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Economic and Exergo-Advance Analysis of a Waste Heat Recovery System Based on Regenerative Organic Rankine Cycle under Organic Fluids with Low Global Warming Potential

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Abstract: The waste heat recovery system (WHRS) is a good alternative to provide a solution to the waste energy emanated in the exhaust gases of the internal combustion engine (ICE). Therefore, it is useful to carry out research to improve the thermal efficiency of the ICE through a WHRS based on the organic Rankine cycle (ORC), since this type of system takes advantage of the heat of the exhaust gases to generate electrical energy. The organic working fluid selection was developed according to environmental criteria, operational parameters, thermodynamic conditions of the gas engine, and investment costs. An economic analysis is presented for the systems operating with three selected working fluids: toluene, acetone, and heptane, considering the main costs involved in the design and operation of the thermal system. Furthermore, an exergo-advanced study is presented on the WHRS based on ORC integrated to the ICE, which is a Jenbacher JMS 612 GS-N of 2 MW power fueled with natural gas. This advanced exergetic analysis allowed us to know the opportunities for improvement of the equipment and the increase in the thermodynamic performance of the ICE. The results show that when using acetone as the organic working fluid, there is a greater tendency of improvement of endogenous character in Pump 2 of around 80%. When using heptane it was manifested that for the turbine there are near to 77% opportunities for improvement, and the use of toluene in the turbine gave a rate of improvement of 70%. Finally, some case studies are presented to study the effect of condensation temperature, the pinch point temperature in the evaporator, and the pressure ratio on the direct, indirect, and fixed investment costs, where the higher investment costs were presented with the acetone, and lower costs when using the toluene as working fluid.

Keywords: economic analysis; exergo-advanced study; internal combustion engine; organic Rankine cycle; waste heat recovery

1. Introduction

In the past few years, developed countries have shown interest in the possibility of reducing carbon dioxide emissions, which has been brought about by the rational use of energy, and the drive to decrease the energy consumption generated through fossil fuels [1]. The Climate Change Convention in 2009 set the limit to 2 °C growth in the global average surface temperature, and based on the Intergovernmental Panel on Climate Change, warming of more than two degrees would be catastrophic for both humans and nature [2].

The main factor responsible for the enhancement in surface global average temperature is the high atmospheric concentration of Greenhouse Gases (GHGs). At the current growth rate of these gases, there is at least a 77% chance that the growth in average global temperature will exceed 2 °C by 2035. From the gases cited in the Kyoto Protocol as GHGs, carbon dioxide (CO_2) accounts for three quarters, and more than 90% of it originates from the energy transformations that occur in means of transport, industry, and residences. However, today there is no viable technology capable of absorbing CO_2 emissions [3].

The only way to limit it is through the efficient use of energy in the energy generation systems, and the increase of the green mass of the planet [4]. Two different methodologies have been proposed to promote rational energy use through the WHRS to increase the energy efficiency of combustion engine systems [5].

Since a century ago, when the first gasoline engines were produced, the thermal efficiency of the internal combustion engine (ICE) have reached their maximum values, and the energy is still not fully used, because around 65% is a loss to the atmosphere using heat [6]. Therefore, increasing engine efficiency through WHRSs will lead to a reduction of carbon dioxide emissions, which would reduce the negative impact on the environment through bottoming cycles based on the organic Rankine cycle (ORC) [7].

Gas engines for power generation have become a high impact alternative for global energy decentralization, which is expected to have an even more significant presence in the industry, due to their high power densities, high efficiencies and low emissions, as well as a high degree of availability [8].

Natural gas is a successful fuel in replacing conventional liquid fuels such as diesel and gasoline worldwide, since it can be extracted from large fossil fuel reserves [9]. Thus, natural gas engines are an attractive option to current diesel engine technology in industrial applications due to the price of the fuel, and a growing gas distribution network worldwide [10]. However, the operating and design conditions of the integrated engine system with a WHRS configuration must be determined to allow the adoption of these systems in practical applications at competitive costs in respect to renewable energies [11].

The use of an ORC system has several advantages, such as high reliability and easy maintenance, making it a cost-effective system for transforming waste heat from various sources into useful energy [11]. Among the energy sources that have been studied for WHRS based on the ORC system, are the solar radiation [12], geothermal energy [13], the biomass combustion [14], and the energy source evaluated in this research, which is the waste heat of industrial engines [15].

The ORC uses an organic working fluid such as hydrocarbons and refrigerants, which have better performance than water, allowing to reduce the heat source temperature [16]. However, due to the high contamination rates, environmental protection has been chosen as the main criterion, and numerous investigations report the negative impact on the atmosphere of the chlorofluorocarbon (CFC), which makes the selection of the working fluid for the ORC a complex task [17]. Therefore, different methods have been established in ICE to achieve greater energy efficiency with less environmental impact such as waste to energy technologies based on the ORC cycle operating with environmentally friendly fluids [18]. Thus, better efficiency in the Jenbacher gas engine JMS 612 GS-N.L, can be achieved by waste heat recovery using the ORC [19]. However, this arrangement requires a secondary coupling circuit for indirect evaporation, in which the waste heat is used to heat the organic fluid indirectly by first transferring the heat to a thermal oil, which is then used to evaporate the organic fluid.

Additionally, it has been very helpful to introduce working fluids with a lower rate of pollution, which is measured with a low Global Warming Potential (GWP) [20]. Therefore, Toffolo et al. [21] oriented its research towards the economic profitability that can be obtained through the choice of an organic working fluid and the adjustment of operational parameters in the ORC system. In this study, the selection of the cycle configuration was developed attending to several criteria together: an original thermodynamic optimization technique of the process, and the design factors that examine all achievable configurations, the design selections about the best values of the objective function, the economic modeling procedure proved on valid cost data and the contemplation of out-of-design behavior. Then, the use of the regenerative organic Rankine cycle (RORC) increases cycle efficiency by 9.29% over the simple ORC cycle [22]. In environmental aspects, the use and choice of the organic fluid are limited due to the environmental impact involved. For this reason, Suarez et al. [23] evaluated the reduction of emissions in tons that can be generated by the working fluid in one year of operation, which obtained that benzene delivers the greatest reduction of emissions with a value of 849 tons after one year of operation, followed by heptane with 809 tons of carbon dioxide. The other important aspect is to explore about fluids that can work with the high temperatures of engine exhaust gases and offer good thermal performance. Therefore, the residual thermal energy availability must be considered for organic fluid selection [24]. Thus, toluene is a high critical temperature or high boiling point fluid that is used in heat sources with temperatures around 300 °C, higher than the refrigerants that normally work at low temperatures, below 200 °C, such as R227ea, R123, R245FA and HFE7000 [16]. In addition, the toluene was used in an ORC system with a recuperator, which improves operative performance by getting a power of 146.45 kW, and a reduction in s fuel feeding of 7.67% at 1482 rpm [25].

On the other hand, Zare V. [26] evaluated the economic behavior of different ORC configurations, where the ORC presents better results. The economic analysis was proposed as a methodology for designing a cost-effective WHRS to determine total investment capital, maintenance, and operating costs. When the equipment costs are not determined, but nominal details are accessible, they could be computed using a percentage of the total equipment cost. Bejan et al. [27], Smith [28], and Towler [29] propose a correlation and cost orientation for many kinds of equipment.

To increase the productivity of the WHRS based on ORC, normally, a regenerator is added, which achieves a 5% increase in efficiency, thus leading to an increase in power output [30]. Similarly, to increase performance, the components with the greatest irreversibilities in the system are identified using traditional exergetic analysis. However, this analysis does not allow to determine opportunities for improvements in the system [31]. Thus, the implementation of the advanced exergetic analysis in these cases allows obtaining opportunities for improvement in a specific component or the interaction of this one on the system, providing data on the exergy destruction portion that can be avoided [32].

Therefore, the main objective of this study is to determine the components with the greatest irreversibility in a WHRS based on a RORC, through the use of three organic working fluids: acetone, heptane, and toluene. The components that have the greatest opportunity for improvement are identified through advanced exergetic analysis, and changes in capital investment cost rates are identified by varying the pressure ratio, condensing temperature, and evaporator pinch point. Thus, this study is based on a specific gas engine application widely used worldwide so that realistic results of the economic viability of the WHRS are obtained. Furthermore, the results are expected to contribute useful information applicable to other engines to achieve economically viable solutions.

2. Methodology

2.1. Description of the System

The system under study is integrated by an internal combustion engine that uses natural gas as fuel (Jenbacher JMS 612 GS-N) and RORC as a bottoming cycle, as shown in Figure 1. The engine operates with a volumetric flow of 120 L/min, a pressure of 1163.6 mbar in island mode at 1482 rpm. Exhaust gases (St 1–St 2) come out of the industrial engine, which is used to transfer heat to the thermal oil cycle through the heat exchanger (HXC 1), which is a shell and tube heat exchanger designed to ensure the back pressure required to the engine. Then, the thermal oil (Therminol 75) received the heat to circulates through the thermal oil circuit and enters the evaporator (St 3), which consists of three zones; the first preheating, the second evaporation and the third overheating. Then, the fluid enters the compression stage, which causes a pressure increase using Pump 1 in the state 5 (St 5).

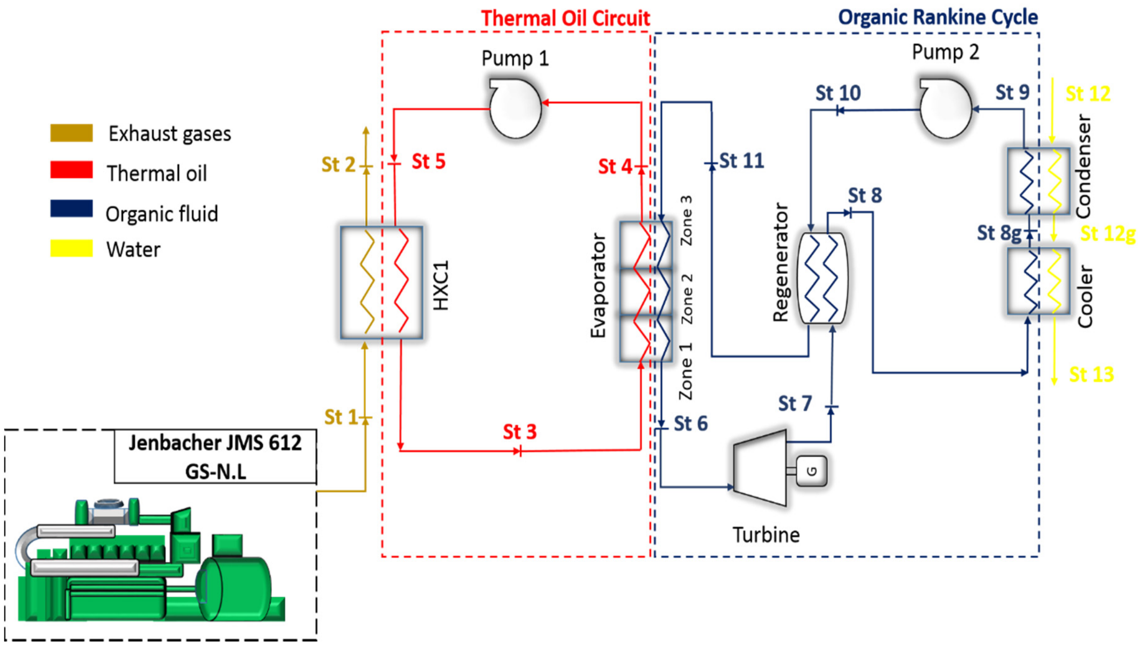

Figure 1. Schematic diagram of the Jenbacher JMS engine integration to the thermal oil cycle configuration and organic Rankine cycle.

The objective of the thermal circuit is to achieve thermal stabilization of the organic fluid and prevent it from exceeding its critical temperature. The organic fluid in the RORC receives the heat from the thermal oil by means of an evaporator and starts entering the turbine (St 6) where an expansion of the organic fluid occurs, and the temperature decreases considerably to enter the regenerator (St 7), where a heat exchange takes place, and later it enters the cooler and condenser (St 8–St 9) where the lowest temperature of the organic fluid in the RORC system is achieved. Then, the fluid enters in Pump 2 in a compression stage and increases of temperature and pressure (St 10), and finally, the regenerator enters again to go to the evaporator and thus to complete the RORC cycle. Figure 1 shows the schematic configuration of the suggested system under study.

2.2. Thermodynamics Analysis

Taking into account the mass conservation law and the steady-state consideration assumed to all components of the WHRS based on RORC, mass (Equation (1)), and energy (Equation (2)) conservation laws were applied:

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = 0 \tag{1}$$

$$\sum \dot{m}_{in}.\, h_{in} - \sum \dot{m}_{out}.\, h_{out} - \sum \dot{Q} + \sum \dot{W} = 0 \tag{2}$$

Exergetic analysis based on the exergy balance (Equation (3)) is described by the second law of thermodynamics as a function of the environmental conditions, in which the system under study operates. The exergy destruction ratio (ϕ_d) is a function of the mass flow rate and the generation of specific entropy ($\dot{S}_{gen}$).

$$\phi_{d,k} = \sum_{in}^{n} \dot{m}_{ex} - \sum_{out}^{n} \dot{m}_{ex} - \phi_{\text{in}} - \phi_{\text{out}} = T_0 \dot{S}_{gen} \tag{3}$$

where ϕ_{in} and ϕ_{out} are the exergy of heat input and work output. The calculation of the flow exergy (Ψ) is done by means of Equation (4).

$$\Psi = (h_i - h_0) - T_0 \cdot (s_i - s_0) \tag{4}$$

where h is the enthalpy, s is the entropy, and the sub-index zero indicates the property is in a dead state at reference temperature (T_0). The definition of input-output is applied to traditional exergetic analysis, where the input is the amount of exergy that enters a component to produce an amount of product. Similarly, the product is defined as the amount of exergy left by a component converted by the input that previously entered the same component. For the specific case of the component under study k, the exergy of input, output, and destruction is given by Equation (5).

$$\phi_{F,k} = \phi_{P,k} + \phi_{d,k} \tag{5}$$

Table 1 shows in detail the exergy balance by components, where the term ($\phi_{d,\ evap}$), ($\dot{\phi}_{d,\ turb}$), ($\dot{\phi}_{d,pum}$), and ($\dot{\phi}_{d,cond}$) represents the destroyed exergy of the evaporator, turbine, pump, and condenser, respectively.

Table 1. Exergy balance applied to each component.

Component	Exergy Balance
Evaporator	$\left(1-\frac{T_0}{T_{in}}\right)\cdot Q_{in} + \phi_{in} = \phi_{out} + \phi_{d,\ evap}$
Turbine	$\phi_{in} = \phi_{out} + \phi_{turb} + \phi_{d,\ turb}$
Pump	$\dot{w}_p + \phi_{in} = \phi_{out} + \phi_{d,pum}$
Condenser	$\phi_{in} = \phi_{out} + \phi_{d,cond}$

The ratio of the exergy rate ($Y^*{}_{D,k}$), which describes the percentage of exergy destroyed that the component generates relative to the rest of the RORC components, is defined by Equation (6).

$$Y^*{}_{D,k} = \frac{\phi_{d,k}}{\sum \phi_{d,k}} \tag{6}$$

With the data obtained, the exergetic efficiency (ε_k) of each equipment can be estimated as described in Equation (7).

$$\varepsilon_k = \frac{\phi_{P,k}}{\phi_{F,k}} \tag{7}$$

2.3. Advanced Exergetic Analysis

The advanced exergetic analysis allows investigating in more detail the reason the exergy destruction, with the purpose of observing the improvement opportunities that each component in the system has. As shown in Figure 2, the exergy destroyed endogenously ($\phi_{D,k}^{EN}$) is the one that produces the same component (k) that is being analyzed without taking into account its interaction with the environment.

However, there is another type of exogenous destruction called exogenous ($\phi_{D,k}^{EX}$), which is defined as that caused by the irreversibilities of the other components. This is the distinction between the exogenous destruction of the equipment ($\phi_{d,k}$), and the endogenous portion ($\phi_{D,k}^{EN}$), as shown in Figure 2.

Both endogenous and exogenous exergy destruction can be divided as inevitable ($\phi_{D,k}^{UNA}$) and evitable ($\phi_{D,k}^{AVA}$), respectively. The unavoidable part refers to the destruction of exergy that does not decrease due to the technological and physical limitations of the component under study; and conversely, the avoidable part refers to the opportunities for improvement in the components. Table 2 shows the equations of the advanced exergetic analysis, where the Exergy Destruction Equations ($\phi_{d,k}$), taking into account the endogenous and exogenous, avoidable/unavoidable part is presented.

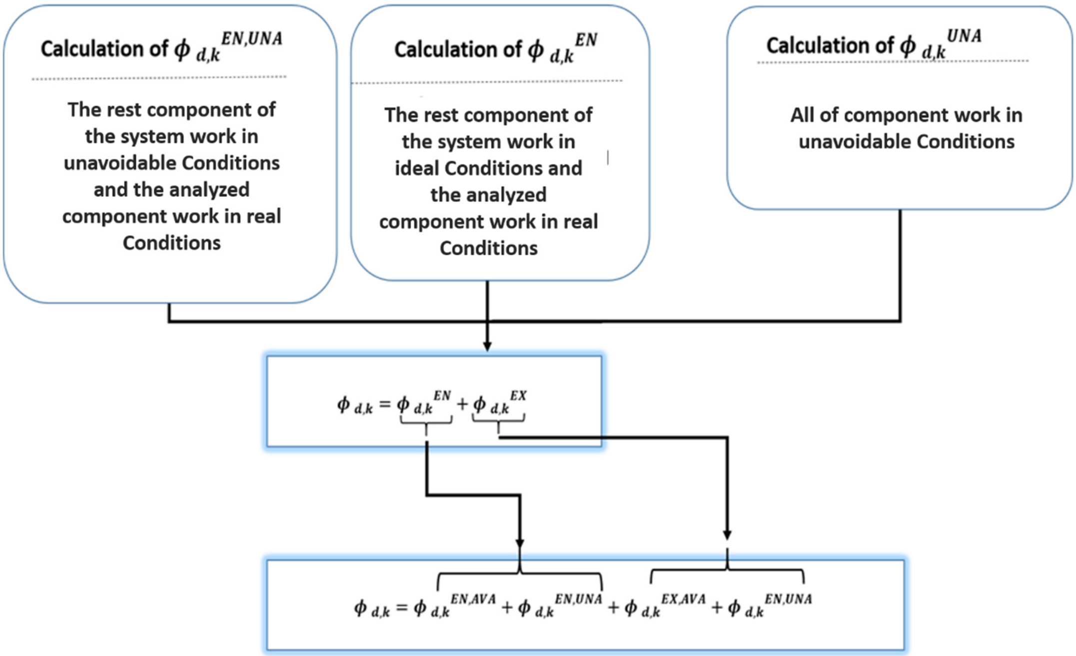

Figure 2. Outline of advanced exergetic analysis.

Table 2. Equations of advanced exergetic analysis.

Unavoidable exergy destruction	
$\phi_{D,k}^{UNA} = \phi_{P,k} \cdot \left(\frac{\phi_{d,k}}{\phi_{P,k}}\right)^{UNA}$	(8)
Avoidable exergy destruction	
$\phi_{D,k}^{AVA} = \phi_{D,k} - \phi_{D,k}^{UN}$	(9)
Unavoidable endogenous exergy destruction	
$\phi_{D,k}^{EN,UNA} = \phi_{D,k}^{EN} \cdot \left(\frac{\phi_{D,k}}{\phi_{P,k}}\right)^{UNA} = \phi_{D,k}^{UNA} \cdot \left(\frac{\phi_{D,k}}{\phi_{P,k}}\right)^{EN}$	(10)
Avoidable endogenous exergy destruction	
$\phi_{D,k}^{EN,AVA} = \phi_{D,k}^{EN} - \phi_{D,k}^{EN,UNA}$	(11)
Avoidable exogenous exergy destruction	
$\phi_{D,k}^{EX,\ AVA} = \phi_{D,k}^{AVA} - \phi_{D,k}^{EN,AVA}$	(12)
Unavoidable exogenous exergy destruction	
$\phi_{D,k}^{EX,\ UNA} = \phi_{D,k}^{UNA} - \phi_{D,k}^{EN,UNA}$	(13)

In this study the advanced exergetic analysis has been selected for the study of the WHRS based on ORC in order to obtain complementary information to the traditional exergetic analysis, that is useful to understand better the operation of the system, besides proposing improvements from the operational and design point of view of this thermal system that at the present time has not been widely studied nor installed at world-wide level in real contexts of operation coupled to a natural gas generation engine. The results obtained with this approach cannot be obtained by any other method of analysis. However, among the limitations of the advanced exergetic analysis developed in this study, are the subjectivities involved in the calculation of the destruction of avoidable exergy and the criteria used to define the operating conditions of the ideal process, in addition to the significant amount of calculations that must be made to obtain the component of exergy that destroys avoidable endogenous exergy and the component of exergy that destroys avoidable exogenous exergy for the equipment used in the process.

2.4. Economic Analysis

For RORC systems, total production cost (*TPC*) analysis involves the total capital to be provided (*TCI*) and the maintenance and operating costs (O&M), which is calculated by Equation (14).

$$TPC = TCI + \text{O\&M} \tag{14}$$

Equation (15) represents the total capital to be provided (*TCI*) in the WHRS based on ORC and is shown below [33].

$$TCI = FCI + OC \tag{15}$$

where (*FCI*) refers to the investment of fixed assets of the thermal process, which is a sum of the direct costs (*DFCI*) and the indirect costs (*IFCI*), as indicated the Equation (16).

$$FCI = DFCI + IFCI \tag{16}$$

The other costs (*OC*) are estimated with Equation (17), as follows.

$$OC = SUC + WC + LRD + AFUDC \tag{17}$$

where are included the start-up costs (*SUC*), the cost to place the equipment into operation, the initial working capital (*WC*) of the thermal system, the cost associated with development and research (*LRD*), and the costs related to the provision of funds during construction (*AFUDC*).

Direct costs are the expenses that correspond to the purchase of equipment, pipes, the instrumentation, the installation and assembly, and electrical components and materials related to the civil work system and work area. Equations (18) to (20) were used to estimate the acquisition cost of the devices. In this case, correlations were used for each of the equipment in terms of its energy, as is the case for the turbine and pump, and in terms of the heat transfer area, which collect data from constructers and calculate the costs. For the turbine, the costs were estimated by means of Equation (18) [18,26].

$$Log_{10}Z = 2.6259 + 1.4398 \cdot Log_{10}\dot{w}_t - 0.1776 \cdot \left(Log_{10}\dot{w}_t\right)^2 \tag{18}$$

Similarly, Equation (19) represents the costs for the heat exchanger, and Equation (20) calculates the costs for the pump [26,27].

$$Z = 1000 + 324 \cdot \left(A^{0.91}\right) \tag{19}$$

$$Log_{10}Z = 3.3892 + 0.0536 \cdot Log_{10}\dot{w}_p - 0.1538 \cdot \left(Log_{10}\dot{w}_t\right)^2 \tag{20}$$

Table 3 represents a description of the associated direct costs and some considerations for the proposed economic model.

Table 3. Description of associated direct costs.

Direct Cost Description	Reference
Installation and assembly: these costs are those related to the transportation and nationalization of the equipment, including the costs generated by the working fluids for the start-up and the thermal cycle.	[33]
Piping and accessories: these represent the total investment required in the project development time used directly in the system. It has as a reference 20%–90% of the equipment acquisition cost.	[33]
Instrumentation and control: to generate the most optimal operation of the system, sensors, and components that allow the control and monitoring of the plant are required. It has a reference between 6%–20% of the acquisition cost of the equipment.	[34]
Civil work: it is related to the conditioning of the working environment, of the components, due to the handling of high temperatures. It has as a reference 20%–90% of the equipment acquisition cost.	[33]
Electrical equipment and materials: this cost is related to materials and installation of power distribution lines and required connections, as well as control centers and emergency failure equipment. It handles 10%–15% of the cost of equipment acquisition.	[33]
Work area: this cost varies concerning geographic location but is estimated to be no more than one-tenth of the acquisition cost of the equipment.	[33]

3. Results and Discussions

3.1. Base Operating Conditions for Cycle RORC

For the RORC system in this study, the following baseline condition shown in Table 4 was taken into account. These considerations were applied to the system operating with acetone, heptane, and toluene.

Table 4. Base condition parameters for a regenerative organic Rankine cycle (RORC) system.

Parameters	Values	Unit	Parameters	Values	Unit
Cooling temperature	50	°C	Hours of operation per year	7446	h
Pinch point Evaporator	100	°C	Turbine isentropic efficiency	80	%
Pinch point Condenser	15	°C	Pumps isentropic efficiency	75	%
Exhaust gas temperature	435.07	°C	Regenerator effectiveness	85	%
Outlet gas temperature	270	°C	Pressure ratio Pump 2	4	
Pressure ratio Pump 1	2.5		Fuel mass flow	9986.04	kg/h
Ambient temperature	30	°C	Ambient pressure	101.3	kPa

According to the above values, the pinch point condenser is 15 °C, so the condensation temperature is 65 °C. From the base condition parameters, the thermodynamic properties shown in Table 5 for each working fluid were calculated from the thermodynamic model of the RORC system.

Table 5. Thermodynamic properties of the waste heat recovery system (WHRS) system based on RORC system for acetone as working fluid.

Fluid	State	Temp [K]	Pressure [kPa]	Enthalpy [kJ/kg]	Entropy (S-S0) [kJ/kg K]	Exergy [kW]
Acetone	3 ORC	338.15	136.21	20.04	0.24	3.77
	4 ORC	338.36	544.84	20.78	0.24	4.28
	4 ORCr	383.78	544.84	127.10	0.53	19.51
	4f ORC	388.64	544.84	139.01	0.56	21.81
	4g ORC	388.64	544.84	566.49	1.66	106.02
	1 ORC	460.42	544.84	702.50	1.98	140.57
	2 ORC	415.22	136.21	636.91	2.02	70.99
	2 ORCr	350.00	136.21	530.58	1.74	51.35
	2g ORC	338.15	136.21	511.47	1.69	49.32
	3 ORC	338.15	136.21	20.04	0.24	3.77

Based on the exergy values found in Table 5 for each state of the RORC system, using the above-mentioned fluids and exergy balance were made for each component, from which different exergy values for input, output, and loss are shown in Table 6, using acetone as the working fluid [35,36]. The exergy values using heptane and toluene are found in Table A2 on Appendix A.

Table 6. Exergy analysis for each component of the WHRS system based on the RORC system using acetone.

Fluid	Components	ϕ_F [kW]	ϕ_P [kW]	ϕ_D [kW]	ϕ_L [kW]	ε_k	$Y_{D,k}$
Acetone	HXC 1	541.20	191.63	53.11	296.45	35.40	0.3419
	Pump 1	0.38	0.04	0.34	-	10.83	0.0021
	Turbine	69.57	58.73	10.84	-	84.40	0.0698
	Evaporator	191.67	136.29	70.61	-	71.10	0.4545
	Pump 2	0.66	0.51	0.14	-	77.5993	0.0009
	Regenerator	19.54	15.23	4.41	-	77.5457	0.0283
	Condenser	-	-	15.87	87.3083	-	0.1021

3.2. Results of Traditional and Advanced Exergetic Analysis

Using Equation (3), the fraction of exergy destroyed for each organic fluid in each component could be determined and is presented in Figure 3.

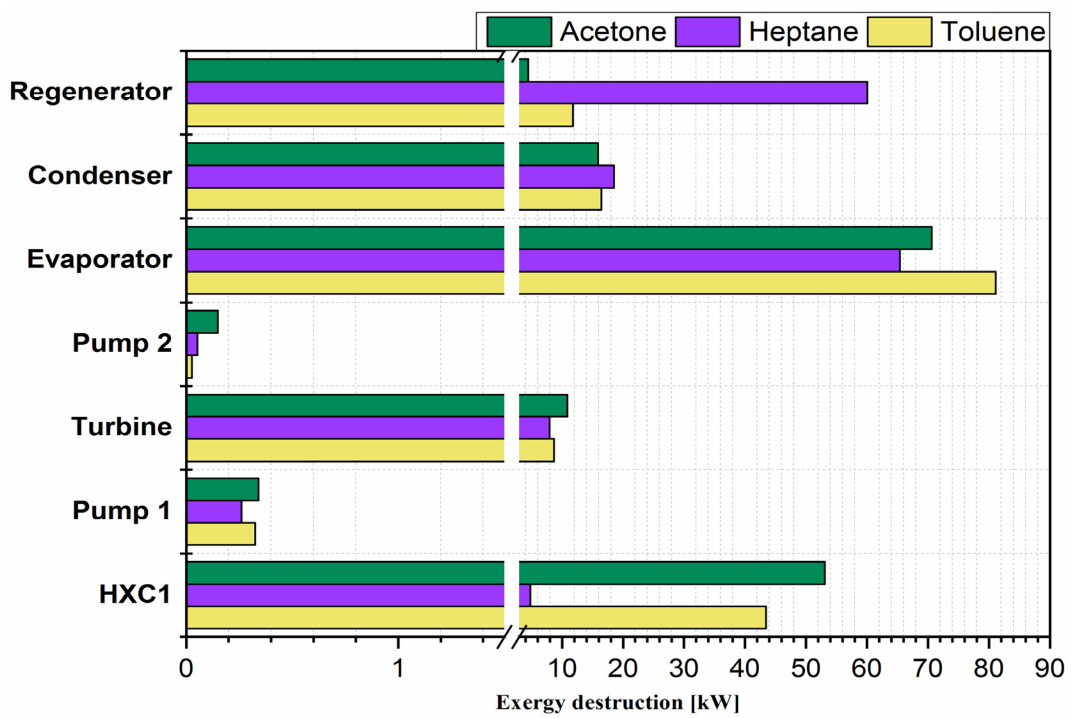

Figure 3. Fraction of exergy destroyed per component.

It should be noted that higher exergy destruction above 70 kW is observed in the HXC 1 evaporator and heat exchanger when using toluene and acetone as working fluid. In a different case, the highest exergy destruction for heptane was above 53 kW in the evaporator and regenerator. Due to these exergy destruction values, we can obtain a significant reduction in the exergy destroyed from the cycle if any technological/operational improvement of these components is carried out. However, the real improvement opportunities will be analyzed using advanced exergetic analysis.

By means of the advanced exergetic analysis, an analysis was made for each of the components to know the exergy that is destroyed by its very nature, operating conditions, and interaction with other components. In this way, through the interception of the inclined line with ϕ_F-ϕ_P-ϕ_L there is the endogenous exergy, which must be greater than zero and less than the exergy destroyed ϕ_D for each component of the RORC system using acetone as the working fluid as shown in Figure 4a), in which the inclined line represents the regression of the four experimental runs is intercepted at point 0.33 of the vertical axis for Pump 1. Likewise, in Figure 4b), the interception with point 0.12 is shown for Pump 2, in Figure 4c); it is intercepted at point 2.92 for the condenser. Additionally, in Figure 4d, the intercept in point 23.22 for the experimental runs made in the evaporator, and in Figure 4e–f, the intercepts of 4.20 and 4.74 are reported for the study conducted in the regenerator and turbine, respectively. For the previous intercepts, it was taken into account that each value was lower than the traditional exergy destruction of each component. For more detail on endogenous exergy using heptane and toluene fluids, see Figures A1 and A2 in Appendix B.

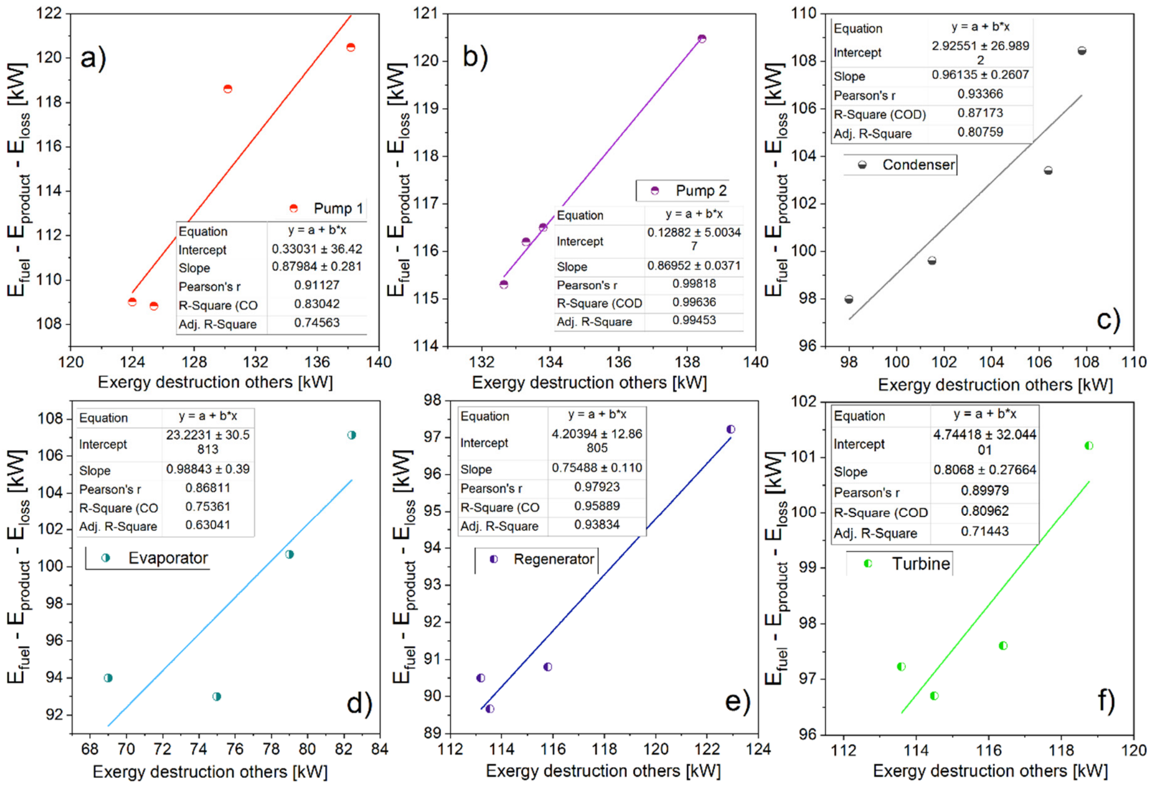

Figure 4. Endogenous destruction of exergy of acetone (**a**) Pump 1, (**b**) Pump 2, (**c**) condenser, (**d**) evaporator, (**e**) regenerator, and (**f**) turbine.

Based on the basic and unavoidable operating conditions, the corresponding studies were carried out for the implementation of the advanced exergetic analysis. These values are shown in Table 7.

Table 7. Actual and unavoidable operating conditions for each component [37,38].

Components/Parameter	Real	Unavoidable
r_p	4	10
Turbine	$\eta_{iso} = 0.8$	$\eta_{iso} = 0.95$
Pumps	$\eta_{iso} = 0.75$	$\eta_{iso} = 0.95$
Condenser	$\Delta T_{min} = 15$ $\Delta P = 1\%$	$\Delta T_{min} = 5$ $\Delta P = 0.5\%$
Evaporator	$\Delta T_{min} = 100$ $\Delta P = 2\%$	$\Delta T_{min} = 95$ $\Delta P = 1\%$

Taking into account the values of the operational conditions indicated in Table 7, the equations described in Section 2.3 were developed where the exergy destroyed is divided into endogenous/exogenous, avoidable/inevitable of each component for each fluid, except the capacitor that functions as a heat sink. Figure 5 shows the different destruction fractions of exogenous avoidable (EX, AVA), endogenous avoidable (EN, AVA), exogenous unavoidable (EX, UNA), and endogenous unavoidable (EN, UNA) exergy for each component of the RORC system.

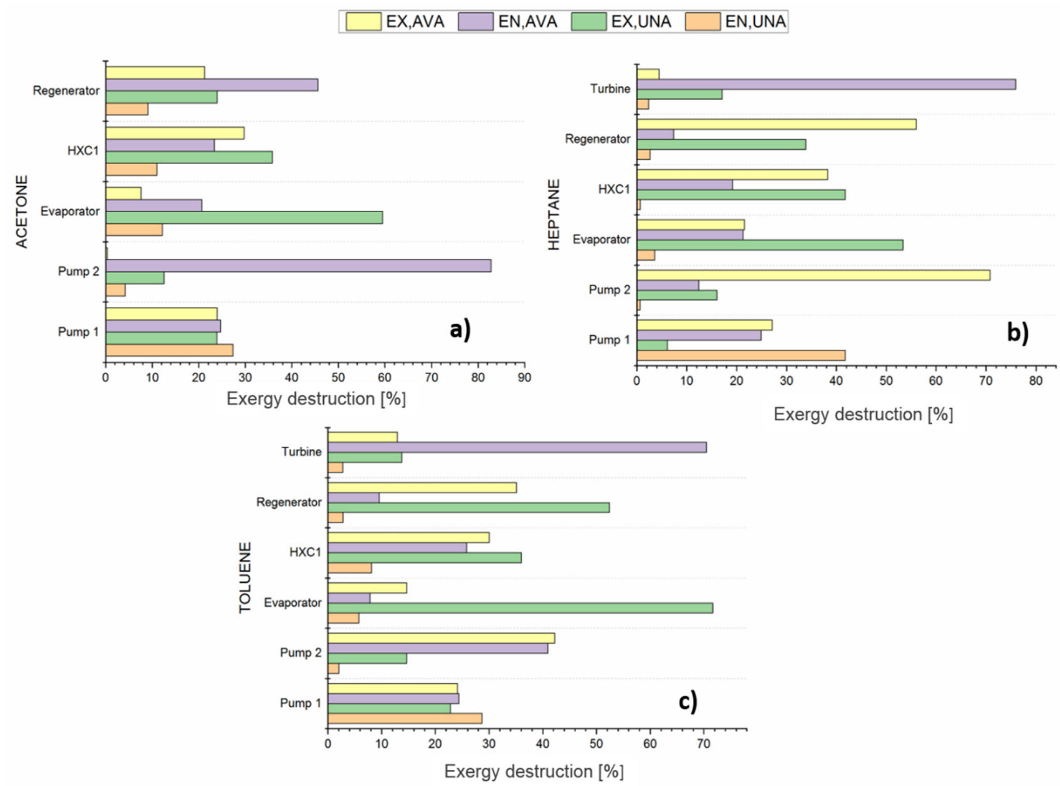

Figure 5. Disaggregation of exergy into the avoidable and unavoidable endogenous part and avoidable and unavoidable exogenous part for (**a**) acetone, (**b**) heptane, and (**c**) toluene.

According to Figure 5a, it can infer that in the case of using acetone as a working fluid, the greatest opportunities for improvement are reflected in Pump 2 of an endogenous nature with a percentage higher than 80%. Next, the regenerator with a percentage of about 45% of endogenous character and 23% of exogenous character. In the case of the use of heptane Figure 5b as the working fluid, greater opportunities for improvement in the turbine were shown to be close to 77% of an endogenous nature. However, exogenous Pump 2 has greater opportunities for improvement, with a percentage of about 71%, followed by the regenerator with approximately 55%. Therefore, considering the values obtained for the components mentioned, it is concluded that Pump 2 is the component that can achieve the greatest opportunities for improvement in the system through the use of Acetone; otherwise, it occurs when using heptane, where the greatest opportunities for improvement of Pump 2 are observed in the interaction with the other components, that is, in the destruction of exogenous exergy. In addition, the use of toluene allowed us to observe greater opportunities for improvement in the turbine.

In the case of toluene, the greatest opportunity for improvement was found in the turbine with a percentage of about 70% of endogenous character. Thus, the advanced exergetic analysis allowed to ratify the results obtained in the traditional exergetic analysis, because the values of the endogenous exergy in the evaporator and the turbine with the different organic fluids studied are higher. However, in the case of acetone, the highest values of avoidable endogenous exergy were presented by the thermal oil pump, due to the high values of exergy destruction that moving this fluid implies.

On the other hand, for the case of the regenerator with a percentage close to 34%, and Pump 2 with a percentage of 42% of exogenous character. Thus, with the help of this advanced exergetic analysis, the interactions between the system components for each working fluid are shown, as well as the potential for improving the energy and exergetic efficiency of each piece of equipment, and the overall performance of the overall heat recovery system, which implies greater energy generation through ORC from the waste gases of the generating engine.

Table 8 shows in more detail the values of exogenous/exogenous destroyed energy, avoidable, and unavoidable for the components of the system when the Acetone is used as the organic working fluid. Also, Appendix A in Table A3 is shown the advance exergy results of the main components using toluene and heptane.

Table 8. Disaggregation of exergy for system components using acetone as working fluid.

Fluid	Components	ϕ_D	$\phi_{D,k}^{EN}$	$\phi_{D,k}^{EX}$	$\phi_{D,k}^{UN}$	$\phi_{D,k}^{AV}$	$\phi_{D,k}^{EN,UN}$	$\phi_{D,k}^{EX,UN}$	$\phi_{D,k}^{EN,AV}$	$\phi_{D,k}^{EX,AV}$
Acetone	HXC 1	53.11	45.14	7.96	61.50	−8.38	14.49	47.01	30.65	−39.04
	Pump 1	0.34	0.33	0.01	0.42	−0.07	3.34	−2.92	−3.01	2.93
	Turbine	10.84	4.74	6.10	2.29	8.55	0.18	2.11	4.55	3.99
	Pump 2	0.14	0.12	0.01	0.02	0.12	0.00	0.01	0.12	0.00
	Evaporator	70.61	23.22	47.39	50.65	19.96	8.63	42.02	14.59	5.37
	Regenerator	4.41	4.20	0.20	2.53	1.870	0.70	1.83	3.50	−1.63
	Condenser	15.87	2.92	12.95	-	-	-	-	-	-
	Total	155.35	80.70	74.65						

The results shown in Table 8 show that the total endogenous exergy destruction of the system is higher (51.94%) compared to the exogenous (48.05%), which indicates that the exogenous and endogenous exergy destruction for acetone as a working fluid remains almost equal fractions. According to Appendix A Table A3, where we observe that the destruction of exogenous exergy is greater through the use of toluene and heptane as working fluid with a percentage of 63.98% and 67.83%, respectively. For the components that present negative exogenous values, they are associated with changes in flows and temperatures that are very variable between the real and avoidable conditions [31,32].

3.3. Evaluation of Total Investment Costs

Currently, the 2 MW Jenbacher Generation JMS 612 GS-N gas engine is commonly used for auto-generation reasons, and it is operating in the plastic industry in Barranquilla, Colombia, without any WHRS. The engine operates with a thermal performance of 38.58%, which is an average value of this type of engine functioning in Colombia [4]. Additionally, it has been proposed to optimize thermo-economically the integration of different configurations of ORC cycles to the Jenbacher JMS 612 GS-N Engine, seeking to obtain both the lowest level cost of electric energy and the highest thermal efficiency of the heat recovery system [5,6]. However, in this section, the main focus is the study of the costs of the equipment supplied, where purchased equipment cost (PEC) is taken into account, and the other costs are calculated based on PEC or fixed capital investment (FCI) percentages.

The use of the percentages is referenced by different authors in Table 9 that allowed the result of total capital investment in a RORC system through the use of heptane with a value of 3986.65 USD/kW, when using toluene, the value is 3966.01 USD/kW and when using acetone 4025.19 USD/kW being this last one the highest investment cost of the system.

Therefore, for the application of these solutions at an industrial scale, it is necessary to develop tax incentive laws, which translate into money savings through investment in equipment or technological solutions that minimize negative environmental impact, which had been applied in Colombia in the case of energy generation from renewable energy [39]. Thus, this alternative will be more noticeable for those technologies that present high specific costs as it is the case of the system operating with acetone since the incentives only impact the FCI, which plays a significant role in the final costs of energy generation.

By adopting a tax incentive law, ORC-based waste gas recovery technology operating with high investment costs will present the greatest reduction in the level of energy costs [40], since it has a higher specific cost. In the case of Colombia, the generation with renewable energy [41,42], and acquisition and installation of this solution in an industrial context with acetone could achieve a reduction of approximately 12%, when considering tax incentives with asset depreciation at 10 years, financing of 50% of the initial investment costs (IFCI+DFCI), and a grace period of 5 years [5,22]. Therefore, solutions with organic fluids that imply high investment costs should not be discarded in case they deliver an important energy potential, and it is suggested to carry out a thermo-economic analysis with indicators that support the decision-making process.

Table 9. Total investment costs estimation for the different working fluid.

Cost Breakdown	**Percentage Range**	**Applied Percentage**	**Cost Estimate (USD/kW)**		
Fluids			Heptane	Toluene	Acetone
Fixed- capital investment (FCI)			3796.81	3777.16	3833.52
Direct fixed-capital investment (DFCI)					
Onsite cost (ONSC)					
Purchased-equipment cost (PEC)	15%–40% of FCI [33]	/	1560.57	1592.68	1575.66
Purchased-equipment installation	6%–14% of FCI; 20%–90% of PEC [29,33]	20% of PEC	312.11	318.53	315.13
Pipping	3%–20% of FCI; 10%–70% of PEC	9% of PEC	140.45	143.34	141.80
Instrumentation and controls	2%–12% of FCI; 6%–40% of PEC	5% of PEC	78.02	79.63	78.78
Electrical equipment and materials	2%–10% of FCI; 10%–15% of PEC	4% of PEC	62.42	63.70	63.02
Offsite cost (OFSC)					
Civil, structural, and architectural work	5%–23% of FCI; 15%–90% of PEC	5% of PEC	78.02	7.16	78.78
Buildings	2%–18% of FCI	15% PEC	234.08	238.90	236.34
Total DFCI			2465.67	2443.96	2489.51
Indirect Fixed-capital investments (IFCI)					
Engineering and supervision	4%–(20% or 21%) of FCI 25%–75% of PEC [33,43]	30% of PEC	468.17	447.80	472.69
Construction cost including contractor's profit	4%–17% or 6%–22% of FCI 15% of DFCI [33,43]	15% of DFCI	369.85	366.59	373.42
Contingencies	5%–(15% or 20%) of FCI 8%–25% of all direct or indirect cost [33,43]	20% of DFCI	493.12	488.79	497.90
Legal cost	1%–3% of FCI [43]				
Total IFCI			1331.14	1333.19	1344.01
2. Other outlays					
Startup cost	5%–12% of FCI [33]	5% of FCI	189.84	188.85	191.67
Working capital	10%–20% of TCI [33]				
Total capital investment			3986.65	3966.01	4025.19

3.4. Economic Analysis

3.4.1. Effect of the Pressure Ratio on the Investment Costs

In order to propose a cost-effective thermal design of the WHRS ORC-based system, the project costs for the three evaluated organics are evaluated to select the most cost-effective configuration. The total investment costs are evaluated for the proposed systems, which will allow the development of a thermo-economic analysis and optimization. The total investment capital is determined, which is a cost at the beginning of the project, and the operation and maintenance costs, which are maintained over time [44]. A comparative analysis of the effect of the pressure ratio variation at Pump 2 for the heptane, toluene, and acetone as organic fluids on the investment costs are shown in this section. In this case, the indirect fixed capital investments (IFCI), the direct fixed capital investments (DFCI), and the fixed capital investment (FCI) were studied as function of the pressure ratio (r_p) from 5 to 9, keeping the condensing temperature (Tc) constant at 65 °C, and the evaporator pinch point at 100 °C. The results show the higher investment costs for toluene, as shown in Figure 6a, where the DFCI for toluene was 3093 USD/kW with a r_p of 5. Therefore, thermo-economic optimization should be carried out considering this cost indicator, which allows to propose a cost-effective thermal solution [34]. In the case of heptane, the DFCI was 2951 USD/kW, and for acetone 2911 USD/kW. Similarly, at the same pressure ratio, the FCI for acetone was 4492 USD/kW, for heptane 4528 USD/kW and for toluene 4780 USD/kW, which confirm the preference of acetone at law pressure ratio, but values larger than 8 the pumping cost of toluene and acetone increase, and the best organic fluid is the Heptane. Similarly, the same tendency was presented with the IFCI, where the toluene with a r_p of 5 presented a value of 1641 USD/kW, the heptane 1562 USD/kW, and the acetone 1547 USD/kW. However, each fluid presents its ideal operating conditions in economic terms. Thus, it is necessary to evaluate cases of multi-objective optimization studies that consider economic and environmental criteria to achieve the ideal conditions that enable the implementation and adoption of these systems in real operational industrial contexts [35].

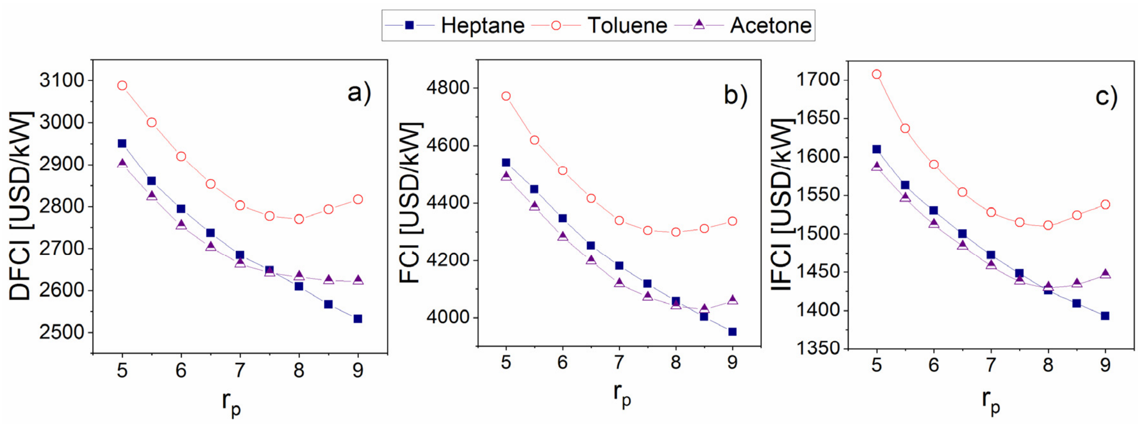

Figure 6. Effect of pressure ratio on investment costs for a RORC system varying (**a**) DFCI, (**b**) FCI, and (**c**) IFCI.

The results show that the increase in the system pressure ratio causes investment costs to decrease for heptane, while for acetone and toluene, these costs begin to increase from the pressure ratio in a range of 7 to 8. These results are due to the fact that for the exchangers, especially in the evaporators, the acquisition cost of the equipment presents a significant decrease when the evaporation pressure grows, because of the decrease of both the differences in operating temperatures and the irreversibilities for the transfer of energy in the form of heat. This behavior shows that there is an optimal evaporation pressure to obtain the maximum energy generated by the system, with the lowest equipment cost.

3.4.2. Effect of the Condensing Temperature on the Investment Costs

In this section, a comparative analysis of the effect of the variability of the condensing temperature (Tc) is presented for the three fluids heptane, toluene and acetone where we appreciate the influence of the variation of this temperature from 65 °C to 70 °C in which we notice different behaviors for the different organic fluids, as in the case of Figure 7a, and Figure 7c, wherein all the variation of the condensing temperature the toluene remains with a direct and indirect investment cost higher than the other fluids. However, for the case of FCI in Figure 7b, where it is observed that for a condensing temperature higher than 68 °C the fixed investment cost for toluene is higher than the other fluids.

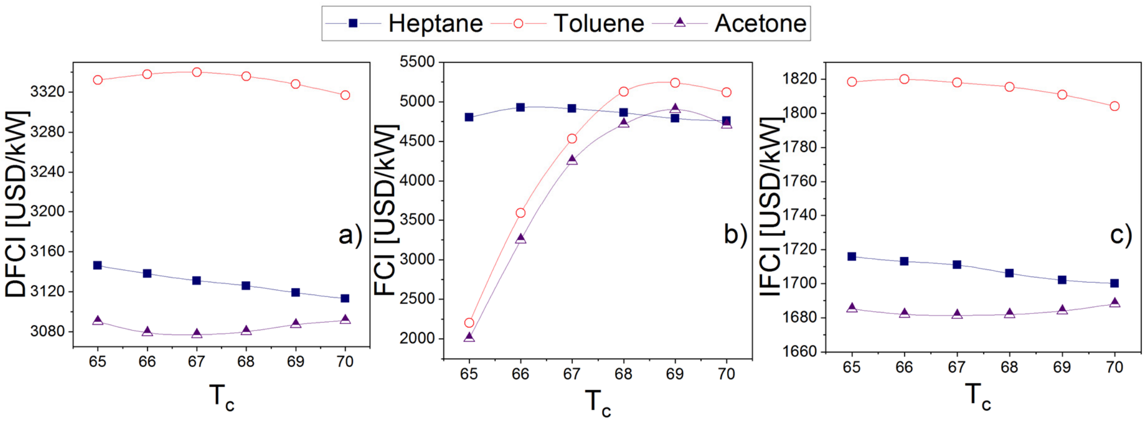

Figure 7. Effect of condensing temperature on investment costs for a RORC system varying (**a**) DFCI, (**b**) FCI, and (**c**) IFCI.

3.4.3. Effect of the Pinch Point Evaporator on the Investment Costs

In this case, the impact of the variation of the evaporator pinch point had a similar behavior for all the direct and indirect investment costs (DFCI and IFCI) and the fixed investment costs FCI on the 3 fluids indicated in Figure 8 where it is observed that toluene has a higher investment cost than the other organic fluids, followed by heptane and finally acetone. The pressure ratio conditions were kept constant at 4, the condensation temperature at 65 °C and the evaporator pinch point was varied from 90 °C to 100 °C. It was observed that at a pinch point of the AP evaporator of 94 °C, the DFCI Figure 8a for toluene is 3392 USD/kW, for heptane is 3177 USD/kW and for acetone is 3134 USD/kW. Figure 8b with an AP of 94 °C for toluene, the FCI is 5240 USD/kW for toluene, for heptane is 4924 USD/kW, and finally for acetone is 4839 USD/kW. Taking into account the same value of AP, the fixed indirect investment costs (IFCI) are approximately 1850 USD/kW for toluene, 1735 USD/kW for heptane, and 1709 USD/kW for acetone.

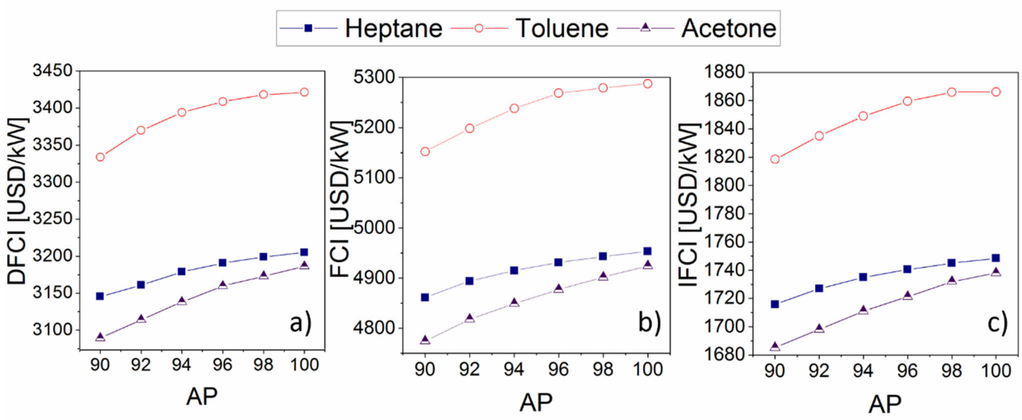

Figure 8. Effect of evaporator pinch point on investment costs for a RORC system varying (**a**) DFCI, (**b**) FCI, and (**c**) IFCI.

The results show that for low pinch values in the evaporator, the temperature of the organic fluid increases at the evaporator outlet, therefore, there is a greater amount of energy loss in the evaporator, so more efficient equipment with lower acquisition costs is required. However, for a lower evaporation temperature, less power will be obtained, and exergy losses in the turbine will be dominant, being this the component with an important acquisition cost, especially for the toluene. Therefore, as the pinch in the evaporator increases, both direct and indirect acquisition costs in the evaporator and the turbine increase, which is because of the energy loss and exergy destruction in the evaporator increases significantly. The above suggests to consider this variable in future economic optimizations that allow to determine the optimal pinch in the evaporator to obtain the lowest possible costs without sacrificing the performance of the system.

4. Conclusions

Another contribution is the methodology suggested for the best design of secondary circuits of ORC systems for WHRS with indirect evaporation, which allows the necessary energy to be supplied to the organic fluid and does not affect the admissible back pressure of the motor. This methodology can be useful to any type of WHRS with indirect evaporation, and is more appropriate for situations where there are restrictions on the back pressure of the heat source with medium and high temperatures, just in cases where ORC equipment has not been extensively applied commercially.

The advanced exergetic analysis allowed to determine opportunities for improvement in the components with the greatest irreversibilities of the waste heat recovery systems based on RORC the system, focusing only on those fractions of exogenous or endogenous exergy destruction that can be avoided. An economic investigation has been conducted to understand the economic dimension and financial viability of the equipment acquisition project. Therefore, such economic evaluation and cost resolution achieve precision in a range of magnitude under a study or previous estimates.

An additional contribution of the present work in the area of WHRS from exhaust- gases in high-powered natural gas engines, is the identification of the design and operation variables that contribute most to the economic viability of the integrated system, which allows focusing future efforts that lead to the application of these solutions in industrial environments.

For the operating states considered in the study, the results showed higher exergy destruction when using toluene and acetone as working fluid, reaching around 70 kW for the evaporator and heat exchanger. For the heptane, the maximum exergy destruction was shown for the evaporator and regenerator with a value of 53 kW. The breakdown of exergy increased opportunities for improvement in Pump 2 of an endogenous nature with a percentage of about 80% by using acetone as a working fluid. Similarly, greater opportunities for improvement were obtained in the turbine with a rate of 77% using heptane and through the use of toluene with a percentage close to 70% for the endogenous turbine, 34%, and 42% for the regenerator and exogenous Pump 2.

The research allowed a variation of the system operation parameters, condensation temperature, pressure ratio, and evaporator pinch point in order to find the adequate fluid and operational values that provide a cost reduction in the system. In such a way that it was achieved for the acetone lower acquisition costs at a pressure ratio of 8, a condensation temperature of 65 °C and a pinch point of the evaporator of 90. Similarly, for heptane, lower costs were achieved at a 70 °C condensation temperature, a pressure ratio of 9, and an evaporator pinch point of 90 °C.

It is necessary to study in detail the heat exchange equipment for the thermal process of the plant, in search of deficiencies and areas of high heat transfer to the environment, or irreversibilities, which would imply an increase in the power recovered. On the other hand, this study must be complemented with a thermo-economic analysis to evaluate in financial terms implementations of new equipment or changes in the process in order to achieve efficient use of the energy and resources available in the exhaust gases of these type of natural gas generation engines.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

$\phi_{d,k}$	Exergy destruction [kW]
$\phi_{D,k}^{EN}$	Endogenous exergy destruction [kW]
$\phi_{D,k}^{EX}$	Exogenous exergy destruction [kW]
m	Mass [kg]
$\dot{m}$	Mass flow rate [kg/s]
Q	Heat [kJ]
ε_{hr}	Heat recovery efficiency [%]
T	Temperature [K]
$\dot{W}_{net}$	Net power [kW]
Ψ	Flow exergy
ε_k	Exergetic efficiency
ε_{hr}	Heat recovery efficiency
D	Destroyed
in	Input
out	Output
G	Gases
o	Reference condition
Superscripts	
FCI	Fixed cost investment [USD/kW]
TCI	Total capital investment [USD/kW]
IFCI	Indirect fixed cost investment [USD/kW]
DFCI	Indirect fixed cost investment [USD/kW]
AVA	Avoidable
EN	Endogenous
EX	Exogenous
EN, AVA	Endogenous avoidable
EN, UNA	Endogenous unavoidable
EX, AVA	Exogenous Avoidable
EX, UNA	Exogenous unavoidable
UNA	Unavoidable

Appendix A

The thermodynamic properties at each stage of the ORC System with recuperator using heptane and toluene as working fluid is shown in Table A1.

Table A1. Thermodynamic properties of the WHRS system based on RORC system for heptane and toluene as working fluids.

Fluid	State	Temp [K]	Pressure [kPa]	Enthalpy [kJ/kg]	Entropy (S-S0) [kJ/kg K]	Exergy [kW]
Heptane	3 ORC	338.15	33.13	−82.84	0.25	4.87
	4 ORC	338.20	135.25	−82.63	0.25	5.05
	4 ORCr	381.67	135.25	298.24	1.27	87.58
	4f ORC	381.67	135.25	26.22	0.55	24.40
	4g ORC	381.67	135.25	335.63	1.36	96.26
	1 ORC	555.31	135.25	754.67	2.26	262.23
	2 ORC	536.13	33.81	705.12	2.28	198.37
	2 ORCr	373.13	33.81	324.24	1.44	55.77
	2g ORC	338.15	33.81	256.93	1.25	44.57
	3 ORC	338.15	33.81	−82.84	0.25	4.87
Toluene	3 ORC	338.15	22.52	−87.52	0.19	3.67
	4 ORC	338.18	90.11	−87.41	0.19	3.76
	4 ORCr	379.66	90.11	56.14	0.58	32.04
	4f ORC	379.66	90.11	−8.14	0.41	17.53
	4g ORC	379.66	90.11	355.22	1.37	99.54
	1 ORC	477.94	90.11	516.24	1.74	152.29
	2 ORC	450.69	22.52	470.57	1.77	92.49
	2 ORCr	357.19	22.52	327.01	1.41	52.41
	2g ORC	338.15	22.52	301.63	1.34	48.77
	3 ORC	338.15	22.52	−87.52	0.19	3.67

Results of traditional exergy analysis are presented by input-product definition, shown in Table A2.

Table A2. Exergy analysis results for each component of the WHRS system based on RORC system using toluene and heptane.

Fluid	Components	ϕ_F [kW]	ϕ_P [kW]	ϕ_D [kW]	ϕ_L [kW]	ε_k	$Y_{D,k}$
Toluene	HXC 1	541.20	201.31	43.42	296.45	37.19	0.26
	Pump 1	0.37	0.05	0.32	-	13.58	0.002
	Turbine	59.80	51.13	8.66	-	85.51	0.05
	Evaporator	201.37	148.53	81.11	-	73.76	0.50
	Pump 2	0.12	0.09	0.02	-	77.58	0.0001
	Regenerator	40.07	28.27	11.79	-	70.55	0.07
	Condenser	-	-	16.46	87.34	-	0.10
Heptane	HXC 1	541.20	239.45	4.77	296.45	44.34	0.03
	Pump 1	0.36	0.09	0.26	-	27.57	0.001
	Turbine	63.86	55.92	7.94	-	87.56	0.05
	Evaporator	240.07	257.17	65.42	-	107.12	0.41
	Pump 2	0.23	0.18	0.05	-	77.59	0.0003
	Regenerator	142.59	82.52	60.06	-	57.87	0.38
	Condenser	-	-	18.51	80.85	-	0.11

Table A3 shows the breakdown of exergy using toluene and heptane as working fluids.

Table A3. Disaggregation of exergy in the RORC system devices for toluene and heptane.

Fluid	Components	ϕ_D	$\phi_{D,k}^{EN}$	$\phi_{D,k}^{EX}$	$\phi_{D,k}^{UN}$	$\phi_{D,k}^{AV}$	$\phi_{D,k}^{EN,UN}$	$\phi_{D,k}^{EX,UN}$	$\phi_{D,k}^{EN,AV}$	$\phi_{D,k}^{EX,AV}$
Toluene	HXC 1	43.42	36.91	6.51	48.04	−4.61	8.81	39.23	28.10	−32.72
	Pump 1	0.32	0.24	0.07	0.39	−0.01	1.65	−1.31	−1.40	1.39
	Turbine	8.66	8.56	0.10	1.93	6.72	0.32	1.61	8.23	−1.51
	Pump 2	0.02	0.01	0.01	0.00	0.02	0.00	0.00	0.01	0.01
	Evaporator	81.11	0.02	81.09	62.78	18.33	0.00	62.77	0.01	18.32
	Regenerator	11.79	1.46	10.33	6.53	5.26	0.33	6.19	1.12	4.14
	Condenser	16.46	11.05	5.40	-	-	-	-	-	-
	Total	161.82	58.27	103.54						
Heptane	HXC 1	4.77	4.05	0.71	8.64	−3.87	0.14	8.49	3.90	−7.78
	Pump 1	0.26	0.11	0.14	0.24	0.01	0.28	−0.04	−0.17	0.18
	Turbine	10.6373	9.16	1.47	2.28	8.35	0.28	2.00	8.88	−0.52
	Pump 2	0.0530	0.00	0.04	0.00	0.04	0.00	0.00	0.00	0.03
	Evaporator	65.4201	16.34	49.07	37.30	28.11	2.37	34.93	13.97	14.14
	Regenerator	60.0693	6.05	54.01	21.96	38.10	1.61	20.35	4.44	33.66
	Condenser	18.5149	15.63	2.87	-	-	-	-	-	-
	Total	159.72	51.37	108.35						

Appendix B

To determine the destruction of endogenous exergy for each component using heptane and toluene as working fluid, as shown in Figures A1 and A2.

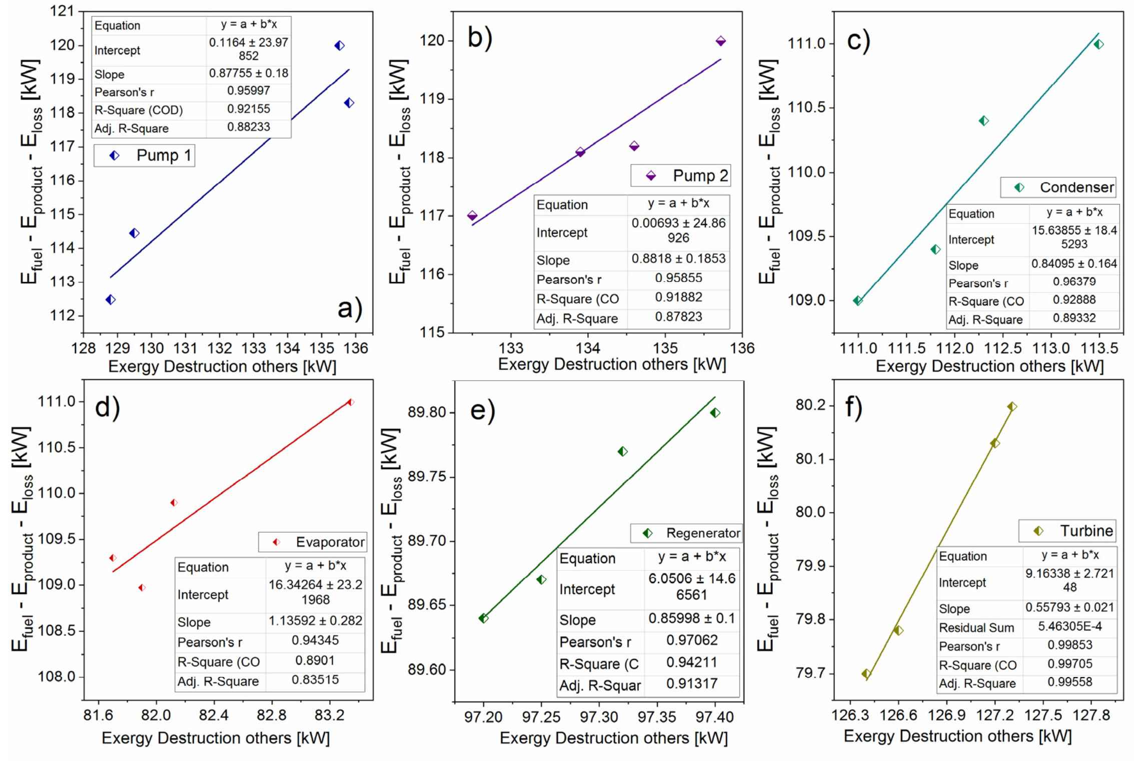

Figure A1. Endogenous destruction of exergy for heptane (**a**) Pump 1, (**b**) Pump 2, (**c**) condenser, (**d**) evaporator, (**e**) regenerator, and (**f**) turbine.

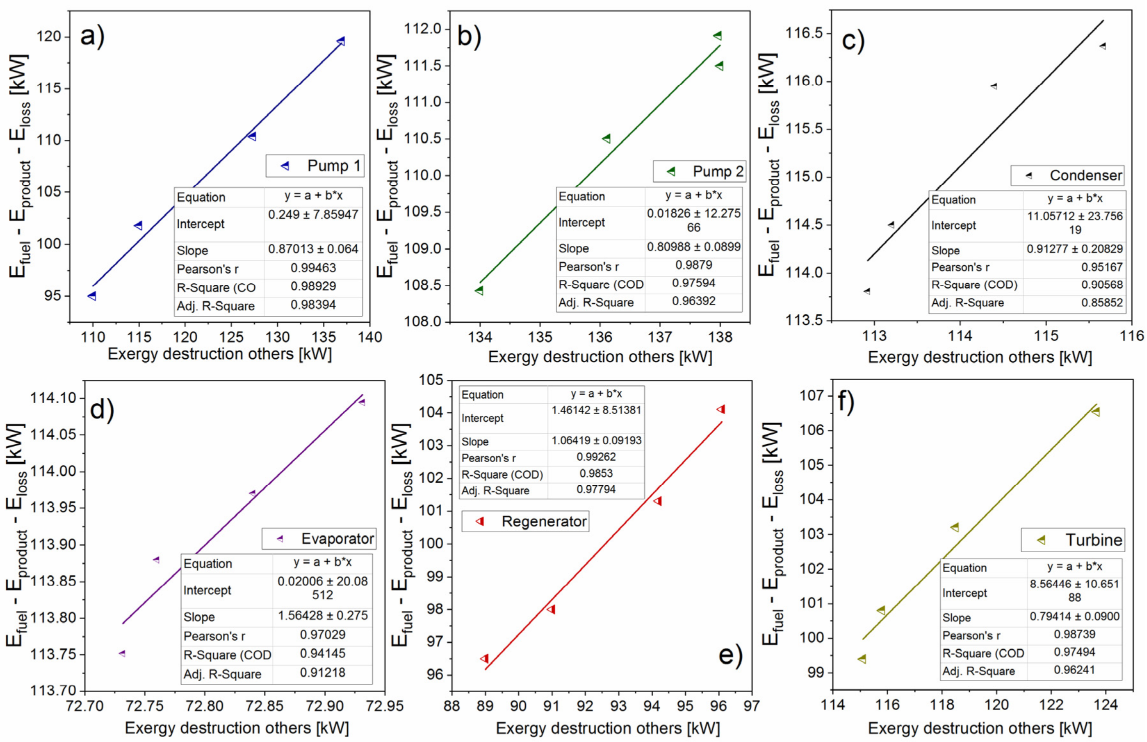

Figure A2. Endogenous destruction of exergy for toluene (**a**) Pump 1, (**b**) Pump 2, (**c**) condenser, (**d**) evaporator, (**e**) regenerator, and (**f**) turbine.

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