considered. Efficient and rational energy production and supply is one of the main assumptions of sustainable development. Cogeneration systems of electricity, heat and cooling have clear environmental benefits by increasing energy efficiency, reducing the emission of environmental pollutants and optimizing the use of thermal energy from fossil fuels. Afshari [11] in an article aimed to introduce the types of combined heat and power systems and to examine their performance in detail based on fuel cells. They reported that their durability and reliability are also high and pollutants such as nitrogen oxides and sulfur oxides in fuel cells are close to zero. Qarghani et al. [12] in a study investigated a dual power and cooling production system using an organic Rankine cycle and a VCC cycle. In this system, the organic and VCC cycles perform power and cooling production in parallel. The results indicate that by converting the system from the basic mode to the combined mode, the efficiency of the energy unit production cost shows an average decrease of 45%. Arianfar et al. [13] in a study, an article investigated the two-stage Rankine cycle. In their study, two fluids R116 and R227ea were selected as the working fluids of the system. Based on thermodynamic mathematical models, the effect of key design parameters, including flue gas outlet temperature and turbine inlet pressure, on system performance was studied from a thermodynamic perspective as an objective function. The output results after simulation show that the optimized two-stage organic Rankine cycle can have a net output power of 2035 kW with a first-law efficiency of 31.37% and an exergy efficiency of 35.2%. Mousavi Ghasemloui et al. [14] modeled a ternary generation system based on a solid oxide fuel cell and an organic Rankine cycle in a paper. Energy and exergy analyses were also performed on the proposed system in EES software, and the effect of important system parameters such as current density, fuel cell temperature, and fuel consumption coefficient on its thermodynamic performance was investigated. They reported that the exhaust gases from the solid oxide fuel cell have a high temperature that can be used to drive gas turbine cycles and organic Rankine cycles or other cycles, resulting in increased overall efficiency.

Sanjari and Iranmanesh [15] in an article studied the technical and economic aspects of using cogeneration systems in a number of selected high-consumption industries, considering different approaches based on which the electrical capacity of the system was designed. The studies showed that in all approaches, using a reciprocating engine as the primary driver with natural gas fuel leads to satisfactory results. Haj Abdollahi and Ghamari [16] in a study modeled a desalination system and a cogeneration system for cooling, heating and power. Their results show that the annual cost and emission penalty for the cogeneration system have decreased by 39.34% and 40.65%, respectively, compared to the traditional system. Also, the increase in energy consumption of equipment with their performance and efficiency at optimal partial load compared to the maximum performance and efficiency at a specific partial load was calculated, and their maximum was achieved in the eighth month for absorption and electric chillers, 91% and 94%, and in the twelfth month for backup boiler and diesel engine, 45% and 6%, respectively. Qorghani et al. [17] In the study, a dual power and cooling generation system was investigated using an organic cycle and a VCC cycle. Pekkari et al. [18] first simulated a heating heat pump with an intermediate heater and with geothermal energy as the driver, and then investigated the effect of changing various parameters, including the pressure of different parts of the cycle, superheating at the evaporator outlet, subcooling at the condenser outlet, and ambient temperature, on the coefficient of performance and economic efficiency of the heat pump. The results indicate that despite the good thermodynamic performance, R-12 fluid cannot be a suitable option due to the high severity of environmental damage, and hence R134a fluid is selected as the appropriate fluid for this cycle. Abdolalipour Adl et al. [19] in a study developed an integrated system based on geothermal, two-stage flash evaporation, organic Rankine cycle, proton membrane electrolyzer, reverse osmosis unit and internal water heater. The optimization results show that the net power produced is 5091 kW, fresh water produced is 41.75 kg/s, thermal efficiency is 15.58%, exergy efficiency is 43.44% and hydrogen produced is 2.83 kg/h, heating value is 350.6 kW. Despite the studies, its operating limitations in low temperature environments limit its effectiveness in recovering waste heat from sources such as industrial exhaust gases and hot flue gases. To overcome these limitations, the integration of organic Rankine cycle technology has been considered. This paper presents a comprehensive analysis of the combined Rankine and organic cycle system for waste heat recovery, with an emphasis on optimizing thermal efficiency.

II. MATERIALS AND METHODS

2.1 Combined Rankine steam and organic Rankine cycles

The schematic diagram of the combined Rankine steam and organic Rankine cycle can be seen in Figure 1. As mentioned earlier, the high-temperature waste gases exiting the gas turbine first enter the vapor Rankine cycle evaporator and after decreasing the temperature, enter the organic Rankine cycle evaporator. This temperature is suitable as the organic cycle actuator, considering the range considered for the gas cycle outlet temperature, the vapor cycle evaporator temperature, and the pinch temperature difference in the vapor cycle evaporator. In this research, 600R fluid is used in the organic Rankine cycle. This fluid has very good environmental properties, is also a dry fluid (has a positive slope in the S-T diagram) and, considering the temperature of the working fluid exiting the steam Rankine cycle and entering the organic Rankine cycle, and assuming that the organic cycle operates under the critical pressure of the working fluid, it has an acceptable performance in increasing the temperature coordination in the organic cycle evaporator (and reducing irreversibility) with a critical temperature of 152 degrees Celsius. Also, in this research, ambient temperature water is used to remove heat in the steam and organic cycle condenser [20-21].

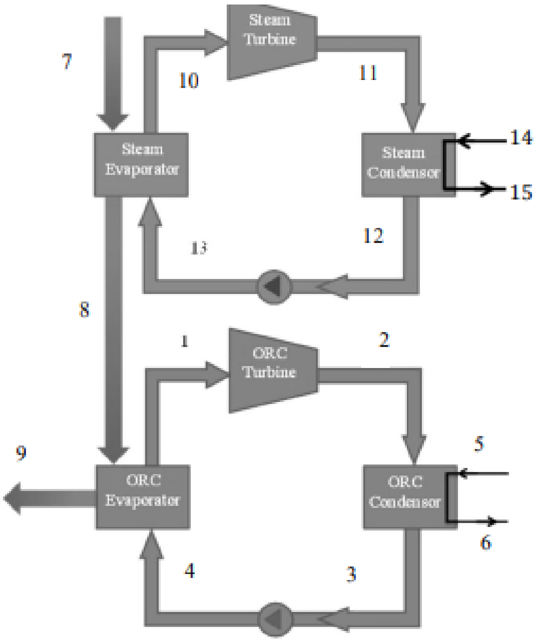

Figure 1: Combined cycle configuration schematic

2.2. Research methodology

In this paper, first, the combined steam and organic Rankine cycles are simulated using EES software and the performance of the combined cycle in the base input state is investigated from the perspective of energy, exergy and exergy-economics. Then, the effect of changing various parameters, including the change in the evaporator and condenser temperature of the organic and steam cycles, etc., on the energy and exergy efficiency, output work, overall irreversibility and exergy-economic parameters is investigated. The proposed combined cycle in this study is modeled from reference [22], with the difference that in the mentioned reference, in order to calculate the required area of heat exchangers in the organic cycle, the simplifying assumption of taking the overall heat transfer coefficient as constant is used, but in this study, the heat exchanger used is simulated using ASPEN EDR software. The developed combined cycle is simulated using Thermoflow software, which is a commercial software in the field of mechanical and power engineering. Then, in order to develop the energetic, exergetic, economic and environmental model, EES and MATLAB software will be used. Also, in the upcoming research, a comprehensive parametric analysis is carried out on the effect of changing various parameters on the performance of the combined cycle. In the following, the governing equations related to the thermodynamic analysis are presented. In order to analyze the thermodynamic system, the mass, energy and exergy balance equations for different components are written according to relations (1) to (3) [23].

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{1}$$

$$\overline{\dot{Q}} + \sum \overline{\dot{m}_i h_i} = \dot{W} + \sum \dot{m}_e h_e \tag{2}$$

$$\dot{E}x_Q + \sum_i \dot{m}_i ex_i = \dot{E}x_w + \sum_e \dot{m}_e ex_e + \dot{E}x_D \qquad 3$$

III. RESULTS AND DISCUSSION

In this section, the results obtained from the simulation are reviewed. The aim of the study is to evaluate the performance of a combined Rankine and organic Rankine cycle for waste heat recovery, focusing on maximizing its thermal efficiency. Comprehensive simulations were conducted under different operating conditions, which resulted in several key performance metrics including thermal efficiency, net power output, and exergy efficiency.

3.1. Mass and energy analysis (thermodynamic)

In all heat recovery cycles, one of the best options is to use the Rankine cycle. With temperatures above 500 °C, the best option for heat recovery is also this cycle. Figure 2 shows the schematic of the heat recovery Rankine cycle. In this cycle, a deaerator is used to prevent air from entering the turbine. An economizer, evaporator, and superheater are also used to produce steam. The steam turbine and condenser also produce and consume power. The temperature and pressure of the working fluid remain below the critical temperature and pressure. In a supercritical Rankine cycle, the pressure of the fluid is increased above the critical pressure and heat addition continues until the critical temperature is exceeded. The heat rejection remains subcritical. Supercritical operation avoids the isothermal part of the heat addition in the subcritical cycle, thereby increasing the average temperature during heat addition and reducing the irreversibility of the heat transfer process. Supercritical Rankine cycles are sometimes referred to as supercritical cycles. Due to the fact that the heat rejection in a Rankine cycle is through condensation from a gas to a liquid, the heat rejection returns the working fluid to the subcritical state. Cycles in which the working fluid remains in the supercritical state during heat rejection are possible with the Brayton cycle. The thermodynamic characteristics of each of the flows are given in Table 1.

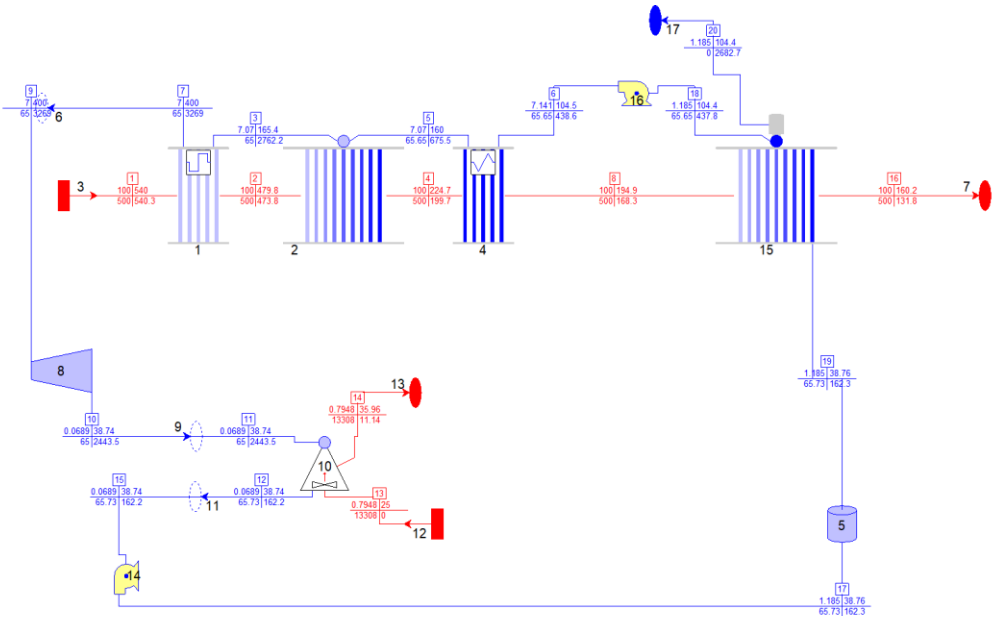

Figure 2: Rankine cycle schematic

Table 1: Thermodynamic characteristics of the Rankine cycle

Stream	Fluid	P	T	M	H*	H
		bar	C	kg/s	kJ/kg	kJ/kg
1 - Outlet of Gas/Air Source [3] -> Gas inlet of Superheater (PCE) [1]	Gas/Air	100.04	540	500	540.28	
2 - Gas outlet of Superheater (PCE) [1] -> Gas inlet of Evaporator (PCE) [2]	Gas/Air	100.02	479.83	500	473.76	

3 - Steam outlet of Evaporator (PCE) [2] -> Steam inlet of Superheater (PCE) [1]	Water	7.07	165.36	65	214.73	2762.22
4 - Gas outlet of Evaporator (PCE) [2] -> Gas inlet of Economiser (PCE) [4]	Gas/Air	100.01	224.67	500	199.74	
5 - Water outlet of Economiser (PCE) [4] -> Water inlet of Evaporator (PCE) [2]	Water	7.07	160	65.65	1872.01	675.48
6 - Discharge of Pump (PCE) [16] -> Water inlet of Economiser (PCE) [4]	Water	7.141	104.54	65.65	2108.86	438.63
7 - Steam outlet of Superheater (PCE) [1] -> Inlet of Water Sink [6]	Water	7	400	65	721.34	3268.83
8 - Gas outlet of Economiser (PCE) [4] -> Gas inlet of Integral Deaerator (PCE) [15]	Gas/Air	100	194.87	500	168.33	
9 - Alternate sink of Water Sink [6] -> Inlet of ST Group [8]	Water	7	400	65	721.34	3268.83
10 - Outlet of ST Group [8] -> Inlet of Water Sink [9]	Water	0.0689	38.74	65	-103.95	2443.54
11 - Alternate sink of Water Sink [9] -> Steam inlet of Air-cooled Condenser [10]	Water	0.0689	38.74	65	-103.95	2443.54
12 - Condensate outlet of Air-cooled Condenser [10] -> Inlet of Water Sink [11]	Water	0.0689	38.74	65.73	-2385.3	162.19
13 - Outlet of Gas/Air Source [12] -> Cooling air inlet of Air-cooled Condenser [10]	Gas/Air	0.7948	25	13307.6	0	
14 - Cooling air outlet of Air-cooled Condenser [10] -> Inlet of Gas/Air Sink [13]	Gas/Air	0.7948	35.96	13307.6	11.14	
15 - Alternate sink of Water Sink [11] -> Suction of Pump (PCE) [14]	Water	0.0689	38.74	65.73	-2385.3	162.19
16 - Gas outlet of Integral Deaerator (PCE) [15] -> Inlet of Gas/Air Sink [7]	Gas/Air	100	160.22	500	131.85	
17 - Discharge of Pump (PCE) [14] -> Inlet of Water Specification [5]	Water	1.185	38.76	65.73	2385.15	162.34
18 - Water outlet of Integral Deaerator (PCE) [15] -> Suction of Pump (PCE) [16]	Water	1.185	104.44	65.65	2109.69	437.8
19 - Outlet of Water Specification [5] -> Water inlet of Integral Deaerator (PCE) [15]	Water	1.185	38.76	65.73	2385.15	162.34
20 - Steam vent of Integral Deaerator (PCE) [15] -> Inlet of Water Sink [17]	Water	1.185	104.44	0	135.22	2682.71

The exhaust temperature of the Rankine cycle deaerator is 160.2°C, which is still far below the acid dew point. Therefore, in order to make optimal use of this heat, a low temperature organic Rankine cycle will be used to utilize the exhaust waste heat as much as possible. The schematic of the organic Rankine cycle is shown in Figure 3.

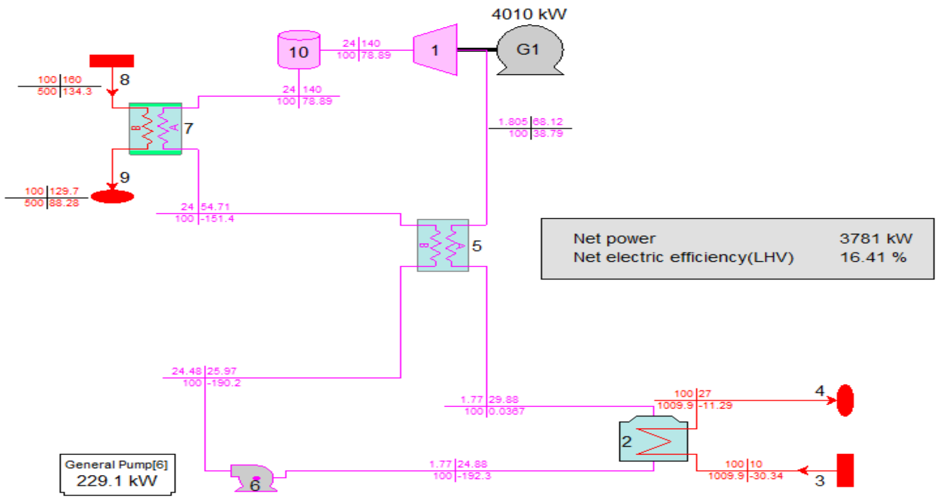

Figure 3: Rankine cycle schematic

The thermodynamic characteristics of the flows in this cycle are as shown in Table 2.

Table 2: Thermodynamic characteristics of organic Rankine cycle flows

Stream	Fluid	P	T	M	H*	H
		bar	C	kg/s	kJ/kg	kJ/kg
1 - Outlet of Gas/Air Source [3] -> Gas inlet of Superheater (PCE) [1]	Gas/Air	100.04	540	500	540.28	
2 - Gas outlet of Superheater (PCE) [1] -> Gas inlet of Evaporator (PCE) [2]	Gas/Air	100.02	479.83	500	473.76	
3 - Steam outlet of Evaporator (PCE) [2] -> Steam inlet of Superheater (PCE) [1]	Water	7.07	165.36	65	214.73	2762.22
4 - Gas outlet of Evaporator (PCE) [2] -> Gas inlet of Economiser (PCE) [4]	Gas/Air	100.01	224.67	500	199.74	
5 - Water outlet of Economiser (PCE) [4] -> Water inlet of Evaporator (PCE) [2]	Water	7.07	160	65.65	-1872.01	675.48
6 - Discharge of Pump (PCE) [16] -> Water inlet of Economiser (PCE) [4]	Water	7.141	104.54	65.65	-2108.86	438.63
7 - Steam outlet of Superheater (PCE) [1] -> Inlet of Water Sink [6]	Water	7	400	65	721.34	3268.83
8 - Gas outlet of Economiser (PCE) [4] -> Gas inlet of Integral Deaerator (PCE) [15]	Gas/Air	100	194.87	500	168.33	
9 - Alternate sink of Water Sink [6] -> Inlet of ST Group [8]	Water	7	400	65	721.34	3268.83
10 - Outlet of ST Group [8] -> Inlet of Water Sink [9]	Water	0.0689	38.74	65	-103.95	2443.54
11 - Alternate sink of Water Sink [9] -> Steam inlet of Air-cooled Condenser [10]	Water	0.0689	38.74	65	-103.95	2443.54
12 - Condensate outlet of Air-cooled Condenser [10] -> Inlet of Water Sink [11]	Water	0.0689	38.74	65.73	-2385.3	162.19
13 - Outlet of Gas/Air Source [12] -> Cooling air inlet of Air-cooled Condenser [10]	Gas/Air	0.7948	25	13307.6	0	

14 - Cooling air outlet of Air-cooled Condenser [10] -> Inlet of Gas/Air Sink [13]	Gas/Air	0.7948	35.96	13307.6	11.14	
15 - Alternate sink of Water Sink [11] -> Suction of Pump (PCE) [14]	Water	0.0689	38.74	65.73	-2385.3	162.19
16 - Gas outlet of Integral Deaerator (PCE) [15] -> Inlet of Gas/Air Sink [7]	Gas/Air	100	160.22	500	131.85	
17 - Discharge of Pump (PCE) [14] -> Inlet of Water Specification [5]	Water	1.185	38.76	65.73	-2385.15	162.34
18 - Water outlet of Integral Deaerator (PCE) [15] -> Suction of Pump (PCE) [16]	Water	1.185	104.44	65.65	-2109.69	437.8
19 - Outlet of Water Specification [5] -> Water inlet of Integral Deaerator (PCE) [15]	Water	1.185	38.76	65.73	-2385.15	162.34
20 - Steam vent of Integral Deaerator (PCE) [15] -> Inlet of Water Sink [17]	Water	1.185	104.44	0	135.22	2682.71

Since the use of waste heat from the exhaust gas leads to power generation, one of the most important output results should be the net power output from each of the cycles. The power output from the elementary Rankine cycle is as shown in Table 3. The net power output is 49.6 MW.

Table 3: Rankine cycle output power

Gross power	[kW]	52540
Net power	[kW]	49607
Total auxiliaries	[kW]	2932.6
Net process heat output	[kW]	0

Also, the consumed and produced micropowers of this cycle are according to Table 4.

Table 4: Power of each Rankine cycle device

Power Devices		
Generator[1] of Steam Turbine[8] power	kW	52540
Air-cooled Condenser[10]: fan	kW	2336
Economiser(PCE)[4]: aux	kW	0
Evaporator(PCE)[2]: aux	kW	0
Integral Deaerator(PCE)[15]: aux	kW	0
Pump(PCE)[14]	kW	11.21
Pump(PCE)[16]	kW	59.98
Specified total misc. auxiliary	kW	525.4
Shaft-1 net power	kW	53510

The highest power output is from the steam turbine and the highest power consumption is from the condenser with about 2.3 MW of power consumption. The power output from the organic Rankine cycle is also as shown in Table 5. In this cycle, the net power output is 3.8 MW.

Table 5: Net power of organic Rankine cycle

HHV	Unit	LHV
Gross power	[kW]	4010
Net power	[kW]	3781

Total auxiliaries	[kW]	229.1
Net process heat output	[kW]	0

The production and consumption power of each equipment is also specified in the organic Rankine cycle according to Table 6.

Table 6: Power of each organic Rankine cycle device

Power Devices		
Generator[1] of Refrigerant Turbine[1] power	kW	4010
General Pump[6]	kW	229.1
Specified total misc. auxiliary	kW	0
Shaft-1 net power	kW	4010

The highest production is from the organic Rankine cycle turbine with 4 megawatts of production power, and the highest consumption is from the cycle pump with about 230 kilowatts of power consumption.

3.2. Exergy analysis

Exergy analysis is used in this study to evaluate the potential performance enhancement of the combined cycle. Exergy, which quantifies the maximum useful work that can be obtained from a thermodynamic system at a given state, is crucial for identifying how energy conversion in the cycle can be controlled and maintained. In this study, the exergy destruction rate and the overall exergy efficiency of the combined cycle are used to highlight areas of improvement and quantify the potential benefit of utilizing waste heat. The results presented in this paper provide a detailed breakdown of exergy flows across the system components, including the heat exchanger, turbine, and condenser. By examining the exergy destruction of each component, inefficiencies arising from irreversible processes, such as friction, heat losses, and non-ideal phase changes in the working fluids, were identified. A comparative analysis between the organic Rankine cycle and the combined cycle demonstrates the advantages of combining organic systems, especially in recovering low-grade waste heat. In this context, this study elucidates how the selection of working fluids with lower boiling points and better thermodynamic properties can significantly increase the exergy efficiency, which in turn increases the overall thermal efficiency of the waste heat recovery system. In addition, this paper discusses the implications of exergy analysis for system design and optimization. The energy flow information of the Rankine cycle is as shown in Table 7.

Table 7: Rankine cycle exergy flow

Stream	Ex_Physical	Ex_Chemical	Ex_total
	kW	kW	kW
1 - Outlet of Gas/Air Source [3] -> Gas inlet of Superheater (PCE) [1]	270140	0	270140
2 - Gas outlet of Superheater (PCE) [1] -> Gas inlet of Evaporator (PCE) [2]	236880	0	236880
3 - Steam outlet of Evaporator (PCE) [2] -> Steam inlet of Superheater (PCE) [1]	179544.3	0	179544.3
4 - Gas outlet of Evaporator (PCE) [2] -> Gas inlet of Economiser (PCE) [4]	99870	0	99870
5 - Water outlet of Economiser (PCE) [4] -> Water inlet of Evaporator (PCE) [2]	44345.262	0	44345.26
6 - Discharge of Pump (PCE) [16] -> Water inlet of Economiser (PCE) [4]	28796.0595	0	28796.06
7 - Steam outlet of Superheater (PCE) [1] -> Inlet of Water Sink [6]	212473.95	0	212474
8 - Gas outlet of Economiser (PCE) [4] -> Gas inlet of Integral Deaerator (PCE) [15]	84165	0	84165
9 - Alternate sink of Water Sink [6] -> Inlet of ST Group [8]	212473.95	0	212474
10 - Outlet of ST Group [8] -> Inlet of Water Sink [9]	158830.1	0	158830.1
11 - Alternate sink of Water Sink [9] -> Steam inlet of Air-cooled Condenser [10]	158830.1	0	158830.1

12 - Condensate outlet of Air-cooled Condenser [10] -> Inlet of Water Sink [11]	10660.7487	0	10660.75
13 - Outlet of Gas/Air Source [12] -> Cooling air inlet of Air-cooled Condenser [10]	0	0	0
14 - Cooling air outlet of Air-cooled Condenser [10] -> Inlet of Gas/Air Sink [13]	148246.664	0	148246.7
15 - Alternate sink of Water Sink [11] -> Suction of Pump (PCE) [14]	10660.7487	0	10660.75
16 - Gas outlet of Integral Deaerator (PCE) [15] -> Inlet of Gas/Air Sink [7]	65925	0	65925
17 - Discharge of Pump (PCE) [14] -> Inlet of Water Specification [5]	10670.6082	0	10670.61
18 - Water outlet of Integral Deaerator (PCE) [15] -> Suction of Pump (PCE) [16]	28741.57	0	28741.57
19 - Outlet of Water Specification [5] -> Water inlet of Integral Deaerator (PCE) [15]	10670.6082	0	10670.61
20 - Steam vent of Integral Deaerator (PCE) [15] -> Inlet of Water Sink [17]	0	0	0

The exergy flow for the organic Rankine cycle is also as shown in Table 8.

Table 8: Organic Rankine cycle exergy flow

Stream	Ex_physical	Ex_chemical	Ex_total
	kW	kW	kW
1 - Outlet of Refrigerant Turbine [1] -> Inlet A of General HX [5]	3879	0	huu/
2 - Outlet of Gas/Air Source [3] -> Coolant inlet of General Condenser [2]	30640.366	0	-30640.4
3 - Coolant outlet of General Condenser [2] -> Inlet of Gas/Air Sink [4]	11401.771	0	11401.8
4 - Outlet A of General HX [5] -> Vapor inlet of General Condenser [2]	4	0	4
5 - Condensate outlet of General Condenser [2] -> Suction of General Pump [6]	19232	0	19232
6 - Discharge of General Pump [6] -> Inlet B of General HX [5]	19020	0	19020
7 - Outlet of Refrigerant Specification [10] -> Inlet of Refrigerant Turbine [1]	7889	0	7889
8 - Outlet of Gas/Air Source [8] -> Inlet B of General HX [7]	67175	0	67175
9 - Outlet B of General HX [7] -> Inlet of Gas/Air Sink [9]	44140	0	44140
10 - Outlet B of General HX [5] -> Inlet A of General HX [7]	15145	0	15145
11 - Outlet A of General HX [7] -> Inlet of Refrigerant Specification [10]	7889	0	7889

Figure 4 shows the exergy efficiency of various Rankine cycle equipment and Figure 5 shows the exergy efficiency of organic Rankine cycle equipment. The highest exergy efficiency in the Rankine cycle is related to the superheater of the steam generation section, which is about 86%, and the highest exergy efficiency in the organic Rankine cycle is related to the reheater of the preheating section, which has an efficiency of 85%. While the overall efficiency of the combined Rankine and organic Rankine cycles is about 80%, the exergy efficiency of this power generation cycle is about 72%, which indicates the exergy destruction of the equipment in this combined system.

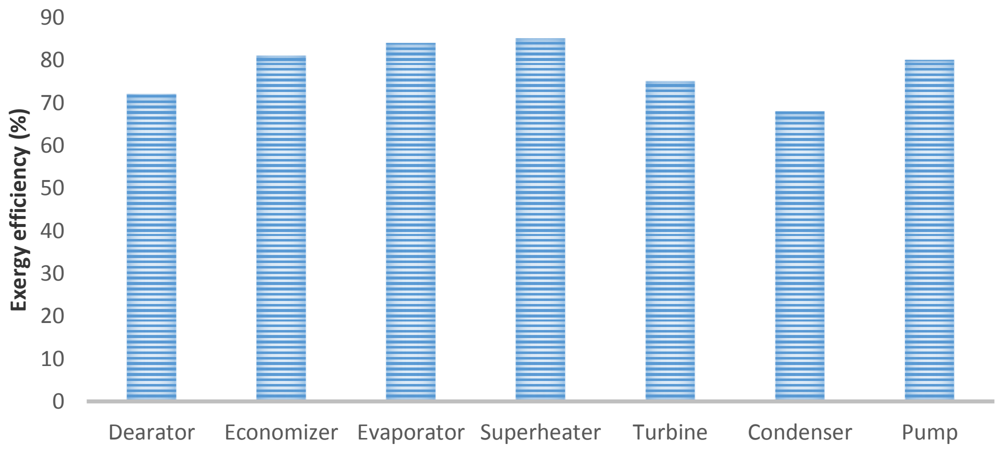

Figure 4: Exergy efficiency of various Rankine cycle equipment

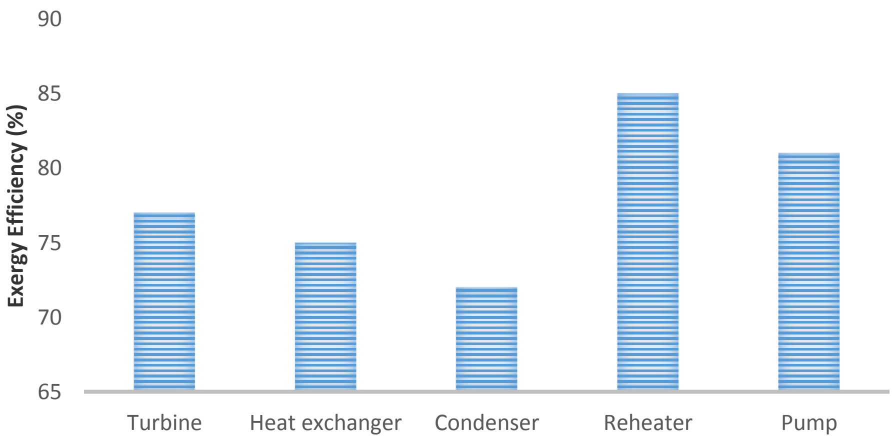

Figure 5: Exergy efficiency of organic Rankine cycle equipment

3.3. Exergy-economic analysis

As mentioned in Chapter 3, in exergy-economic analysis, a series of coefficients are defined for each cycle flow, which are multiplied by the exergy value to calculate the cost per unit time. For each Rankine cycle flow, the values are as shown in Table 9.

Table 9: Exergy-economic cost flow of the Rankine cycle

Stream	Ex_total	c_dot	C_dot
	kW	$/kJ	$/hr
[1]	270140	8.99E-06	2.43E+00
[2]	236880	8.99E-06	2.13E+00
[3]	179544.3	8.85E-06	1.59E+00
[4]	99870	2.99E-06	2.99E-01
[5]	44345.262	5.69E-06	2.52E-01
[6]	28796.0595	1.44E-05	4.15E-01
[7]	212473.95	1.33E-06	2.83E-01
[8]	84165	2.14E-05	1.80E+00
[9]	212473.95	1.45E-06	3.08E-01

[10]	158830.1	7.89E-06	1.25E+00
[11]	158830.1	8.88E-06	1.41E+00
[12]	10660.7487	2.58E-06	2.75E-02
[13]	0	0.00E+00	0.00E+00
[14]	148246.664	2.87E-05	4.25E+00
[15]	10660.7487	1.25E-04	1.33E+00
[16]	65925	8.89E-06	5.86E-01
[17]	10670.6082	8.77E-05	9.36E-01
[18]	28741.57	1.11E-04	3.19E+00
[19]	10670.6082	2.54E-05	2.71E-01
[20]	0	3.56E-04	0.00E+00

In order to calculate the exergy-economic degradation rate of each equipment and the exergy-economic efficiency of each equipment, it is necessary to calculate the cost of each flow and obtain the fuel and product costs of the cycle equipment. The results related to the cost of each flow of the organic Rankine cycle are also as shown in Table 10.

Table 10: Exergy-economic costs of organic Rankine cycle flows

Stream	Ex_total	c_dot	C_dot
	kW	$/kJ	$/hr
[1]	3879	3.79E-06	1.47E-02
[2]	30640.366	3.79E-06	1.16E-01
[3]	11401.771	3.73E-06	4.26E-02
[4]	4	1.26E-06	5.05E-06
[5]	19232	2.40E-06	4.62E-02
[6]	19020	6.08E-06	1.16E-01
[7]	7889	5.61E-07	4.43E-03
[8]	67175	9.03E-06	6.07E-01
[9]	44140	6.12E-07	2.70E-02
[10]	15145	3.33E-06	5.04E-02
[11]	7889	3.75E-06	2.96E-02

The cost of exergy destruction in equipment is a very important parameter in economic exergy analysis. This parameter determines how much of the cycle costs will be accounted for by the exergy destruction in each equipment, given the cost being paid for each flow. Figures 6 and 7 below show the cost of exergy destruction in equipment for the two cycles under consideration.

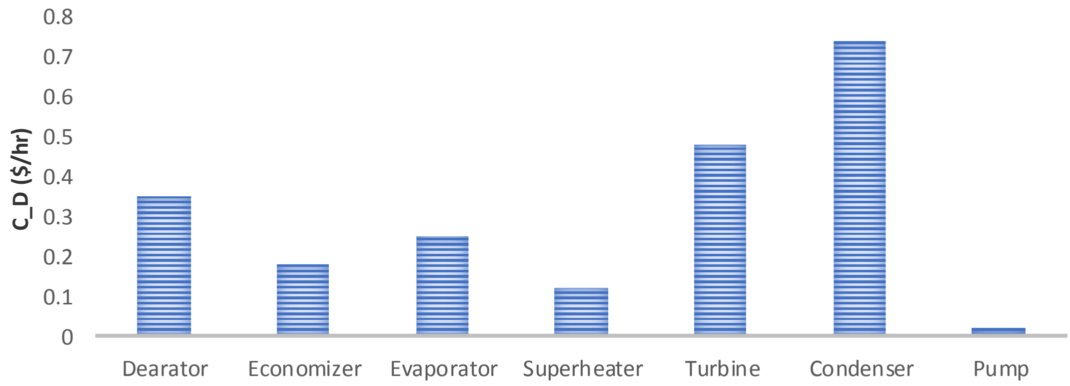

Figure 6: Cost of exergy destruction in the Rankine cycle

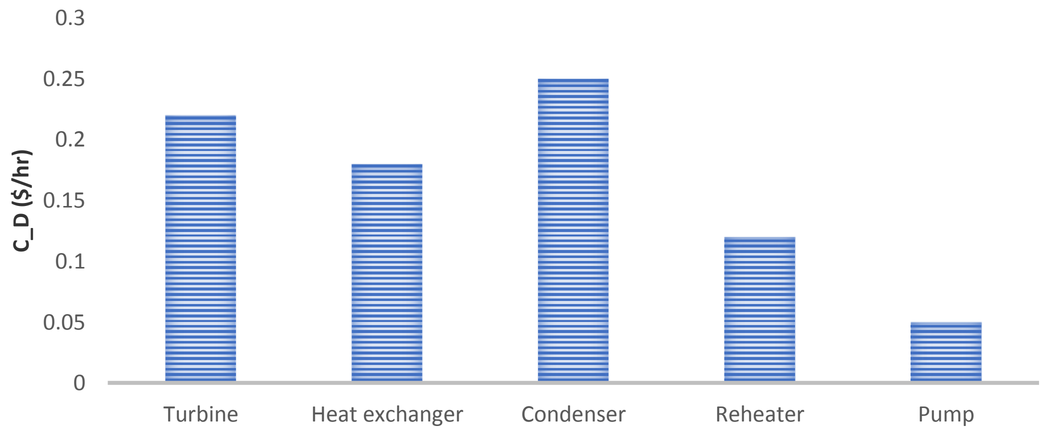

Figure 7: Cost of exergy destruction in organic Rankine cycle

Since there is more than one output exergy of the subsystem, the energy grades of different output exergies are different. Therefore, cost sharing of different output exergies is required. Only based on the ability to quantify the energy quality differences uniformly, multi-energy PIES can be analyzed and evaluated. When the output includes multiple energy sources with different energy grades, for example, a CCHP system produces both high-grade electricity and low-grade cooling and heating energy. The traditional cost sharing method assumes that all output exergies have the same unit economic cost, which cannot reflect the difference in the value of different exergies. For the shortcomings of the traditional cost sharing method, the energy level coefficient method is proposed. In other words, the unit economic cost of output exergies is determined by the energy level coefficient, thus reflecting the difference in exergy quality. However, sharing simply using the energy level coefficient can lead to a significant reduction of low-grade exergies. Therefore, this paper uses the improved energy level coefficient method, which means that the exponential function of the energy level coefficient is used as a parameter to reflect the difference in the quality of the output exergy. Figure 8 shows the economic exergy efficiency of the Rankine cycle equipment and Figure 9 shows the exergy-economic efficiency of the organic Rankine cycle equipment.

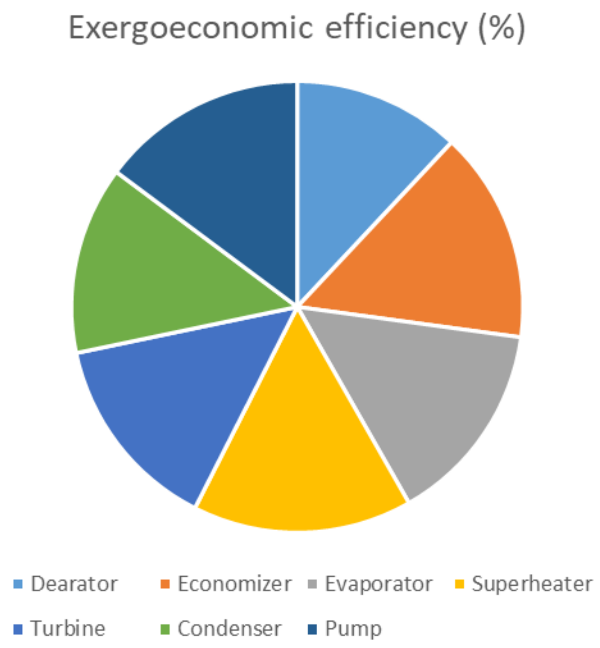

Figure 8: Economic exergy efficiency of Rankine cycle equipment

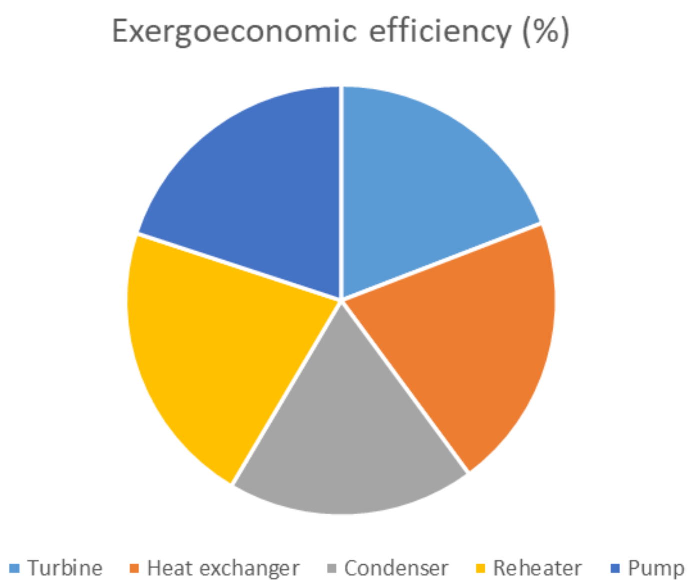

Figure 9: Exergy-economic efficiency of organic Rankine cycle equipment

The Rankine cycle condenser has the highest exergy destruction cost, which is about $0.8 per hour of operation. The organic Rankine cycle condenser also destroys about $0.25 per hour. In terms of economic exergy efficiency, the best performance is seen in the superheater and reheater of the Rankine cycle and the organic Rankine cycle, respectively.

3.4. Environmental exergy analysis

Similar to the economic exergy analysis of heat recovery cycles, an environmental exergy analysis also includes similar parameters. These parameters, which determine the environmental effects, follow the formation of matrices similar to the solution method in the economic exergy analysis process. The results of the environmental exergy coefficients for the Rankine cycle are given in Table 11.

Table 11: Environmental exergy coefficients of Rankine cycle flows

Stream	Ex_total	b_dot	B_dot
	kW	mpts/kJ	mpts/hr
[1]	270140	1.71E-06	4.61E-01
[2]	236880	1.71E-06	4.05E-01
[3]	179544.3	1.68E-06	3.02E-01
[4]	99870	5.68E-07	5.67E-02
[5]	44345.262	1.08E-06	4.79E-02
[6]	28796.0595	2.74E-06	7.88E-02
[7]	212473.95	2.53E-07	5.37E-02
[8]	84165	4.06E-06	3.42E-01
[9]	212473.95	2.75E-07	5.85E-02
[10]	158830.1	1.50E-06	2.38E-01
[11]	158830.1	1.69E-06	2.68E-01
[12]	10660.7487	4.90E-07	5.22E-03
[13]	0	0.00E+00	0.00E+00
[14]	148246.664	5.45E-06	8.08E-01
[15]	10660.7487	2.37E-05	2.53E-01
[16]	65925	1.69E-06	1.11E-01
[17]	10670.6082	1.67E-05	1.78E-01
[18]	28741.57	2.11E-05	6.06E-01
[19]	10670.6082	4.82E-06	5.15E-02
[20]	0	6.76E-05	0.00E+00

The most common power plants that use the Rankine cycle to generate power are coal-fired and gas-fired power plants. The main problem of these power plants is the high emission of pollutants into the environment. Rising fuel prices, strict environmental regulations, and increasing energy demand indicate that these systems need to be improved for sustainable development so that they can generate power in a more efficient, cost-effective, and environmentally friendly way. The most important factor in the development of these power plants is to increase efficiency and reduce emissions and environmental pollutants. To minimize environmental impacts, a major goal is to increase the efficiency of energy conversion processes, thereby reducing fuel consumption and environmental impacts. Exergy methods are of great importance because they are useful for improving efficiency. The relationships between energy, exergy, economics, and the environment make it clear that exergy is directly related to sustainable development. Table 12 shows the environmental pollution levels of organic Rankine cycle streams.

Table 12: Environmental exergy coefficients of organic Rankine cycle flows

Stream	Ex_total	b_dot	B_dot
	kW	mpts/kJ	mpts/hr
[1]	3879	4.22E-07	1.64E-03
[2]	30640.37	4.22E-07	1.29E-02
[3]	11401.77	4.15E-07	4.73E-03

[4]	4	1.40E-07	5.61E-07
[5]	19232	2.67E-07	5.13E-03
[6]	19020	6.75E-07	1.28E-02
[7]	7889	6.24E-08	4.92E-04
[8]	67175	1.00E-06	6.74E-02
[9]	44140	6.80E-08	3.00E-03
[10]	15145	3.70E-07	5.60E-03
[11]	7889	4.16E-07	3.29E-03

By obtaining the environmental impact coefficients of each flow and the amount of environmental degradation of each cycle flow, it is now possible to report the amount of environmental impact of each equipment and the environmental impact resulting from exergy degradation. The amount of environmental degradation resulting from exergy degradation in Rankine cycle equipment is as shown in Figures 10 and 11.

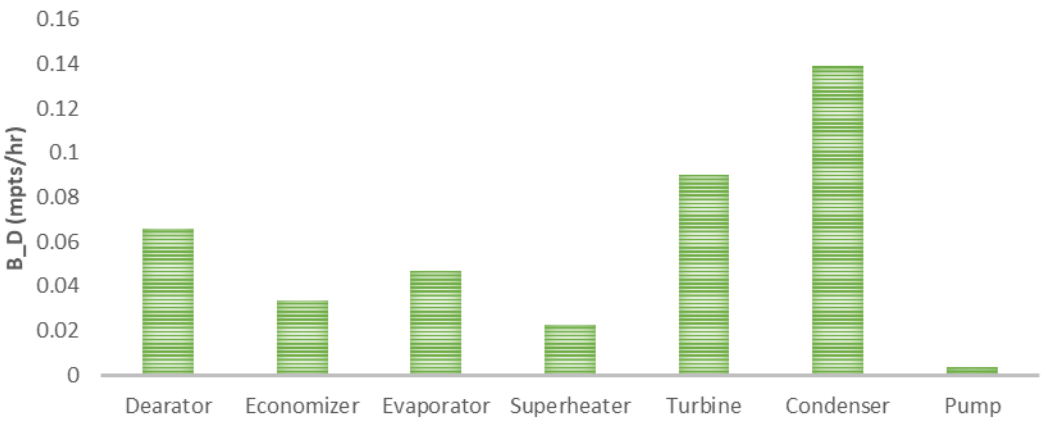

Figure 10: Environmental pollution caused by exergy destruction in the Rankine cycle

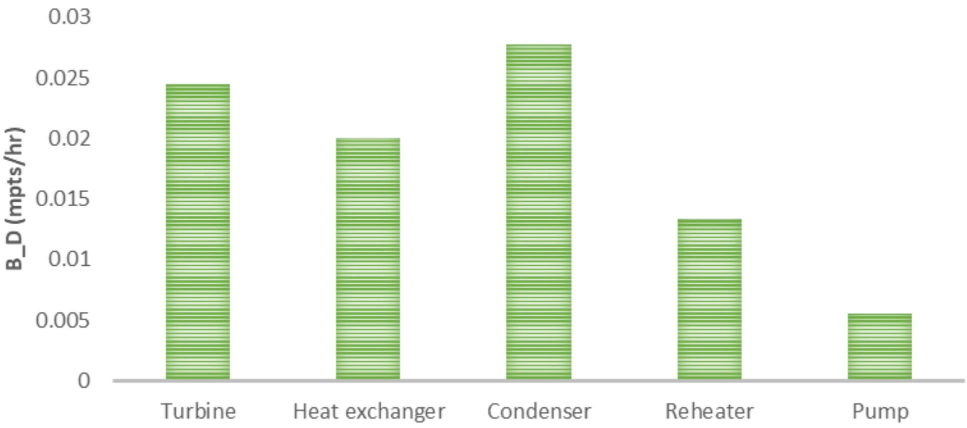

Figure 11: Environmental pollution caused by exergy destruction in the organic Rankine cycle

Given the high exergy destruction in the condenser of both cycles, it is natural that the cost and environmental pollution caused by exergy destruction in these two equipment are higher than in other cycle equipment. Also, turbines have a high cost or environmental pollution rate of the input flow (due to high temperature and pressure), so the more this flow is wasted, the more the cost and pollution caused by exergy destruction in this equipment will increase significantly.

IV. CONCLUSION

In this paper, a combined Rankine cycle system with water and organic Rankine cycle has been investigated. This cycle has been created in order to optimally use the heat wasted in the exhaust. The cogeneration cycle has finally been subjected to technical, energy, exergy, economic and environmental analysis. The detailed design of the heat exchangers and their construction drawings have also been presented. A summary of the important results obtained is as follows.

- The output power of the Rankine cycle is 49.6 MW.
- In the organic Rankine cycle, the net output power is 3.8 MW.
- The highest exergy destruction in both cycles is related to the condenser, in the Rankine cycle condenser the exergy destruction is 3254 kW and in the organic Rankine cycle the exergy destruction is 714 kW.
- The highest exergy efficiency in the Rankine cycle is related to the superheater of the steam generation section, which is about 86%, and the highest exergy efficiency in the organic Rankine cycle is related to the reheater of the preheating section, which has an efficiency of 85%.
- While the overall efficiency of the combined and organic Rankine cycles is about 80%, the exergy efficiency of this power generation cycle is about 72%, which indicates the exergy destruction of the equipment of this combined system.
- The Rankine cycle condenser has the highest exergy destruction cost, which is about $0.8 per hour of operation. An organic Rankine cycle condenser also costs about $0.25 per hour.
- Given the high exergy destruction in the condenser of both cycles, it is natural that the cost and environmental pollution caused by exergy destruction in these two equipment are higher than in other cycle equipment.

REFERENCES

[1]. Farzad, M.A., et al., Energy, exergy analysis and optimization of a cogeneration system based on a plate solid oxide fuel cell for residential application. Structural and Fluid Mechanics, 2015. 5(4): p. 213-228.

[2]. Fathi, H., M.M. Ardehali, and M.A. Fatahi Ardekani, Determination of Optimal Operational Point for a Combined Heat and Power System with Thermal Energy Storage Tank Utilizing Evolutionary Programming Methodology. jiaeee, 2009. 6(1): p. 51-62.

[3]. Assad, M.E.H., et al., Energy and exergy analyses of single flash geothermal power plant at optimum separator temperature. International Journal of Low-Carbon Technologies, 2021. 16(3): p. 873-881.

[4]. Pishkariahmadabad, M., et al., Thermo-economic analysis of working fluids for a ground source heat pump for domestic uses. Case Studies in Thermal Engineering, 2021. 27: p. 101330.

[5]. Fan, G., et al., Energy and exergy and economic (3E) analysis of a two-stage organic Rankine cycle for single flash geothermal power plant exhaust exergy recovery. Case Studies in Thermal Engineering, 2021. 28: p. 101554.

[6]. El Haj Assad, M., et al., Energy, exergy, economic and exergoenvironmental analyses of transcritical CO2 cycle powered by single flash geothermal power plant. International Journal of Low-Carbon Technologies, 2021. 16(4): p. 1504-1518.

[7]. Farrokh Bakht, E. and V. Heibatollahpour, Optimization of Combined Heat and Power Systems using a Hybrid Algorithm of Ant and Bee Colony Optimization. iaud-jeps, 2018. 7(1): p. 17-26.

[8]. Taghinasab, H. and H. Barati, Optimal Operation of CHP Combined Heat Generation Systems Using the Crow Search Optimization Algorithm. iaud-jeps, 2017. 6(1): p. 25-39.

[9]. Optimization of Location, Size and Operation of Various Combined Heat and Power Technologies in Heat and Electricity Distribution Networks. QEER, 2018. 14(57): p. 1-37.

[10]. Shahjouei, M. and A. Taghipour Rezvan, A hybrid model for ranking CCHP systems with regard to sustainability criteria (Case study: Taleghani hospital). NECjournals, 2016. 19(2): p. 1-24.

[11]. Afshari, A., Micro-combined power and heat (mCHP) system with fuel cell. New and Renewable Energy Quarterly, 2014. 1(1): p. 34-43.

[12]. Qorghani, N., et al., Presentation of a solar ORC-VCC cogeneration system for power and cooling, in 10th National Conference on Environment, Energy and Sustainable Natural Resources. 2010, undefined: Tehran.

[13]. Arianfar, Y., et al., Thermodynamic analysis of a two-stage organic Rankine cycle for recovering the refrigeration exergy of liquefied natural gas, in 2nd National Conference on the Development of Civil, Architectural, Electrical and Mechanical Engineering in Iran. 2015, undefined: Gorgan.

[14]. Mousavi Ghasemloui, S.S., P. Jafarmadar, and Y. Arianfar, First and second law analysis of a ternary generation system based on solid oxide fuel cell and organic Rankine cycle, in Fourth National Conference on Mechanical and Aerospace Engineering. 2019, undefined.

[15]. Sanjari, B. and M. Iranmanesh, Investigation of the effect of guaranteed electricity sales and other effective parameters on the application of combined power and heat generation systems in Iranian industries. Modares Mechanical Engineering, 2019. 19(5 #b00838): p. 1221-1227.

[16]. Haj Abdollahi, H. and V. Ghamari, Modeling and technical and economic optimization of hybrid systems for the production of cooling, heat, power and fresh water. Tabriz University Mechanical Engineering, 2022. 51(4): p. 267-276.

[17]. Eftekhari Yazdi, M., N. Qorghani, and Y. Arian Far, Comparative study and thermoeconomic analysis of a solar ORC-VCC triple generation system, in 10th National Conference on Environment, Energy and Sustainable Natural Resources. 2020, undefined: Tehran.

[18]. Peshkari, M., et al., Optimization of a geothermal heat pump cycle to provide cooling for buildings, in New achievements in green studies: calculations, applications and challenges. 2020, undefined: Noor.

[19]. Abdolali Pouradl, M., et al., Energy and exergy analysis of a system based on geothermal energy for simultaneous production of power, fresh water, heating and hydrogen. Mechanical Engineering, University of Tabriz, 2021. 51(3): p. 135-144.

[20]. Yari, M., & Mahmoudi, S. M. S. (2010). Utilization of waste heat from GT-MHR for power generation in organic Rankine cycles. Applied Thermal Engineering, 30(4), 366-375.

[21]. Mohammadkhani, F., Shokati, N., Mahmoudi, S. M. S., Yari, M., & Rosen, M. A. (2014). Exergoeconomic assessment and parametric study of a Gas Turbine-Modular Helium Reactor combined with two Organic Rankine Cycles. Energy, 65, 533-543.

[22]. Javanshir, A., Sarunac, N., & Razzaghpanah, Z. (2017). Thermodynamic analysis of a regenerative organic Rankine cycle using dry fluids. Applied Thermal Engineering, 123, 852-864.
[23]. Bejan, A., Tsatsaronis, G., & Moran, M. (1996). Thermal Design and Optimization John Wiley and Sons. Inc. New York.