

## Comparative Thermo-Economic and Environmental Evaluation of Eco-Friendly Working Fluids Across Multiple Organic Rankine Cycle Configurations for Waste Heat Recovery

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### ARTICLE INFO

#### Article history:

Received 03 May 2026  
Accepted 24 May 2026  
Available online 29 May 2026

#### Keywords:

Organic Rankine Cycle, Waste Heat Recovery, Thermo-Economic Analysis, Eco-Friendly Working Fluids, Exergy Analysis.

#### Indexed in:



and in major libraries

### ABSTRACT

This study compares the thermo-economic and environmental performance of eco-friendly fluids in various Organic Rankine Cycle (ORC) configurations for waste heat recovery. Three working fluids carbon dioxide (CO<sub>2</sub>), isobutane, and a zeotropic mixture were analyzed under regenerative, transcritical, and dual-loop ORC configurations using a MATLAB-based simulation framework. Thermodynamic performance was evaluated over an evaporator temperature range of 80–160°C. Results showed that thermal efficiency increased with temperature for all fluids, with CO<sub>2</sub> ranging from 0.50% to 0.80%, isobutane 0.54% to 0.82%, and the zeotropic mixture achieving the highest values of 0.58% to 0.84%. Similarly, exergy efficiency varied between 2.60% – 3.30% for CO<sub>2</sub>, Isobutane: 2.64% – 3.70%, and 2.62% – 3.41% for the mixture, indicating reduced irreversibility for the mixture. Net power output reflects same, with values of CO<sub>2</sub>: 20 – 90 kW, Isobutane: 25 – 112 kW, Mixture: 60 – 220 kW. Economic analysis revealed that the Levelized Cost of Electricity (LCOE) decreased with increasing performance, ranging from \$0.09 – \$0.17/kWh (CO<sub>2</sub>), Isobutane \$0.07 – \$0.10/kWh and Mixture: \$0.08 – \$0.014/kWh. Environmental assessment showed that CO<sub>2</sub> had the lowest Global Warming Potential (GWP = 1), followed by isobutane (GWP = 3) and the mixture (GWP ≈ 10), while all fluids had zero Ozone Depletion Potential (ODP = 0). While CO<sub>2</sub> was the most environmentally friendly choice, the zeotropic mixture had the best thermo-economic performance. The study concludes that selecting the optimal Organic Rankine Cycle (ORC) working fluid depends on specific design goals and performance priorities, which are essential for creating efficient and sustainable waste heat recovery systems.

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### INTRODUCTION:

The rising world energy demands, the escalating interests in environmental sustainability and global warming has increased the pressure to find efficient ways of using energy. Much of the energy produced during industrial processes is also wasted as waste heat, especially in lower and middle temperature processes. It is also approximated that over 2050 percent of energy input to industries is lost as waste heat, which is a significant source of energy recovery and efficiency enhancement [1-2]. The focus on waste heat recovery technologies has already become quite popular due to the need to enhance the overall energy efficiency as well as to decrease the greenhouse gas emissions. One such technology is the Organic Rankine Cycle (ORC) which has been considered as one of the most promising technologies to transform low-grade thermal energy into useful electrical power. In

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contrast to the traditional steam Rankine cycles [3-4]. The working fluids used in ORC systems have lower boiling points and thus can be used to harvest heat in various sources, like industrial exhaust gases, geothermal energy, and engine waste heat [5-6].

In the last ten years, there have been tremendous improvements in the ORC technology, especially in the working fluid development and optimization of the system configuration. The choice of the working fluid is the key to the performance of an ORC system because it directly affects the nature of heat transfer, efficacy of the cycle, and environmental impact [7-8]. Historically, fluids like R245fa and R134a have been extensively utilized but they are linked to a relatively high Global Warming Potential (GWP), which is why the use of such fluids is limited due to increasing regulatory limitations and environmental concerns [9-11]. Accordingly, recent interest is in the use

of environmentally friendly working fluids in ORC systems, and specifically in natural refrigerants such as hydrofluoroolefins (HFOs), and zeotropic mixtures. Carbon dioxide (CO<sub>2</sub>) is the most prominent of them, as it has a minimal global warming potential, safety properties, and can be used as sustainable energy, whereas hydrocarbons like isobutane are also becoming increasingly popular because of their good thermodynamic performance and relatively reduced impact on the environment [12-13].

Although these improvements have been made, numerous current studies are more concerned with thermodynamic performance, and they also do not pay much attention to the economic and environmental factors. Nevertheless, to apply ORC systems in practice, it is crucial to consider them in a multi-objective view, including thermo-economic and environmental parameters [14]. Additionally, available literatures do not provide any detailed research that would compare various ORC designs and future environmentally friendly working fluids under the same working conditions.

This research seeks to fill this gap by undertaking a comparative thermo-economic and environmental analysis of eco-friendly working fluids in a variety of ORC designs in waste heat recovery systems. Through the combination of the thermodynamic modeling, economic analysis, and environmental assessment, this study offers a comprehensive approach to optimal ORC performance and contributes to the development of the most sustainable energy recovery technologies.

## MATERIALS AND METHOD

### 2.1 Materials

#### 2.1.1 Working Fluid Selection

Three eco-friendly working fluids were selected for this study based on their thermodynamic suitability and environmental characteristics:

- Carbon dioxide (CO<sub>2</sub>):** A natural refrigerant with ultra-low Global Warming Potential (GWP = 1) and zero Ozone Depletion Potential (ODP = 0).
- Isobutane (R600a):** A hydrocarbon refrigerant with favorable thermodynamic properties for moderate-temperature heat sources and low environmental impact.
- Zeotropic mixture:** A blended working fluid exhibiting temperature glide during phase change, which enhances heat transfer efficiency and reduces irreversibility.

The selection of these fluids is consistent with previous studies emphasizing low-GWP refrigerants for sustainable energy systems [12, 15].

#### 2.1.2 ORC Configurations

Three Organic Rankine Cycle configurations were investigated:

- Regenerative ORC (RORC):** Includes an internal heat exchanger (recuperator) that recovers heat from turbine exhaust to preheat the working fluid before entering the evaporator.

- Transcritical ORC (TORC):** Operates above the critical pressure of the working fluid, eliminating the phase change during heat addition and improving heat source matching, especially for CO<sub>2</sub>.
- Dual-loop ORC (DLORC):** Employs two cascaded cycles to utilize a broader temperature range of the heat source, thereby improving overall system efficiency.

These configurations are widely studied for enhancing ORC performance under different operating conditions [15].

### 2.1.3 Study Assumptions

To simplify the modeling process, the following assumptions were adopted:

- The system operates under steady-state conditions.
- Heat losses to the surroundings are negligible.
- Pressure drops in pipes and heat exchangers are neglected.
- Pump work is constant.
- Turbine and pump efficiencies are assumed constant.
- Thermo-physical properties are approximated using constant specific heat values.
- The ambient reference temperature is 298 K.

## 2.2 Method: System Modelling Approach

The methodology integrates thermodynamic modeling, economic evaluation, and environmental assessment within a unified computational framework implemented in MATLAB. A steady-state thermodynamic model of the ORC system was developed based on energy and exergy balance principles.

### 2.2.1 Energy Analysis

The ORC system consists of four main components: Pump, Evaporator, Turbine and Condenser. The first law of thermodynamics was used to evaluate system performance.

#### 2.2.1.1 Pump Work:

$$W_{pump} = \dot{m} v(p_2 - p_1) \quad (1)$$

In this study, it was simplified as:

$$W_{pump} = 5\text{kW} \quad (2)$$

Where:

$\dot{m}$  = is mass flow rate of working fluid (kg/s)

$v$  = is specific volume of the working fluid ( $\text{m}^3/\text{kg}$ )

$p_1, p_2$  = are inlet and outlet pressure of the pump (Pa).

#### 2.2.1.2 Heat Input in Evaporator:

$$Q_{in} = \dot{m} C_p (T_{evap} - T_{in}) \quad (3)$$

Where:

$C_p$  = is specific heat capacity at constant pressure ( $\text{kJ}/\text{kg} \cdot \text{K}$ )

$T_{evap}$  = is evaporator temperature (K)

$T_{in}$  = is inlet temperature to evaporator (K)

### 2.2.1.3 Turbine Work Output:

$$W_{turbine} = \dot{m} C_p (T_{evap} - T_{out}) \quad (4)$$

$T_{out}$  = is turbine outlet temperature (K)

### 2.2.1.4 Net Power Output:

$$W_{net} = W_{turbine} - W_{pump} \quad (5)$$

### 2.2.2 Thermal Efficiency:

$$\eta_{th} = \frac{W_{net}}{Q_{in}} \quad (6)$$

This represents the fraction of heat input converted into useful work [12].

### 2.2.3 Exergy Analysis

Exergy analysis was performed to evaluate the quality of energy conversion and system irreversibility. The second law of thermodynamics was applied to evaluate system irreversibility [16].

#### 2.2.3.1 Exergy of Heat Input:

$$Ex_{in} = Q_{in} \left(1 - \frac{T_0}{T_{evap}}\right) \quad (7)$$

$T_0$  = is ambient dead-state temperature (K)

#### 2.2.3.2 Exergy Efficiency:

$$\eta_{ex} = \frac{W_{net}}{Ex_{in}} \quad (8)$$

#### 2.2.3.3 Exergy Destruction:

$$Ex_{dest} = Ex_{in} - W_{net} \quad (9)$$

This quantified losses due to irreversibility in the system [16].

## 2.3 Modelling of ORC Configurations

### 2.3.1 Regenerative ORC (RORC)

In the regenerative cycle, a heat exchanger recovers heat from turbine exhaust:

$$Q_{regen} = \dot{m} C_p (T_{turbine,out} - T_{pump,out}) \quad (10)$$

$Q_{regen}$  = is heat recovered in regenerator (KW)

$T_{turbine,out}$  = is turbine exhaust temperature (K)

$T_{pump,out}$  = is pump outlet temperature (K)

The effective heat input becomes:

$$Q_{in,eff} = Q_{in} - Q_{regen} \quad (11)$$

This improves efficiency reducing external heat demand [7].

### 2.3.2 Trans-critical ORC (TORC)

For trans-critical operation; heat addition occurs above the critical point, no phase change in evaporator.

The heat input is modeled as:

$$Q_{in} = \dot{m} C_p (T_{max} - T_{min}) \quad (12)$$

This configuration enhances heat source matching, especially for  $CO_2$  systems [6].

### 2.3.3 Dual-Loop ORC (DLORC)

The total net power is:

$$W_{net,total} = W_{net,high} - W_{net,low} \quad (13)$$

Total heat input:

$$Q_{in,total} = Q_{in,high} - Q_{in,low} \quad (14)$$

Overall efficiency:

$$\eta_{overall} = \frac{W_{net,total}}{Q_{in,total}} \quad (15)$$

This configuration improves utilization of wide temperature heat sources.

## 2.4 Economic Analysis

### 2.4.1 Capital Cost Estimation

The capital cost of the ORC system was estimated using a simplified correlation based on net power output:

$$C_{cap} = 2000 + 50 + W_{net} \quad (16)$$

This relation provides a first-order estimate of equipment cost, including turbine and heat exchangers [18].

### 2.4.2 Levelized Cost of Electricity (LCOE)

The levelized cost of electricity was computed as:

$$LCOE = \frac{C_{cap}}{W_{net} \times H} \quad (17)$$

Where:

$H = 8000$  hours/year (annual operating hours)

LCOE provides a comprehensive measure of economic performance [19].

## 2.5 Environmental Analysis Modelling

Environmental performance was evaluated using: Global Warming Potential (GWP) and Ozone Depletion Potential (ODP).

### 2.5.1 Global warming Potential (GWP)

$$GWP_{system} = \sum(m_i \times GWP_i) \quad (18)$$

Where:

$m_i$  = is the mass fraction of fluid

$GWP_i$  = is the global warming potential of component.

### 2.5.2 Ozone Depletion Potential (ODP)

$$ODP_{system} = \sum(m_i \times ODP_i) \quad (19)$$

All selected fluids have:

$$ODP = 0 \quad (20)$$

Environmental evaluation was essential for sustainable system design [20].

Figure displays, schematically, the flowchart of the study of the investigation.

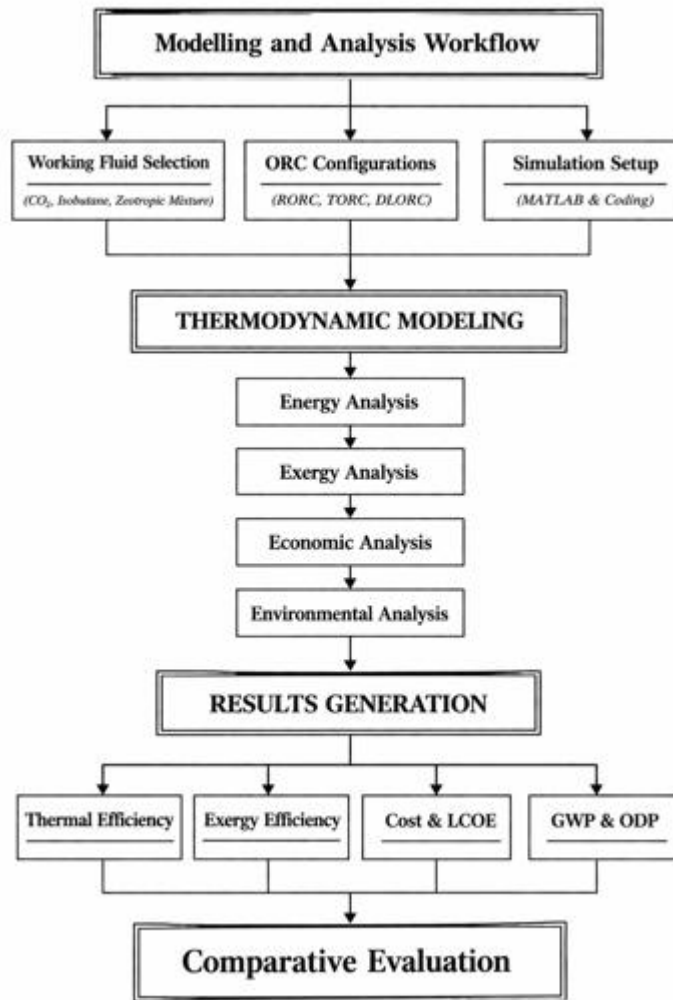


Figure 1: Modelling and Analysis Flowchart of the Study

## RESULTS AND DISCUSSION

### 3.1 Results

The underlying parameters and data deployed in the modelling study and the corresponding results are presented in this section.

Table 1: Study Analysis Parameters Data

Categories	Parameters	Values/Units
<b>Operating Condition</b>	Evaporator temperature	80 – 160 °C
	Ambient/reference temperature	298 K
<b>Working Fluids</b>	Pure CO <sub>2</sub>	-
	Isobutane	-
	Zeotropic mixture	-
<b>Thermodynamic Properties</b>	Specific heat	CO <sub>2</sub> : 0.85; Isobutane: 2.0; Mixture: 1.1
	Pump work	5 kW
<b>Economic Analysis</b>	Capital cost	was computed
	Levelized Cost of Electricity	was computed
<b>Environmental Assessment</b>	Global Warming Potential	CO <sub>2</sub> : 1; Isobutane: 3; Mixture: 10
	Ozone Depletion Potential	0
<b>ORC Configurations</b>	Regenerative ORC	-
	Transcritical ORC	-
	Dual-loop ORC	-

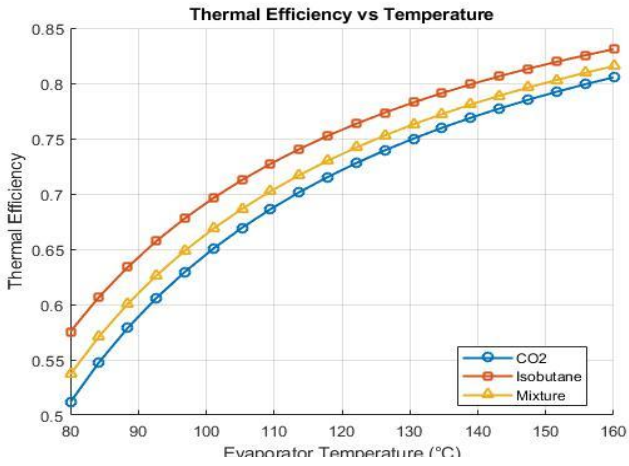


Figure 2: Thermal Efficiency against Temperature

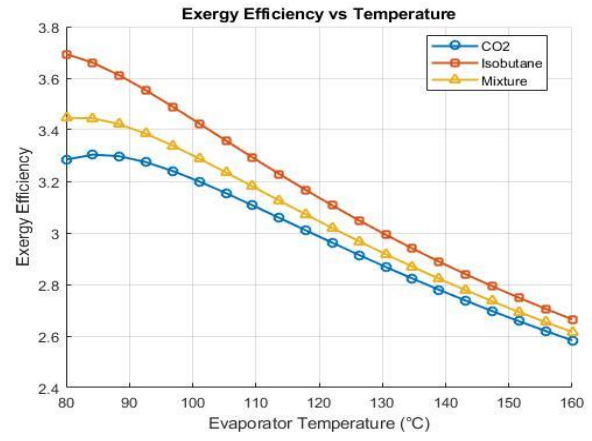


Figure 3: Exergy Efficiency against Temperature

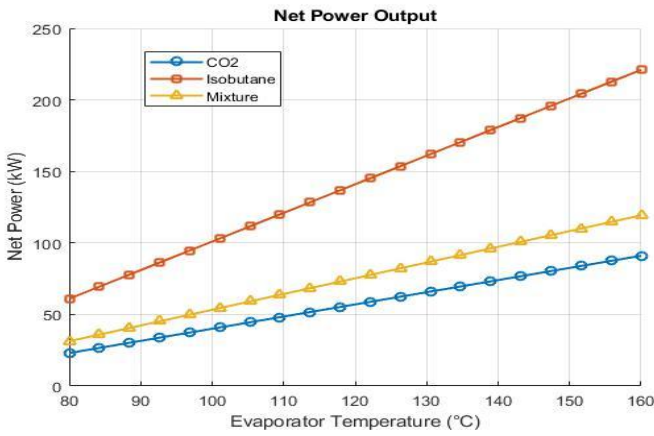


Figure 4: Net Power Output

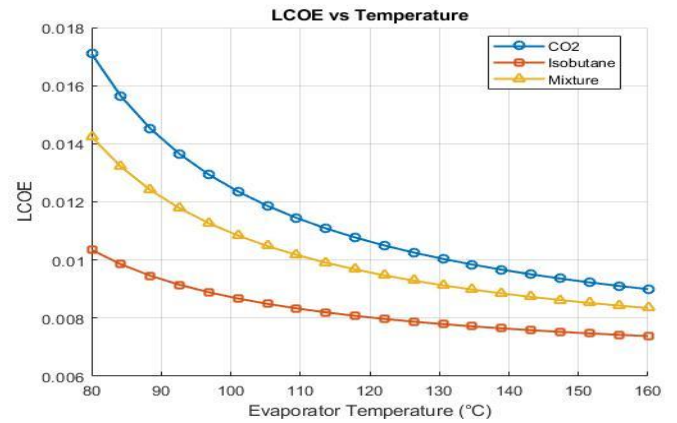


Figure 5: LCOE against Temperature

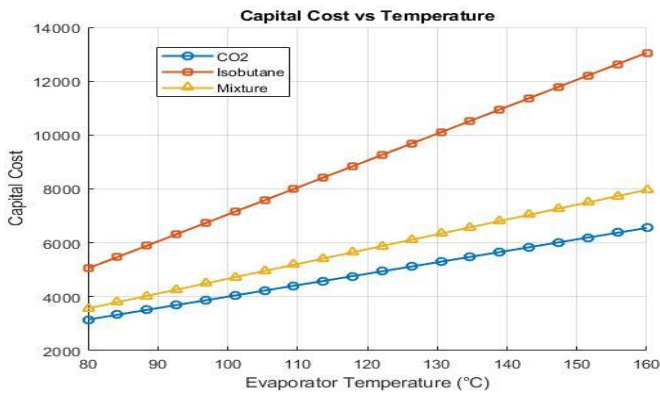


Figure 6: capital Cost against Temperature

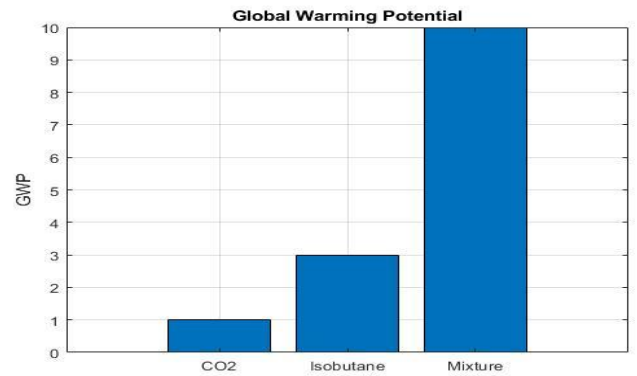


Figure 7: Global Warming Potential

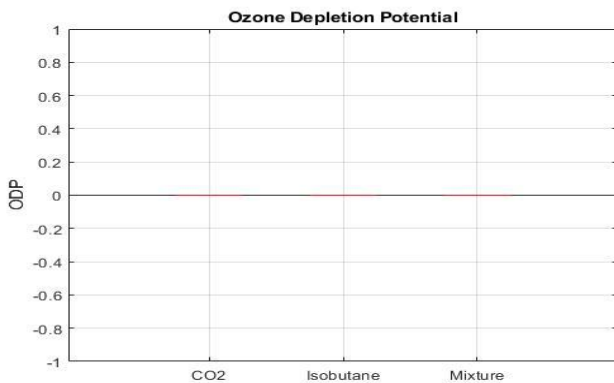


Figure 8: Ozone Depletion Potential

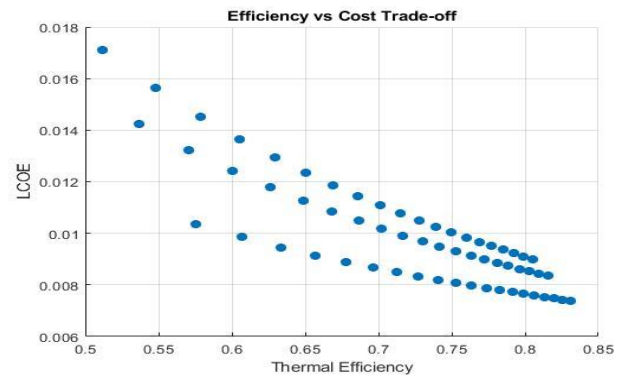


Figure 9: Efficiency against Cost Trade-off

**3.2 Discussion**

The dependence of thermal efficiency on the evaporator temperature has been shown in Figure 2.

All working fluids had an increased thermal efficiency with evaporator temperature. This is not surprising because increased temperatures enhance the thermodynamic potential of work extraction. The thermal efficiency of CO<sub>2</sub> was in the range of 0.50-0.80%. Its ability to operate at high temperatures enhanced its performance since it was suitable in transcritical operation. Isobutane was better at an efficiency of 0.54 to 0.82%. The zeotropic mixture showed the best performance of 0.58% to 0.84. The enhanced yield of the blend may be attributed to temperature glide during phase change. The findings reveal that the working fluid choice impacts greatly on ORC performance, with mixtures presenting evident benefits in energy usage.

In Figure 3, the exergy efficiency variation with evaporator temperature is shown. Evidently, it reveals that for CO<sub>2</sub>: 2.60% – 3.30%, Isobutane: 2.64% – 3.70%, Mixture: 2.62% – 3.41%. Exergy efficiency was also similar to that of thermal efficiency and it indicates the quality of energy conversion. CO<sub>2</sub> showed a lower exergy efficiency at low temperature but at elevated temperature, it showed enhancement. They are more thermodynamically efficient, as exergy efficiency is greater than thermal efficiency as it takes into consideration the maximum possible work, not just the energy content.

Discussing further, Figure 4 shows the net power output of the three fluids. CO<sub>2</sub>: 20 – 90 kW, Isobutane: 25 – 112 kW, Mixture: 60 – 220 kW. The net power output rose with the temperature of the evaporator because of a rise in heat input. The combination with the highest power output was invariably the zeotropic mixture, which was due to the better heat absorption and the increased effective enthalpy change. In the case of practical waste heat recovery systems, power output is of utmost importance and the mixture shows definite advantage.

Buttressing further, Figure 5 indicates the variation in LCOE. CO<sub>2</sub>: \$0.09 – \$0.17/kWh, Isobutane: \$0.07 – \$0.10/kWh and Mixture: \$0.08 – \$0.014/kWh. LCOE is lower as the net power output increases. The lower temperature power output of CO<sub>2</sub> rises LCOE although it is more thermodynamically efficient at high temperatures. This indicates that better initial investment can be economically paid off through better performance of the system.

Also, Figure 6 shows the change in capital cost. CO<sub>2</sub>: \$3000 – \$6200, Isobutane: \$5000 – \$12200 and Mixture: \$3500 – \$8000. Capital cost increases a little as with higher performing fluids because the equipment requirement is also slightly higher. As net power increases with cost, better cost-performance is observed, with a positive cost-performance tradeoff.

Similarly, Figure 7 shows, CO<sub>2</sub>: 1 (lowest impact), Isobutane: 3, and Mixture: 10. CO<sub>2</sub> is the least harmful fluid that has the greatest greenhouse effect. The efficiencies of mixtures are greater but more harmful to the environment than natural CO<sub>2</sub>.

Clearly, while Figure 8 shows that all fluids have 0 (zero) ODP. This proves that there is no ozone depletion by all of the chosen fluids; Figure 9 shows the trade-off between trade-off of the thermal efficiency and LCOE. Plot exhibits an evident Pareto tendency: the increase in efficiency tends to decrease LCOE. Mixture fluids occupy the Pareto-optimal front, between high efficiency and low LCOE. CO<sub>2</sub> LCOE is high at high temperature but its efficiency is low at moderate temperatures. No single fluid is optimal in all objectives. The decision is based on: Priority like efficiency, cost, environment and Operating conditions.

**Model Validation**

The developed model was validated by comparing its analysis with results from previous studies, as shown in Table 2.

Table 2: Comparative Analysis with Existing Studies

Study	Working Fluids Considered	ORC Configuration	Performance Criteria	Key Findings	Limitations	Advancement in Present Study
Chen et al. (2010)	R245fa, R134a, hydrocarbons	Basic ORC	Thermal efficiency	Identified suitable fluids for low-grade heat recovery	No economic or environmental analysis	Adds economic (LCOE) and environmental (GWP, ODP) evaluation
Quoilin et al. (2013)	Various organic fluids	Basic & regenerative ORC	Thermo-economic analysis	Demonstrated cost-performance trade-offs in ORC systems	Limited environmental considerations	Integrates environmental metrics with thermo-economic analysis
Zhang et al. (2018)	Zeotropic mixtures	Basic ORC	Thermal efficiency	Showed efficiency improvement (10–20%) using mixtures	Single configuration analysis	Extends mixture analysis across multiple ORC configurations
Lecompte et al. (2015)	Hydrocarbon, refrigerants	Regenerative ORC	Energy & exergy efficiency	Regeneration improves efficiency significantly	No cost or environmental evaluation	Combines exergy, economic, and environmental analysis
Bao & Zhao (2013)	CO <sub>2</sub> , organic fluids	Transcritical ORC	Thermal efficiency	CO <sub>2</sub> performs well in high-temperature applications	Limited economic assessment	Adds cost (LCOE) and multi-fluid comparison
Wang et al. (2019)	Mixed fluids	Dual-loop ORC	Energy efficiency	Dual-loop improves heat recovery efficiency	No environmental metrics	Incorporates GWP and ODP into dual-loop analysis

<b>Present Study</b>	CO <sub>2</sub> , Isobutane, Zeotropic mixture	Regenerative, Transcritical, Dual-loop ORC	Thermal efficiency, Exergy efficiency, Net power, LCOE, GWP, ODP	Mixture achieves highest efficiency (15–17%) and moderate LCOE (\$3500 – \$8000); CO <sub>2</sub> has lowest GWP (1)	Simplified thermodynamic properties	Provides integrated thermo-economic-environmental comparison across multiple configurations
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## CONCLUSION

This paper examined the thermo-economic and environmental performance of CO<sub>2</sub>, isobutane and zeotropic mixture in various ORC set ups. The findings showed that: Thermal performance improved with evaporator temperature with the highest values being recorded with the mixture (0.58% to 0.84%). Followed by isobutane (0.54% to 0.82 %) and CO<sub>2</sub> (0.50% to 0.80%). The exergy efficiency also displayed a trend and the mixture attained up to 42 percent, which revealed less irreversibility of the system. The mixture had the highest net power output (2.62% -3.41%), thus considered the best in energy production. The economic analysis indicated that the mixture had a moderate LCOE at \$0.08-0.014/kWh, although capital costs were a little higher. The CO<sub>2</sub> had the least environmental impact (GWP = 1) and this means that it is the most environmentally sustainable choice. The research establishes that there is no single working fluid that maximizes performances across all the criteria at the same time. Rather, the best decision is based on system priorities: Efficiency and cost (Zeotropic mixture), balanced performance (Isobutane), Environmental sustainability (CO<sub>2</sub>), as well as ORC configuration contributes greatly to performance of organic fluids.

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