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DETERMINING ENVIRONMENTALLY FRIENDLY WORKING FLUID FOR AN EJECTOR ORGANIC RANKINE CYCLE USING A LOW-TEMPERATURE SOURCE

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ABSTRACT

This paper investigates the thermodynamic performance of various environmentally friendly fluids in an integrated organic Rankine cycle (ORC) and ejector booster refrigeration cycle (EBRC) system. The study aims to identify optimal working fluids that enhance system efficiency while minimizing environmental impact. Several natural and synthetic fluids, including those with low global warming potential (GWP) and zero ozone depletion potential (ODP), are analyzed for their thermodynamic properties such as coefficient of performance (COP), mass flow rate of cycle, expander expansion ratio (EER) and compressor compression ratio (CCR). Detailed thermodynamic analysis, including energy balances, is conducted for each fluid across the system components, assessing their effect on system performance. The results reveal that certain fluids offer significant improvements in both energy efficiency and environmental sustainability compared to other refrigerants. Based on the analyses, in the ORC-EBRC cycle, cyclopentane was found to be fluid with the lowest total mass flow rate and the highest COP. This study provides valuable insights into the selection of sustainable working fluids for ORC-EBRC systems, offering guidance for future applications in renewable energy utilization and cooling technologies.

Keywords: Ejector, Organic Rankine cycle, Refrigeration cycle, Renewable energy.

Nomenclature

T :	Temperature, °C	$\dot{m}$:	Mass flow rate, kg/s
h :	Specific enthalpy, kJ/kg	$\dot{Q}$:	Thermal load, kW
s :	Specific entropy, kJ/(kgK)	$\dot{W}$:	Power, kW
P :	Pressure, kPa	L :	Leakage rate, %
e :	Specific exergy, kJ/kg	N :	Life expectancy, year
$\dot{E}$:	Exergy rate, kW	M :	Mass, g/mol

Acronyms

EBRC : Ejector booster refrigeration cycle
VCRC : Vapor compression refrigeration cycle
COP : Coefficient of performance
CPM : Constant pressure mixing
GWP : Global warming potential
ODP : Ozone depletion potential
ORC : Organic Rankine cycle
EER : Expander expansion ratio
CCR : Compressor compression ratio
NBP : Normal boiling point

Subscript

i : Inlet
o : Outlet
c : Condenser
comp : Compressor
evap : Evaporator
ex : Exergy
sep : Separator
turb : Turbine
b : Boiler
p : Pump
boos : Booster
crit : Critic

Greek symbols

η **:** Isentropic Efficiency

1 INTRODUCTION

The integration of ORC and refrigeration cycles presents a promising approach to improving the efficiency and sustainability of energy systems, particularly for applications involving low-temperature heat sources. By combining power generation through the ORC with cooling capabilities of refrigeration cycles, this system allows for the simultaneous recovery of waste heat and the provision of cooling, addressing both energy generation and thermal management needs. This integrated system is especially beneficial in industries where low-grade heat is readily available but often wasted, as well as in applications that require both power and cooling, such as in industrial processes, data centers, and refrigeration [1]. The present study explores the thermodynamic performance of such a combined ORC-EBRC system, focusing on exploring suitable working fluids and analyzing the potential for energy savings and environmental benefits.

According on an analysis of recent studies, scientists have carried out energy and exergy-based thermodynamic analyses to determine the optimal performance of combined organic Rankine cycle – vapor compression refrigeration (ORC-VCR) systems using different fluids. Ahmed & Kr Mahanta [2] performed an energy analysis of a combined ORC-VCR system to efficiently utilize waste energy from both the exhaust gases and cooling water of a diesel engine. In the designed system, R600, R600a, R601, and R601a were used as working fluids. They determined that R600 was the most optimal fluid for harnessing waste energy from both the exhaust gases and cooling water of the diesel engine. Saleh [3] investigated the performance of the combined ORC-VCR system using different fluids. They observed that high condenser and evaporator temperatures, along with high compressor and turbine isentropic efficiency, enhanced system performance, although total mass flow decreased. While R600 and R245fa exhibited nearly identical COP values, R600 was identified as the best fluid due to its lower environmental impact. Yang et al. [4] used the zeotropic combination of R600/R601 to conduct an exergy analysis on a combined ORC and ejector refrigeration cycle. The results showed that the suggested cycle produced more power output but provided less cooling compared to the traditional cycle, with higher exergy efficiency. Wang and Yang [5] conducted both first and second law analyses on a hybrid system for combined cooling, heating, and power, which was powered by biomass and solar energy. Their findings revealed exergy and energy efficiencies of 16.1% and 57.9%, respectively. Meanwhile, Nasir and Kim [6] assessed various fluid combinations for an ORC-VCR system powered by low-grade heat, concluding that the best fluid to use with this system was R134a. Cihan and Kavasogullari [7] carried out a theoretical energy and exergy analysis of a combined ORC-VCR system that utilizes waste heat, employing fluids such as R600, R245fa, R123, R600a, and R141b. They found that R141b performed better than the commonly used R245fa in ORC systems. Saleh [8] investigated various fluids, including R152a, R600a, R60, R236fa, R1234ze, R601a, R601, RC318, perfluoropentane, R236ea, R245ca, R245fa, RE245cb2, R602, and R1234ze(E), for the combined ORC-VCR system. R602 was found to be the best suitable fluid for the ORC-VCR system out of all the fluids examined, offering the best balance of system performance and environmental sustainability. Saleh et al. [9] performed an energy analysis of a combined ORC-VCR system using different fluids. The results showed that the cyclopentane achieved the highest system performance under all operating conditions investigated. Pektezel & Acar [10] performed an energy and exergy analysis of two vapor compression refrigeration cycles integrated with ORC. Both single and double evaporators were used in the construction of the combined refrigeration cycle, which used distinct fluids. The most effective fluid for the suggested integrated systems was found to be R600a. They found that the ORC-single evaporator VCR cycle performed better than the double evaporator system after examining performance metrics. Javanshir et al. [11] conducted the thermodynamic analysis of an ORC-VCR system using geothermal energy as the heat source, with R134a, R22, and R143a as working fluids. Their results indicated that R143a and R22 exhibited the highest exergy and energy efficiencies, respectively.

Ashwni et al. [12] evaluates the thermodynamic performance of two ORC–VCR systems utilizing the zeotropic mixture Hexane/R245fa. The first system represents a conventional ORC–VCR configuration, while the second is a modified ORC–VCR design. The modified system demonstrates improvements of 23.4%, 23.4% and 29.0%, in cooling capacity (Q_{evap}), COP and exergetic efficiency (η_{ex}), respectively, when compared to the conventional system. Touaibi et al. [13] presents an energy and exergy analysis of a combined cycle, utilizing four organic fluids as working fluids. Given the environmental advantages, the best option for the ORC-VCR system intended to recover low-grade thermal energy is R600a. Maalem & Madani [14] focuses on a comparative analysis of various thermodynamic performance characteristics of the ORC-VCRC system, which is driven by low-temperature heat sources. Cyclopentane gas is considered as an alternative to conventional hydrocarbons (such as butane, isobutene, propane, and propylene), which are commonly used in ORC-VCRC systems.

This study involves the design of a system that integrates ORC and EBRC, utilizing low-grade waste heat (<150°C). Finding the most eco-friendly refrigerant that produces the best performance values for the power-cooling cycle under study is the main goal. For the ORC-EBRC, environmentally friendly fluids are used for the first time and energy-based thermodynamic analysis is performed. The global warming potential of these selected fluids is very low, so they are considered as environmentally friendly fluids. Boiler, condenser and evaporator temperatures are chosen as the operational parameters and how they affect COP_{system}, EER, mass flow rate of the circulating fluid, and CCR parameters are analyzed.

2 THERMODYNAMIC ANALYSIS METHOD

To simplify the analysis, certain assumptions were adopted as suggested in the literature [11, 6, 8, 15, 16, 17]:

(a) Continuous operation conditions apply, with pressure losses considered negligible.

(b) The condenser discharges the fluid as a saturated liquid, having a quality of zero, while It is released as a saturated vapor with a quality of one from the boiler and the evaporator.

(c) A temperature differential of 5°C is maintained between the evaporator and cooled medium, while a consistent 15°C temperature difference is expected between the boiler and the heat source.

(d) Compressor is considered adiabatic, with heat and friction losses in the system disregarded.

(e) At the outlet of the separator, the vapor on the compressor side is in the saturated vapor phase, while the liquid on the evaporator side is in the saturated liquid phase.

(f) It can be assumed that the refrigerant's kinetic energy at both the inlet and outlet of the ejector is negligible, with the flow through the ejector being homogeneous and one-dimensional.

(g) The net work generated by the turbine in the ORC system is equivalent to the work required by the compressor during the refrigeration cycle.

(h) An iterative approach is used to make sure the phase state at the ejector output matches the ejector's mixing ratio.

Table 1 presents the thermodynamic properties of the environmentally friendly refrigerants—cyclopentane, R600a, R600, R602, and R1234yf—used in the analysis throughout the study.

Table 1. Details of the relevant refrigerant [10, 18]

Refrigerant	P_{crit} (MPa)	T_{crit} (°C)	M (g/mol)	NBP (°C)	GWP (100 year)	ODP	Safety group
Cyclopentane	4.571	238.6	70.1	49.3	<0.1	0	A3
R600a	3.629	134.7	58.1	-11.8	~20	0	A3
R600	3.796	152	58.1	-0.49	~20	0	A3
R602	3.034	234.7	86.2	68.7	~20	0	A3
R1234yf	3.38	94.7	114.04	-29.5	<1	0	A2L

The study's operating ranges and parameters are shown in Table 2. Other metrics were assessed within their respective limits, despite the cooling capacity being maintained constant during the research.

Table 2. The study's parameters and ranges.

Variables	Ranges
Boiler temperature (°C)	60 to 90
Condenser temperature (°C)	35 to 55
Evaporator temperature (°C)	-10 to 10
η_{comp}	0.874-0.0135(P_2/P_1)
η_{turb}	0.8
η_{pump}	0.8
$\eta_{booster}$	0.874-0.0135(P_{13}/P_{12})
Cooling capacity (kW)	10

FORTRAN was used to create the ORC-EBRC cycle thermodynamic model for this investigation. Using REFPROP version 9.1, the enthalpy and entropy values required for the thermodynamic analysis of the cycle were obtained. Figure 1 shows the ORC-EBRC's schematic depiction, and Figure 2 shows the ORC-EBRC's T-s and lnP-h diagrams.

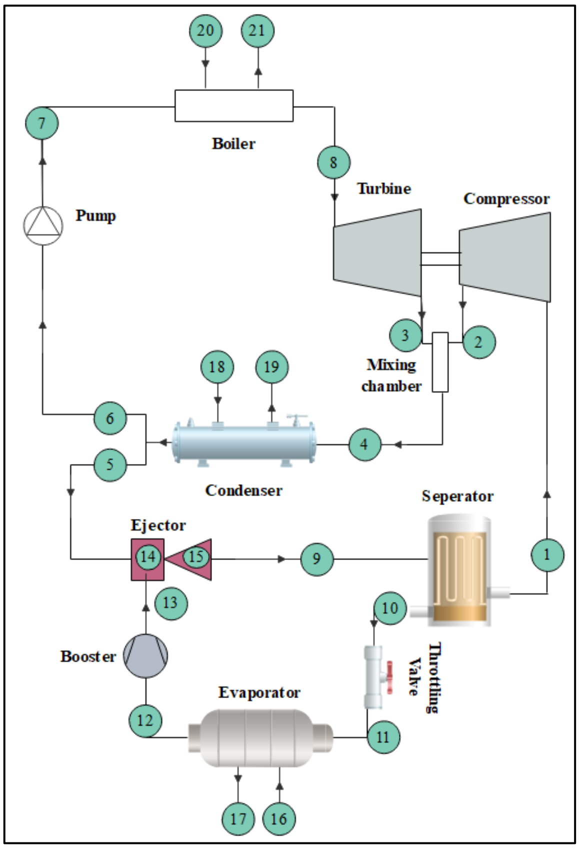


Figure 1. Schematic layout of ORC-EBRC [26].

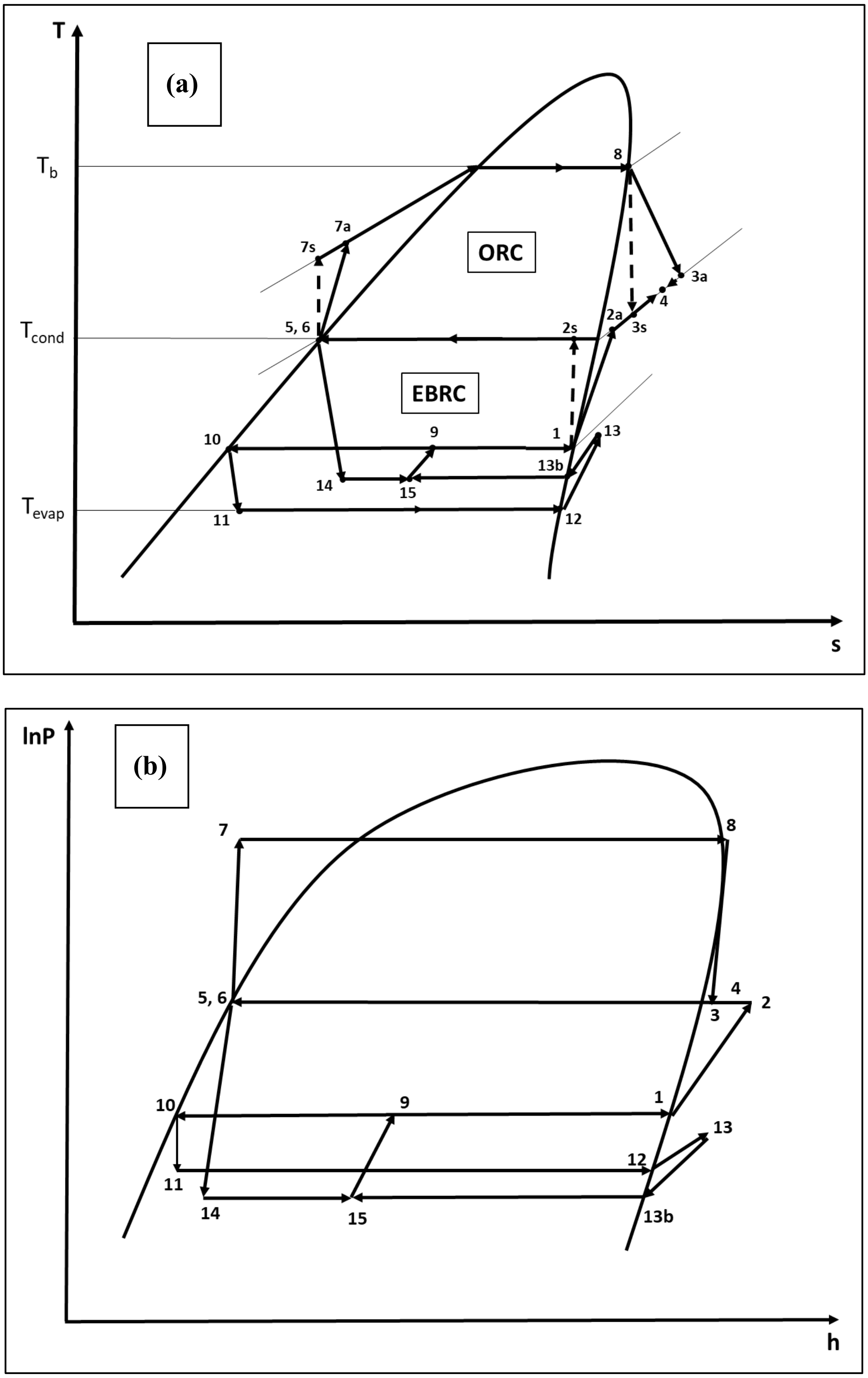


Figure 2. (a) T-s diagram and (b) lnP-h diagram of ORC-EBRC.

2.1 Identifying the Most Environmentally Friendly Refrigerant

In ORC systems, the selection of working fluids plays a crucial part in deciding both the environmental impact and the overall sustainability of the system. Many conventional working fluids are associated with significant drawbacks, such as high ozone depletion potential (ODP) and global warming potential (GWP), contributing to critical environmental challenges like global warming and ozone layer degradation. In contrast, environmentally friendly working fluids are specifically designed to address these concerns by offering low GWP and negligible ODP, ensuring minimal adverse effects on the environment. Furthermore, such fluids are often characterized by low toxicity and non-flammability, which enhance operational safety and reduce risks to human health. Beyond their environmental and safety advantages, these fluids can also improve system performance by optimizing thermodynamic properties, such as critical temperature and pressure, to better match the operating conditions of ORC systems. As a result, the use of eco-friendly working fluids is essential not only for minimizing environmental impacts but also for achieving higher energy efficiency and ensuring the long-term viability of ORC technology in sustainable energy applications. This critical balance between energy production and environmental protection underscores the importance of careful fluid selection in advancing ORC systems as a cornerstone of green energy solutions [19].

2.2 Analysis of the Cycle's Energy Performance

This chapter aims to perform an energy analysis of the evaluated cycle using the chosen environmentally friendly fluids. The thermodynamic model will utilize methods based on mass conservation and energy analysis.

Equation (1), which represents the steady-state mass conservation equation, is utilized for each component of the ORC-EBRC cycle examined in this study.

$$\sum_{i} \dot{m} = \sum_{o} \dot{m} \tag{1}$$

The energy conservation equation for steady-state conditions, presented in Equation (2) [20, 21], is applied to every component of the examined cycle in this study.

$$\dot{Q} - \dot{W} + \sum_{i} \dot{m}_i h_i - \sum_{o} \dot{m}_o h_o = 0 \tag{2}$$

The equations used to create the mass and energy balances for each ORC-EBRC cycle component are shown in Table 3. Additionally, it outlines the methods for figuring out the cycles' COP, thermal efficiency, compressor compression ratio, mass flow rate, and turbine expansion ratio. The use of a booster increases the pressure of the fluid entering the ejector. Thus, the fluid enters the secondary nozzle of the ejector at higher pressure. This increases the pressure of the fluid leaving the ejector. This results in a reduction in the compression work done by the compressor. This is a very convenient way to increase the coefficient of performance of a refrigeration cycle. When the combined cycle is analyzed, the power generated from the turbine and the power consumed in the compressor are equal. Therefore, the booster consumes an external power.

Kornhauser (1990)'s constant pressure mixing (CPM) method was employed for the thermodynamic modeling of the ejector [22].

Table 3. Energy analysis equations for the ORC-EBRC cycle.

Parameter or component	Cycle
Evaporator (Equation 3)	$\dot{Q}_{evap} = \dot{m}_{EBRC}\,(h_{11} - h_{12})$
Compressor (Equation 4)	$\dot{W}_{comp} = \dot{m}_{EBRC}(h_{2a} - h_1) = \dfrac{\dot{m}_{EBRC}(h_{2s} - h_1)}{\eta_{comp}}$
Booster (Equation 5)	$\dot{W}_{boos} = \dot{m}_{EBRC}(h_{13a} - h_{12}) = \dfrac{\dot{m}_{EBRC}(h_{13s} - h_{12})}{\eta_{boos}}$
Pump (Equation 6)	$\dot{W}_p = \dot{m}_{ORC}(h_{7a} - h_6) = \dfrac{\dot{m}_{ORC}(h_{7s} - h_6)}{\eta_{pump}}$
Boiler (Equation 7)	$\dot{Q}_b = \dot{m}_{ORC}\,(h_8 - h_7)$
Condenser (Equation 8)	$\dot{Q}_c = (\dot{m}_{ORC} + \dot{m}_{EBRC})(h_4 - h_5)$
Mass flow rate of ORC (Equation 9)	$\dot{m}_{ORC} = \dfrac{\dot{W}_{turb}}{\eta_{turb}(h_8 - h_{3s})}$
Compressor and turbine equality (Equation 10)	$\dot{W}_{comp} = \dot{W}_{turb}$
Mass flow rate of combine cycle (Equation 11)	$\dot{m}_{total} = \dfrac{\dot{m}_{ORC} + \dot{m}_{EBRC}}{\dot{Q}_{evap}}$
Thermal efficiency of ORC (Equation 12)	$\eta_{ORC} = \dfrac{\dot{W}_{turb}}{\dot{Q}_b + \dot{W}_p}$
COP of refrigeration cycle (Equation 13)	$COP_{EBRC} = \dfrac{\dot{Q}_{evap}}{\dot{W}_{comp} + \dot{W}_{boos}}$
COP of combine cycles (Equation 14)	$COP_{system} = \dfrac{\dot{Q}_{evap}}{\dot{Q}_b + \dot{W}_p + \dot{W}_{boos}}$
Compressor compression ratio (Equation 15)	$CCR = \dfrac{P_2}{P_1}$
Expander expansion ratio (Equation 16)	$EER = \dfrac{P_8}{P_3}$

3 RESULTS AND DISCUSSION

3.1 Model Validation

Due to the absence of literature on the ORC-EBRC cycle, a validation study for the ORC-VCRC cycle was performed through theoretical analysis. The objective of this study was to evaluate the accuracy of the computer code developed for simulations. In Figure 3, the model created in this study is compared with the reference model by Li et al. [23], where R290 is used as the working fluid. The COP is analyzed with varying evaporation temperatures, maintaining the same operating conditions (T_b = 80°C, η_{comp} = 75%, T_{cond} = 40°C, $\dot{m}_{ORC}$ = 1 kg/s and η_{turb} = η_p = 80%). The deviation between the two models is found to be around 0.98%.

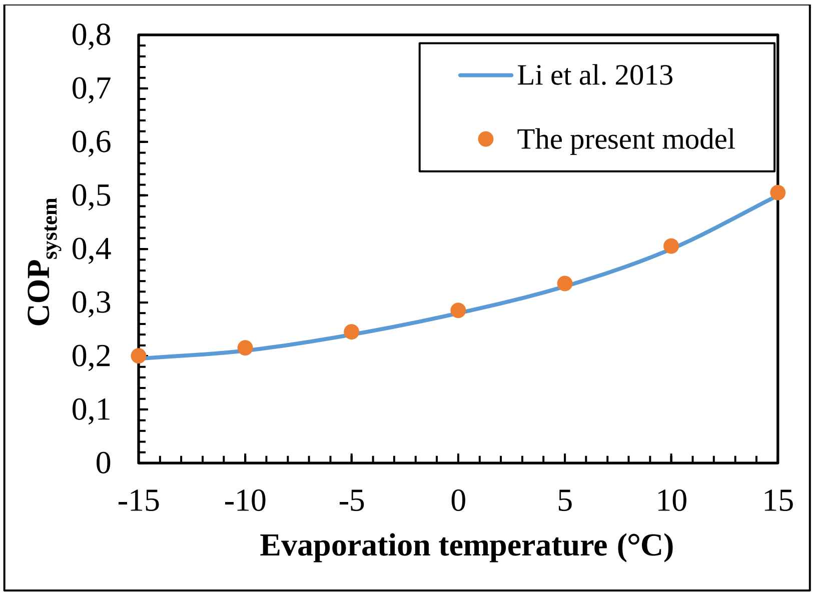


Figure 3. Comparison between Li et al. [23] and the present model utilized in this study.

3.2 Examining the Influence of Boiler Temperature

Figure 4 illustrates the impact of increasing boiler temperature on COP_{system}, EER, and $\dot{m}_{total}$. In Figure 4(a), it is evident that as the boiler temperature increases, COP_{system} exhibits an upward trend for all working fluids. Since both the cooling capacity and the compressor's power consumption remain unchanged, the increase in boiler temperature does not influence COP_{EBRC}. This indicates that COP_{EBRC} remains independent of boiler temperature variations under these conditions. As the boiler temperature rises, the specific work of the turbine also increases. Given that the power consumed by the compressor and the power produced by the turbine are assumed to be equal, the mass flow rate of the ORC ($\dot{m}_{ORC}$) decreases as the boiler temperature increases. The decrease in $\dot{m}_{ORC}$ leads to a reduction in Q_{boil} as the temperature of the boiler rises. Therefore, the thermal efficiency of the ORC improves. As shown in Figure 4a, this results in an increase in COP_{system}. When comparing the working fluids, it was found that for boiler temperatures above approximately 73°C, the cyclopentane fluid provides higher COP_{system} values than the other fluids. After 73°C boiler temperature, the COP_{system} advantage of cyclopentane over R600a is approximately 2.3% at 90°C boiler temperature.

In Figure 3(b), the relationship between EER and boiler temperature is depicted. The results reveal that for all examined working fluids, EER increases as the boiler temperature rises. This trend can be attributed to the rise in saturation pressure with increasing temperature. When the boiler temperature reaches 90°C, the EER values for all working fluids nearly double compared to those at 60°C. Among the fluids analyzed, R602 exhibits the highest EER, whereas R1234yf records the lowest. Furthermore, to achieve a turbine efficiency greater than 80%, the EER must be below 50 [25]. As shown in Figure 3b, the EER is less than 6 for all candidates, meaning that an expansion efficiency greater than 80% can be achieved.

Figure 3 (c) shows the variation in m_{total} according to the boiler's temperature for the environmentally friendly fluids examined in the ORC-EBRC system. As shown in Figure 3 (c), assuming that the mass flow rate of the EBRC fluid remains constant and the mass flow rate of the ORC falls as the temperature of the boiler rises, $\dot{m}_{total}$ decreases as the temperature of the boiler rises. Additionally, Figure 3 shows that among all the fluids examined, cyclopentane reaches the highest COP_{system} and the lowest $\dot{m}_{total}$ values for all the boiler temperatures investigated. It was found that R602 provided the lowest COP_{system} and R1234yf gave the highest m_{total} values.

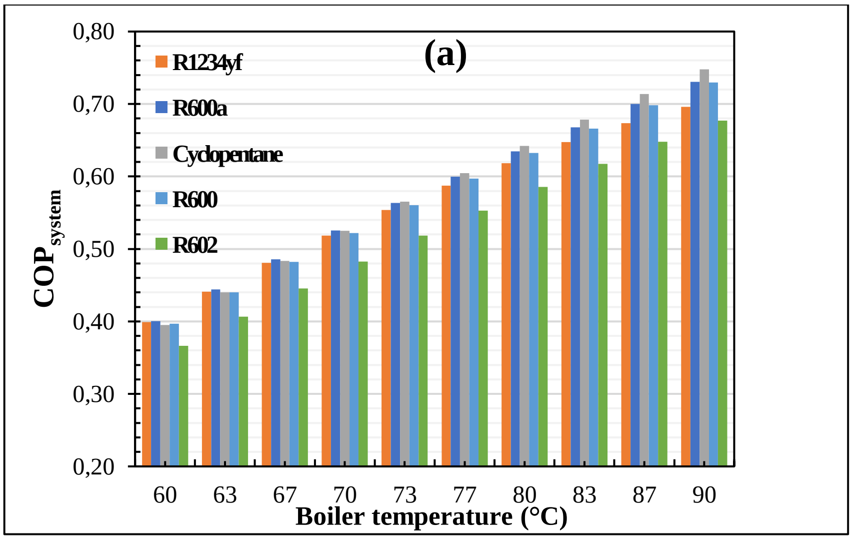


Figure 4. Variation of (a) COP_{system}, (b) EER and (c) $\dot{m}_{total}$ depending on the change of boiler temperature (T_{cond}=35°C and T_{evap}=0°C).

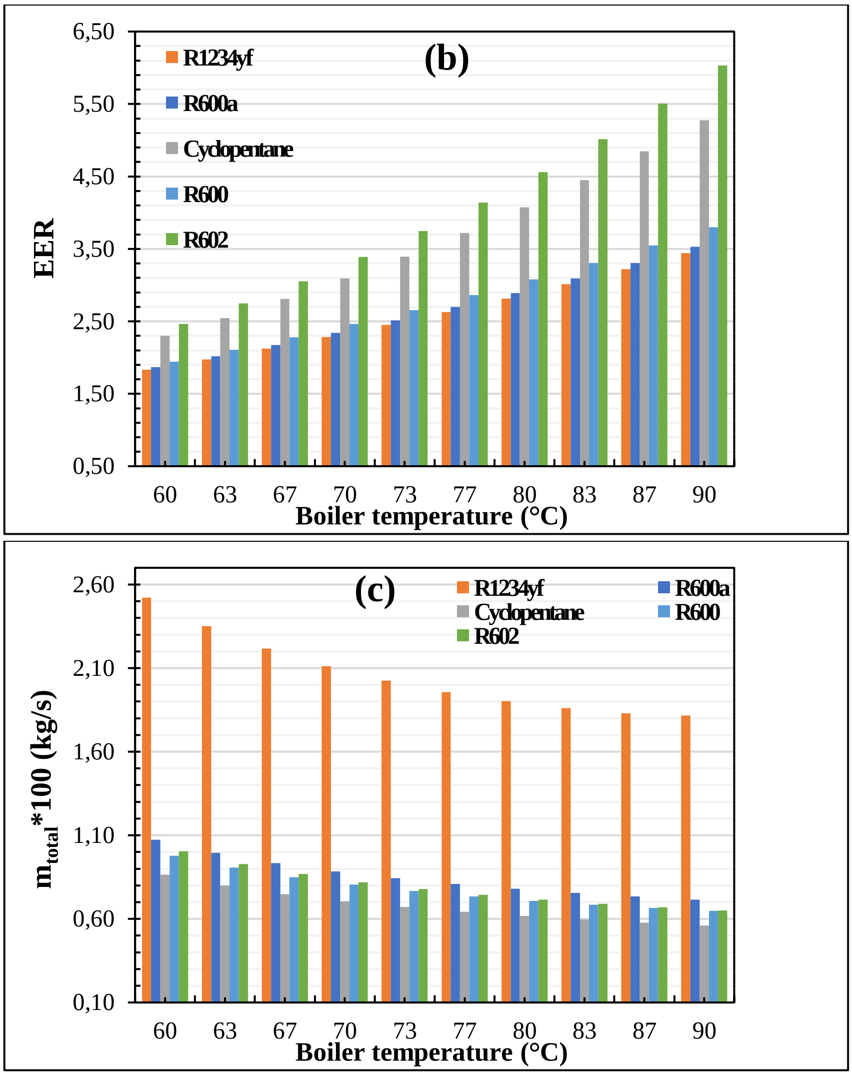


Figure 4 (continued). Variation of (a) COP$_{system}$, (b) EER and (c) $\dot{m}_{total}$ depending on the change of boiler temperature (T$_{cond}$=35°C and T$_{evap}$=0°C).

3.3 Examining the Influence of Condenser Temperature

Figure 5 demonstrates the way condenser temperature affects increase on COP$_{system}$, EER, CCR, and $\dot{m}_{total}$. In Figure 5 (a), it can be observed that the increase in condenser temperature results in a decrease in COP$_{system}$ for all working fluids. This is due to the impact of the temperature of the condenser on both the ORC and EBRC cycles. The pressure and enthalpy at the compressor outlet rise in tandem with the condenser temperature. This results in a rise in power consumption by the compressor, and a decrease in COP$_{EBRC}$. Additionally, condenser temperature rise results in an increase in m$_{ORC}$. The increase in mORC causes a rise in boiler capacity, which leads to a reduction in thermal efficiency of the ORC. Thus, the reduction in both COP$_{EBRC}$ and the thermal efficiency of the ORC leads to a reduction in COP$_{system}$. When all the fluids are considered, it has been found that cyclopentane provides the highest COP$_{system}$ values with an increase in condenser temperature. In terms of COP$_{system}$ with respect to the condenser temperature change, R600 and R600a fluids show very similar values. However, cyclopentane, when compared to R600a, yields a COP_{system} value that is 1.93% higher at a 40°C condenser temperature. The changes in EER and CCR as a function of condenser temperature for all fluids in the ORC-EBRC system are presented in Figures 4(b) and (c), respectively. The overall pattern in both data indicates that EER falls and CCR rises with increasing condenser temperature. When boiler and evaporator pressures are fixed, rising condenser temperature results in rising condenser pressure, which raises CCR and lowers EER. Based on the change in condenser temperature, the highest EER, was observed with R602, while the lowest CCR, also the desired condition, was found with R1234yf.

The change in $\dot{m}_{total}$ as a function of condenser temperature for all the fluids examined in the ORC-EBRC system is provided in Figure 4(d). Since the power generated by the turbine and the power consumed by the compressor are assumed to be equal, $\dot{m}_{ORC}$ must grow as the condenser temperature rises and the necessary compressor power increases. As the condenser temperature rises, $\dot{m}_{total}$ increases due to the ORC's increased mass flow rate and the presumption of a constant EBRC mass flow rate.The general trend in Figure 4(d) shows that $\dot{m}_{total}$ increases showing the rise in condenser temperature for every fluid under investigation. It was found that the lowest mass flow rate is obtained with the cyclopentane fluid at all examined condenser temperatures.

For both the ORC and EBRC cycles, the necessary working fluid mass flow rate can be adjusted flexibly using two flow regulators. This allows the mass flow rate of the working fluid entering both the EBRC cycle and the ORC to be regulated based on the operating conditions.

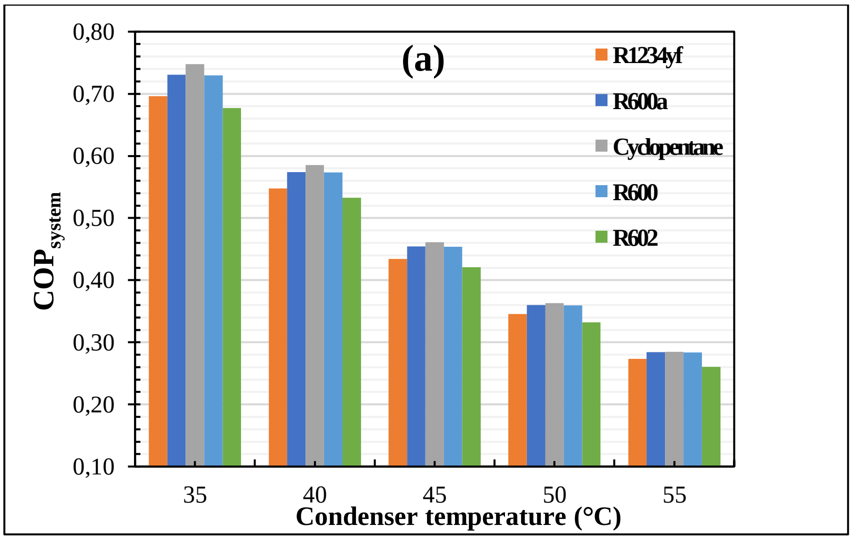


Figure 5. Variation of (a) COP_{system}, (b) EER (c) CCR and (d) $\dot{m}_{total}$ depending on the change of condenser temperature (T_{boiler}=90°C and T_{evap}=0°C).

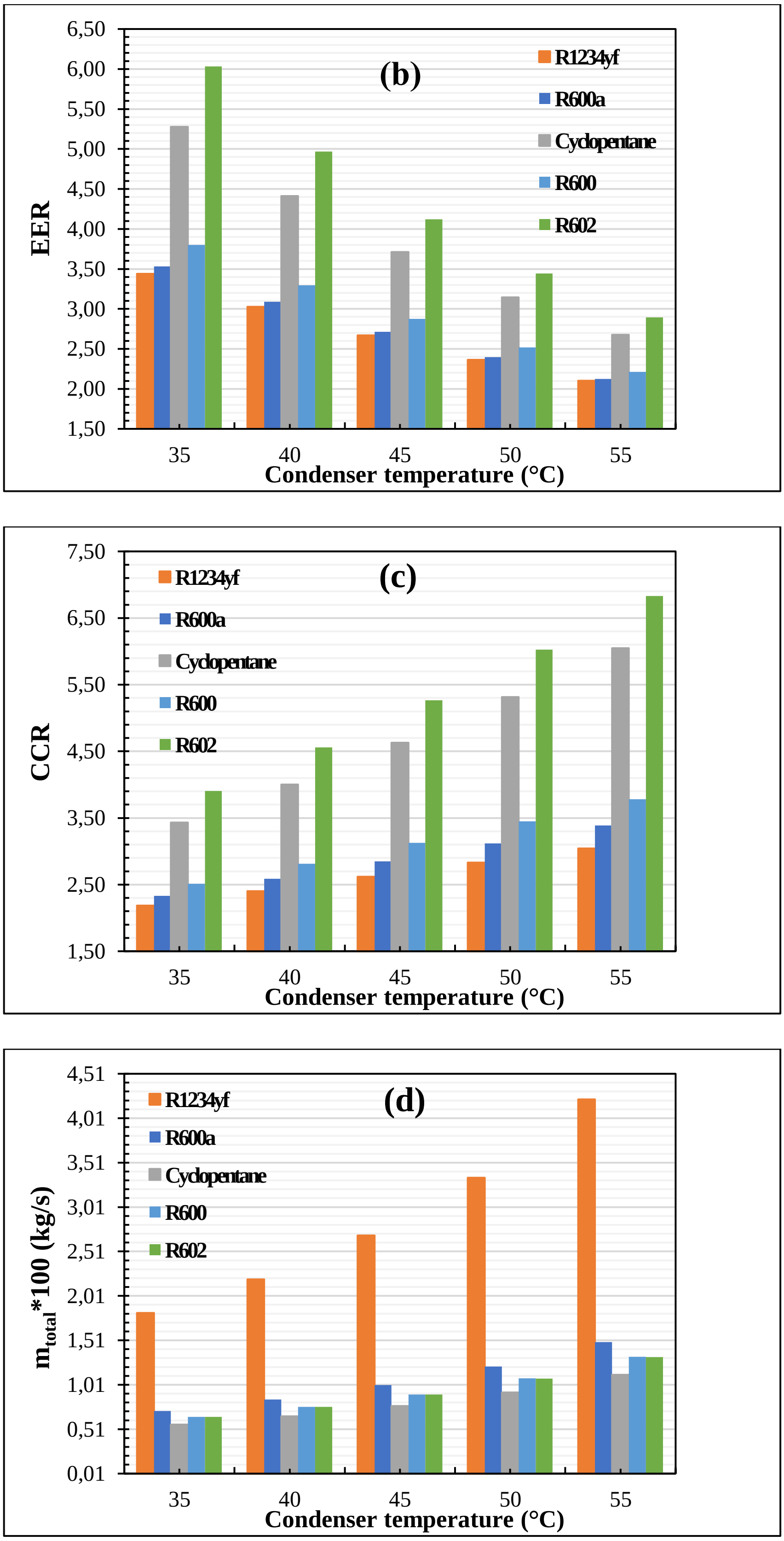


Figure 5 (continued). Variation of (a) COP_{system}, (b) EER (c) CCR and (d) $\dot{m}_{total}$ depending on the change of condenser temperature (T_{boiler}=90°C and T_{evap}=0°C).

3.4 Examining the Influence of Evaporator Temperature

The impact of an increase in evaporator temperature on COP_{system}, CCR, and m_{total} is depicted in Figure 6. It is evident from Figure 6(a) that when the temperature of the evaporator rises, the COP_{system} for all working fluids also rises. The ORC is unaffected by the evaporator temperature change. Consequently, the thermal efficiency of the ORC remains constant for the examined evaporator temperatures. At a certain condenser temperature, the compressor uses less power as the evaporator temperature rises for all fluids and the evaporator pressure rises as well. Also, the rise in evaporator temperature leads to an increase in cooling capacity. Both effects contribute to an increase in COP_{EBRC}. This results in an increase in COP_{system} as the evaporator temperature rises. The highest COP_{system} values are obtained with the cyclopentane fluid, while the lowest COP_{system} values are found with the R602 fluid. Upon examining the graph, a 1.76% increase in COP_{system} is observed for the cyclopentane fluid in contrast to the R600a fluid at -10°C in the evaporator. Figure 6 (b) demonstrates the change in CCR for each fluid in the ORC-EBRC system as a function of evaporator temperature. The overall pattern in the figure indicates that CCR falls as the evaporator temperature rises. This is because, for a certain condenser temperature, a decrease in CCR results from an increase in evaporator pressure brought on by an increase in evaporator temperature. The COPsystem rises as a result of the compressor consuming less power due to the decrease in CCR. R602 yields the greatest CCR value, with cyclopentane coming in second. Figure 6 (c) illustrates how the temperature of the evaporator affects the mtotal for each fluid in the ORC-EBRC system. Additionally, with the assumption of an increase in evaporator temperature and a constant EBRC mass flow rate, the The compressor's power consumption decreases. Given the assumption that the power consumed by the compressor is equal to the power generated by the turbine, the power generated by the turbine decreases as the evaporator temperature rises. As a result, the ORC's mass flow rate drops. Therefore, as the evaporator temperature rises, $\dot{m}_{total}$ falls, as seen in Figure 6(c). In this graph, the lowest $\dot{m}_{total}$ value is obtained with the cyclopentane fluid, while the highest $\dot{m}_{total}$ value is observed with the R1234yf fluid.

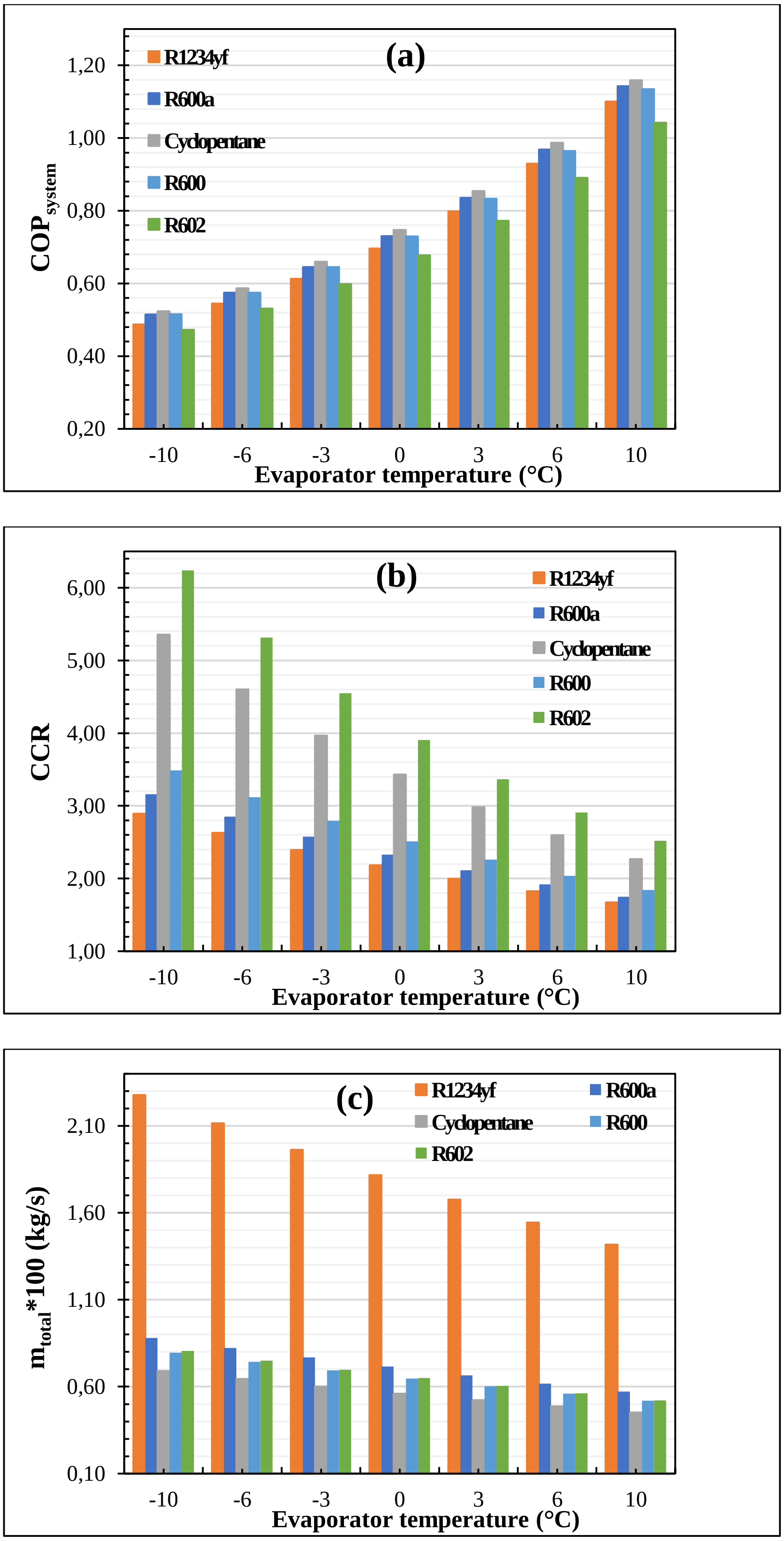
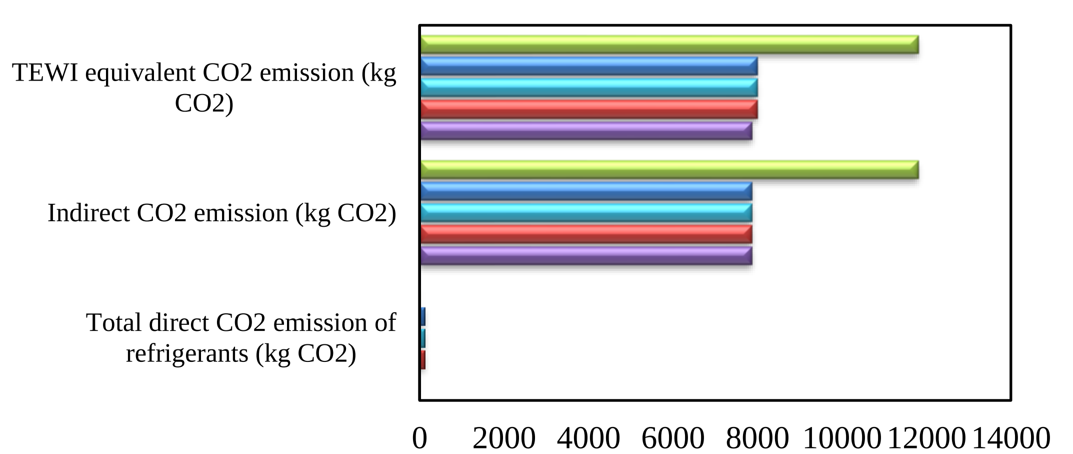


***Figure 6.** Variation of (a) COP_{system}, (b) CCR and (c) $\dot{m}_{total}$ depending on the change of evaporator temperature (T_{cond}=35°C and T_{boiler}=90°C).*

3.5 Examining the Total Equivalent Warming Impact (TEWI)

The Total Equivalent Warming Impact (TEWI), which is expressed in kilos of equivalent carbon dioxide, is a critical indicator for evaluating how systems affect the environment. The TEWI method considers both direct emissions and indirect emissions as their main components. The direct TEWI calculation specifically incorporates several factors, including the refrigerant leakage rate (L) of 12.5%, the system's operational life expectancy (N) of 15 years, the refrigerant consumption volume (M)-kilograms, and the recycling factor (α) of 70%. In contrast, the indirect TEWI calculation accounts for CO_2 emissions brought on by the compressor's electrical energy usage (E_{el}) by applying the indirect emission factor (β), which is 0.481 kg CO_2 per kWh. [24].

Figure 7 contains the TEWI analysis results for the five different fluids studied. Since the direct emission values are very small, they have little effect on the total value. However, when looking at the indirect values, a high value was found, especially for R1234yf compared to the other fluids. In this sense, looking at the total emission values, the lowest TEWI was obtained with cyclopentane fluid.



	Total direct CO2 emission of refrigerants (kg CO2)	Indirect CO2 emission (kg CO2)	TEWI equivalent CO2 emission (kg CO2)
R1234yf	3,18324	11.807,98	11.811,16
R602	118,284	7.878,30	7.996,59
R600a	118,284	7.878,30	7.996,59
R600	118,284	7.878,30	7.996,59
Cyclopentane	0,59142	7.878,30	7.878,90

Figure 7. Total equaivalent warming impact for refrigerants (T_{boiler}=90°C, T_{cond}=35°C and T_{evap}=0°C).

Table 4. Equations for TEWI analysis [25].

Equations	TEWI analysis
Direct (Equation 17)	$(\mathrm{TEWI})_{\mathrm{dir}} = \mathrm{GWP}_1 * \left(\mathrm{L}_1 * \mathrm{N} + \mathrm{M}_1 * (1-\alpha_1)\right) + \mathrm{GWP}_2 * \left(\mathrm{L}_2 * \mathrm{N} + \mathrm{M}_2 * (1-\alpha_2)\right)$
Indirect (Equation 18)	$(\mathrm{TEWI})_{\mathrm{ind}} = \mathrm{E}_{\mathrm{el}} * \beta * \mathrm{N}$
Total (Equation 19)	$\mathrm{TEWI} = (\mathrm{TEWI})_{\mathrm{dir}} + (\mathrm{TEWI})_{\mathrm{ind}}$

4 CONCLUSION

In conclusion, this study has thoroughly examined the thermodynamic performance of various environmentally friendly fluids within an integrated ORC and EBRC system. The primary aim of this research was to evaluate the potential of alternative refrigerants that not only optimize system performance but also minimize environmental impact. A range of natural and synthetic fluids was analyzed, with a focus on their thermodynamic properties, including COP, mass flow rates in the cycle, EER and CCR. The thermodynamic analysis involved detailed calculations of energy balances across different components of the integrated system, identifying the effects of fluid choice on system efficiency and environmental outcomes. The study found that certain fluids offered significant performance improvements over conventional refrigerants, demonstrating their suitability for use in low-grade heat recovery applications. Moreover, the environmental impact of these fluids was carefully considered in terms of their GWP and ODP. The results obtained as a result of the analysis are as follows.

When the cycle's performance is examined in relation to the temperature parameters of the boiler, condenser, and evaporator, it is determined that the best fluid is cyclopentane and the worst performing fluids are R1234yf and R602.

In terms of environmental impact, when the TEWI method was analyzed for each refrigerant, cyclopentane was found to have the lowest emission values in terms of kg CO_2.

The results of this comprehensive analysis provide valuable insights into the selection of optimal working fluids for ORC-EBRC system, offering guidance for future research and real-world applications where both energy efficiency and environmental sustainability are crucial.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

Artificial intelligence-supported language editing tools were employed to improve the clarity and coherence of the final manuscript.

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