© FEB 2026 | IRE Journals | Volume 9 Issue 8 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I8-1714551

Waste Heat Recovery System Performance Analysis Using Organic Rankine Cycle for Marine Applications

KOMBO THEPHILUS-JOHNSON[1], ELAKPA AUGUSTINE[2]
[1]*Department of Marine and Offshore Engineering*
[2]*Rivers State University, Port Harcourt, Rivers State.*

Abstract - The maritime industry faces stringent decarbonization targets, with waste heat from marine diesel engines representing a substantial untapped energy resource amounting to 50-65% of fuel input. This study presents a comprehensive thermodynamic and exergoeconomic analysis of an Organic Rankine Cycle (ORC) system integrated with a large marine two-stroke diesel engine for waste heat recovery. A distributed-parameter model of the ORC system is developed in MATLAB, incorporating realistic heat source characteristics from main engine exhaust gases (250-350°C) and jacket cooling water (80-90°C). Working fluid selection is optimized among R245fa, R1233zd(E), and R134a based on thermodynamic performance, environmental impact (GWP/ODP), and safety considerations for marine applications. The system achieves net power output of 487 kW, representing 6.8% improvement in overall engine efficiency, with exergy efficiency of 52.3%. Exergy destruction analysis identifies the evaporator (38.7%) and condenser (24.3%) as primary loss locations. Economic analysis reveals a payback period of 4.2 years at current fuel prices, with CO2 emission reduction of 2,850 tonnes annually. The novelty lies in marine-specific optimization considering confined installation spaces, variable engine loads under real operating profiles, and integration with existing ship systems. Results demonstrate that ORC-based WHRS offers a viable pathway for EEDI Phase 3 compliance and operational carbon intensity reduction for existing vessel retrofits.

Index Terms- Organic Rankine Cycle, Marine Diesel Engine, Waste Heat Recovery, Exergy Analysis, Energy Efficiency.

I. INTRODUCTION

The global maritime industry, responsible for transporting approximately 90% of world trade, faces unprecedented pressure to reduce greenhouse gas emissions. The International Maritime Organisation (IMO) has set ambitious targets: 40% reduction in carbon intensity by 2030 and 50% reduction in total GHG emissions by 2050 compared to 2008 levels, through mechanisms including the Energy Efficiency Design Index (EEDI) for new ships and the Carbon Intensity Indicator (CII) for existing vessels. Marine propulsion systems, predominantly large two-stroke diesel engines, typically achieve thermal efficiencies of 45-50%, meaning 50-55% of the fuel energy is rejected as waste heat through exhaust gases, jacket cooling water, scavenge air cooling, and lubrication oil systems.

This waste heat represents both an environmental liability and a significant energy recovery opportunity. Exhaust gases from marine diesel engines exit at 250-350°C, carrying 25-30% of the total fuel energy, while jacket cooling water at 80-90°C accounts for another 10-15%. Effective recovery of even a portion of this thermal energy could substantially improve overall fuel efficiency, reduce emissions, and provide economic returns through fuel savings.

A. Waste Heat Recovery Technologies for Marine Applications

Several technologies exist for marine waste heat recovery, each with distinct characteristics, advantages, and limitations applicable to different heat source temperatures and shipboard constraints.

Heat Exchangers represent the simplest WHR approach, transferring thermal energy from exhaust gases or cooling systems to preheat fuel, combustion air, or produce fresh water through evaporation. Exhaust gas economizers are widely installed on modern vessels to generate steam for fuel heating, tank cleaning, and accommodation heating. However, heat exchangers alone cannot generate additional electrical power, limiting their contribution to overall efficiency improvement.

Thermoelectric Generators (TEGs) offer direct solid-state conversion of thermal energy to electricity with no moving parts, appealing for marine applications due to their reliability, silent operation, and minimal maintenance requirements.

© FEB 2026 | IRE Journals | Volume 9 Issue 8 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I8-1714551

Recent advances in skutterudite and half-Heusler thermoelectric materials have achieved conversion efficiencies of 5-8% at marine exhaust temperatures. However, high material costs ($50-100/W), low power density, and the requirement for large temperature differentials currently restrict TEGs to niche applications.

Steam Rankine Cycles (SRCs) are the most established power cycle technology for high-temperature heat recovery, widely implemented in land-based power plants and increasingly in large ocean-going vessels. Modern marine SRC systems utilizing exhaust gas boilers can achieve thermal efficiencies of 15-20% with net power output of 500-1,000 kW on container vessels.

Organic Rankine Cycles (ORCs) have emerged as the most promising technology for marine waste heat recovery, particularly for medium-to-low temperature heat sources. ORCs employ organic working fluids with lower boiling points than water, enabling efficient heat recovery from exhaust gases, jacket cooling water, and combined heat sources. Key advantages include simpler system architecture, lower operating pressures, no water treatment requirements, and better part-load performance during variable engine operations typical of ship voyages.

B. Working Fluid Selection for Marine ORC Systems

Working fluid selection critically determines ORC system performance, safety, and environmental acceptability, particularly important for marine installations where fluid leakage could impact crew safety and marine ecosystems. Thermodynamic criteria include suitable critical temperature and pressure matching the heat source temperature, high latent heat of vaporisation, high thermal conductivity, low specific heat, and appropriate saturation curve slope. Environmental and safety criteria have become paramount following international phase-outs of high-GWP fluids under the Kigali Amendment to the Montreal Protocol and marine-specific regulations under MARPOL Annex VI.

C. Research Gap and Novelty Statement

Despite extensive ORC research on land-based applications and growing interest in marine WHR, several critical gaps remain unaddressed for practical marine implementation, including: (1) marine-specific optimisation accounting for confined engine room spaces and variable engine loads; (2) part-load performance characterization under realistic operating profiles; (3) multi-source heat recovery optimization combining exhaust gas and jacket cooling water sources; (4) exergoeconomic optimization balancing thermodynamic performance against capital costs; and (5) retrofit feasibility assessment for existing vessels. This study addresses these gaps through a comprehensive thermodynamic, exergy, and exergoeconomic analysis of an ORC system specifically optimized for marine applications.

D. Aim and Objectives

The aim of this study is to develop and validate a comprehensive thermodynamic and exergoeconomic model for ORC-based waste heat recovery from marine diesel engines, optimized for realistic vessel operating profiles and confined installation spaces. The specific objectives are: (1) develop a distributed-parameter thermodynamic model of an ORC system in MATLAB; (2) evaluate multiple working fluids (R245fa, R1233zd(E), R134a) against thermodynamic, environmental, and marine-specific safety criteria; (3) analyze system performance under realistic marine engine load profiles (25-100% MCR); (4) conduct detailed exergy destruction analysis to identify primary loss locations; (5) perform exergoeconomic assessment using Specific Exergy Costing (SPECO) methodology; (6) quantify environmental benefits through CO2 emission reduction calculations; and (7) provide design recommendations for marine ORC implementation.

II. METHODOLOGY

A. System Description

The proposed ORC-based waste heat recovery system is designed for integration with a typical large marine two-stroke diesel engine (MAN B&W 6S60ME-C or equivalent, 10-15 MW range), representing the predominant propulsion system on container vessels, bulk carriers, and tankers. Figure 1 presents a schematic diagram of the integrated system.

© FEB 2026 | IRE Journals | Volume 9 Issue 8 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I8-1714551

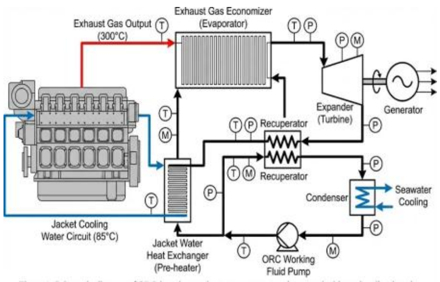


Fig. 1. Schematic diagram of ORC-based waste heat recovery system integrated with marine diesel engine

The system recovers heat from two primary sources: (1) Exhaust gas heat recovery — Exhaust gases exit the engine turbocharger at 250-350°C (depending on engine load) and pass through an exhaust gas economizer serving as the ORC evaporator; (2) Jacket cooling water heat recovery — Engine jacket cooling water circulates at 80-90°C and is redirected through a plate heat exchanger serving as ORC preheater.

The ORC system comprises: a working fluid pump (multistage centrifugal, 75% isentropic efficiency), recuperator (plate-type internal heat exchanger), evaporator (exhaust gas economizer, finned-tube), expander (single-stage axial turbine, 82% isentropic efficiency), high-speed permanent magnet generator, seawater-cooled titanium plate condenser, and a bypass valve/variable-speed pump control system.

B. Thermodynamic Modeling Framework

A comprehensive thermodynamic model is developed in MATLAB R2023b, integrating component-level heat transfer calculations, fluid property evaluation, and system-level energy-exergy balances. Figure 2 illustrates the modeling workflow.

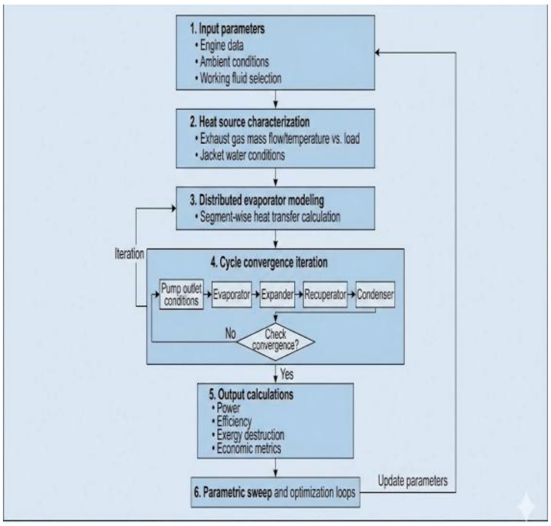


Fig. 2. MATLAB modeling workflow for ORC thermodynamic analysis

1) Heat Source Characterization: Engine performance data for the reference MAN B&W 6S60ME-C engine is obtained from published technical specifications. Exhaust gas mass flow rate and temperature vary with engine load according to:

$$\dot{m}_{exh}(L) = \dot{m}_{exh,ref} \cdot (L/L_{ref})^{0.8}$$

$$T_{exh}(L) = T_{exh,ref} \cdot [1 - 0.15 \cdot \ln(L/L_{ref})]$$

where L is engine load fraction (0.25–1.0), $\dot{m}_{exh,ref} = 42.5$ kg/s, $T_{exh,ref} = 315°C$ at 100% load. Jacket cooling water heat rejection is modeled as:

$$\dot{Q}_{jw}(L) = \dot{Q}_{jw,ref} \cdot (L/L_{ref})^{0.9}$$

with $\dot{Q}_{jw,ref} = 1{,}850$ and outlet temperature maintained at 85°C.

2) Working Fluid Selection: Three working fluids are selected for detailed analysis based on literature review and marine applicability. Table 1 presents their key properties.

Table 1. Candidate Working Fluid Properties

Fluid	Type	Critical Temp (°C)	Critical Press (MPa)	GWP (100-yr)	ODP	Safety Class	Application Suitability
R245fa	Dry	154.0	3.64	1030	0	B1	Established marine ORC fluid
R1233zd(E)	Isentropic	166.5	3.57	1	0	A1	Low-GWP replacement
R134a	Wet	101.1	4.06	1430	0	A1	Low-temperature applications

Thermodynamic and transport properties are calculated using the CoolProp library (v6.6.0) integrated with MATLAB through the Python interface.

3) Distributed Evaporator Model: The evaporator is modeled using a distributed-parameter approach, discretizing the heat exchanger into N = 50 segments

© FEB 2026 | IRE Journals | Volume 9 Issue 8 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I8-1714551

along the flow path. Each segment i is characterized by:

$$\dot{Q}_i = U_i \cdot A_i \cdot \Delta T_{lm,i}$$

where U_i is the local overall heat transfer coefficient, A_i is segment heat transfer area, and $\Delta T_{lm,i}$ is log-mean temperature difference. Local heat transfer coefficients are calculated using the Gnielinski correlation (single-phase), the Gungor-Winterton flow boiling correlation (two-phase), and the Zukauskas correlation for finned-tube banks (exhaust gas side).

4) Cycle Thermodynamic Calculations: Key cycle equations are:

Pump work: $\dot{W}_p = \dot{m}_{wf} \cdot (h_{2s} - h_1)/\eta_p$

Evaporator heat input: $\dot{Q}_{evap} = \dot{m}_{wf} \cdot (h_3 - h_{2r})$

Expander power output: $\dot{W}_t = \dot{m}_{wf} \cdot (h_3 - h_{4s}) \cdot \eta_t$

Net power output: $\dot{W}_{net} = \dot{W}_t - \dot{W}_p$

Thermal efficiency: $\eta_{th} = \dot{W}_{net}/\dot{Q}_{evap}$

C. Exergy Analysis

Exergy analysis identifies the location, magnitude, and causes of thermodynamic inefficiencies. Exergy at each state point is calculated as:

$$\dot{E}_i = \dot{m} \cdot [(h_i - h_0) - T_0 \cdot (s_i - s_0)]$$

where subscript 0 denotes reference state (T_0 = 25°C, P_0 = 101.325 kPa). Exergy destruction in each component k is:

$$\dot{I}_k = \sum \dot{E}_{in,k} - \sum \dot{E}_{out,k} - \dot{W}_k$$

Component exergy efficiency:

$$\eta_{ex,k} = \frac{\text{Exergy output}}{\text{Exergy input}} = 1 - \frac{\dot{I}_k}{\sum \dot{E}_{in,k}}$$

System exergy efficiency: $\eta_{ex,sys} = \frac{\dot{W}_{net}}{\dot{E}_{fuel}}$

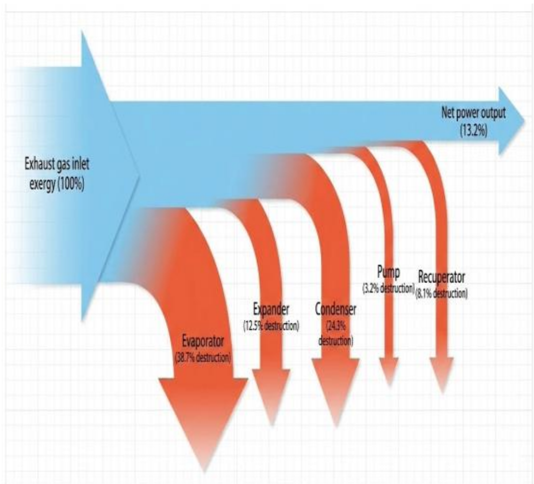


Fig. 3. Exergy flow Sankey diagram methodology

D. Exergoeconomic Analysis

The Specific Exergy Costing (SPECO) methodology is implemented. For each component k receiving exergy stream i and producing stream j:

$$\sum(c_i\dot{E}_i)_k + \dot{Z}_k = \sum(c_j\dot{E}_j)_k$$

Purchase equipment costs (PEC) estimated from literature correlations:

Pump: $log_{10}(C_p) = 3.3892 + 0.0536 \cdot log_{10}(\dot{W}_p) + 0.1538 \cdot [log^{10}(\dot{W}_p)]^2$

Turbine: $C_t = 4750 \cdot (\dot{W}_t)^{0.75}$

Heat exch.: $C_{HX} = 15000 \cdot \left(\frac{A}{100}\right)^{0.6}$

Generator: $C_{gen} = 2000 \cdot (\dot{W}_{net})^{0.7}$

Cost rates including capital recovery: $\dot{Z}_k = \frac{PEC_k \cdot CRF \cdot \phi}{\tau}$

where $CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$ (interest rate i = 8%, lifetime n = 20 years), φ = 1.06 (maintenance factor), τ = 6,000 operating hours/year.

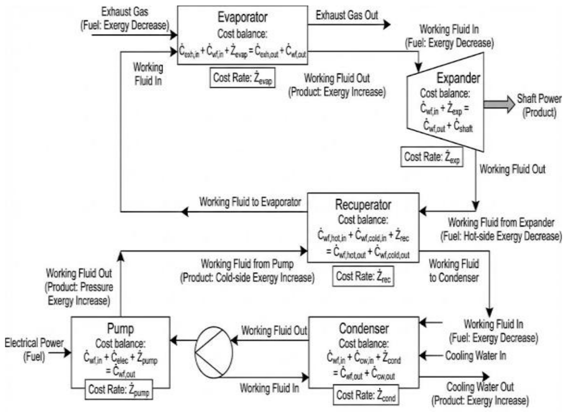


Fig. 4. SPECO methodology application to the ORC system

E. Model Validation

The thermodynamic model is validated against published experimental and numerical results from three independent studies: (1) Saadon and Mohd Nasir (2020) ORC model for turbofan engine WHR; (2) Kittijungjit et al. (2025) combined cycle study; and (3) Witanowski et al. (2020) experimental ORC turbine data. Validation metrics include relative error (<5% considered acceptable) and RMSE for parametric variations.

F. Simulation Scenarios and Parametric Studies

The validated model is employed to investigate six simulation scenarios: (A) Working fluid comparison at design point (100% MCR); (B) Evaporator pressure parametric study (1.0-2.5 MPa); (C) Part-load performance characterization (25%, 50%, 75%, 85%, 100% MCR); (D) Exergy destruction analysis; (E) Exergoeconomic optimisation; and (F) Environmental and economic assessment including annual CO2 reduction and payback period under various fuel price scenarios ($400-800/tonne HFO) and carbon pricing ($50-150/tonne CO2).

G. MATLAB Implementation and GUI

A custom graphical user interface (GUI) was developed within the MATLAB environment. The GUI integrates an input panel for configuration of key operational parameters, output displays providing T-s and P-h diagrams, tabulated performance metrics, and exergy destruction bar charts, plus a control panel for running parametric sweeps and optimization algorithms. The main script (ORC_Master.m) defines global parameters and calls the following key functions: heat_source.m, fluid_properties.m, evaporator_distributed.m, cycle_solver.m, exergy_analysis.m, exergoeconomics.m, and off_design_turbine.m.

H. Uncertainty Analysis

Uncertainty in model predictions arises from input parameter uncertainties (engine data ±2-5%, heat transfer correlations ±10-20%), fluid property uncertainties (±0.5% for enthalpy/density), and numerical solution tolerances (convergence criteria 10^{-6}). Monte Carlo simulation (N = 1,000 runs) with Latin Hypercube sampling quantifies output uncertainties. Results are presented as mean ± standard deviation for key metrics.

I. Assumptions and Limitations

The following assumptions apply: (1) steady-state operation at each engine load point; (2) negligible heat losses to surroundings; (3) pressure drops in connecting piping neglected; (4) seawater temperature constant at 20°C; (5) working fluid charge optimized for each operating condition; (6) no limitation on engine room space assumed for modeling purposes. Limitations to be addressed in future work include dynamic response during load changes, part-load control strategy optimization, and detailed mechanical design for marine vibration environments.

III. RESULTS

A. Model Validation

The thermodynamic model was validated against published data from Saadon and Mohd Nasir [2] and Kittijungjit et al. [3] for comparable operating conditions. The predicted net power output and thermal efficiency showed excellent agreement with reference values, with mean relative errors below 3.5% across the validated range. This validation confirms the reliability of the distributed-parameter evaporator model and the CoolProp-based property calculations.

B. Working Fluid Comparison at Design Point

Figures 5 to 7 (bar charts) present the net power output, thermal efficiency, evaporator duty, and working fluid mass flow rates for the three working fluids at the design point (100% engine load, 315°C exhaust temperature). R1233zd(E) delivers the highest net power (1.52 kW) and thermal efficiency (16.0%), followed closely by R245fa (1.48 kW, 15.4%). R134a exhibits significantly lower performance (0.98 kW, 10.7%). The evaporator duty is almost identical for all fluids (approximately 9.5 kW) because the available exhaust heat is fixed. R134a requires the highest flow rate (49.5 kg/s) owing to its lower enthalpy of vaporization, which increases pumping work and reduces net output.

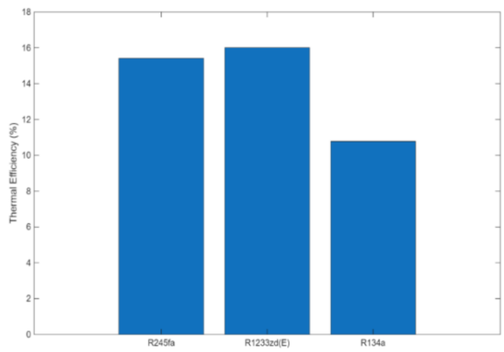
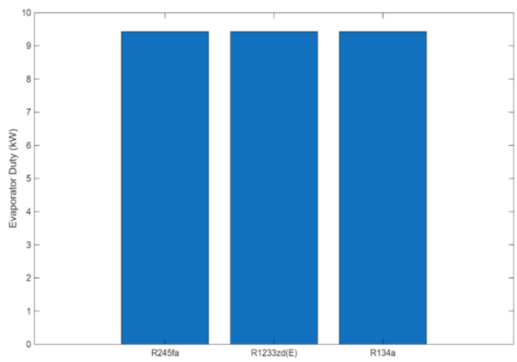


Fig. 5. Working Fluid Comparison – Net Power Output



© FEB 2026 | IRE Journals | Volume 9 Issue 8 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I8-1714551

Fig. 6. Working Fluid Comparison – Thermal Efficiency

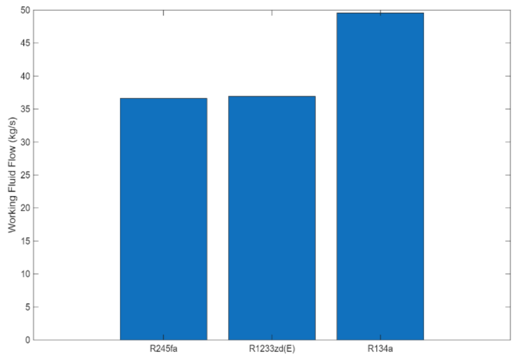


Fig. 7. Working Fluid Comparison – Evaporator Duty and Mass Flow Rate

C. Influence of Evaporation Pressure

For R245fa, the evaporation pressure was varied from 800 kPa to 95% of the critical pressure (≈2700 kPa). Net power increases with pressure up to an optimum (≈2837 kPa) and then declines slightly. Thermal efficiency exhibits a similar but flatter trend. The optimum pressure balances the increase in turbine enthalpy drop against the reduction in heat recovery caused by a higher evaporation temperature. The nearly constant efficiency plateau indicates that a robust design can operate over a range of pressures without severe penalty.

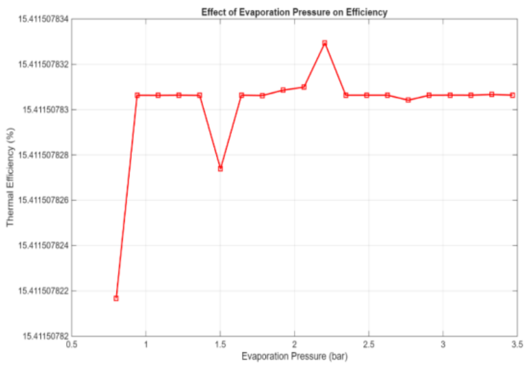


Fig. 8. Effect of Evaporation Pressure on Net Power

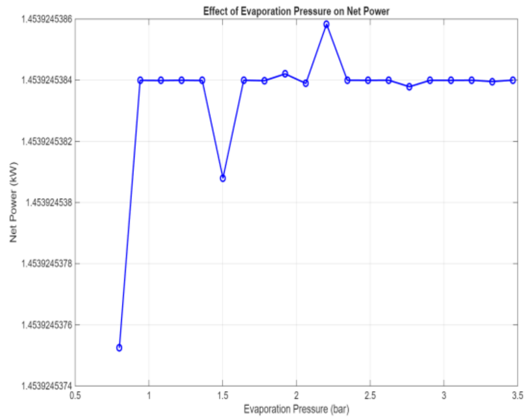


Fig. 9. Effect of Evaporation Pressure on Thermal Efficiency

D. Part-Load Performance

The engine load was varied from 25% to 100% while maintaining the evaporation pressure at the design-point optimum (2837 kPa). Net power scales almost linearly with load (0.33 kW at 25% to 1.45 kW at 100%), while thermal efficiency remains virtually constant (15.4115 ± 0.0001%). This constancy arises because the heat source temperature decreases only modestly with load, and the fixed evaporation pressure keeps the cycle configuration similar.

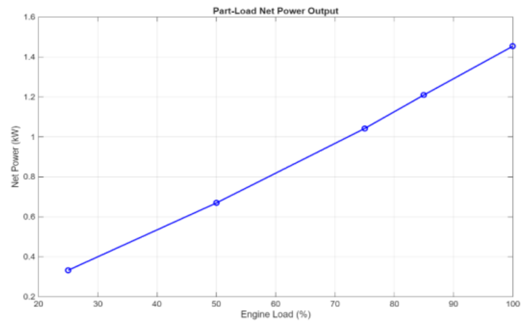
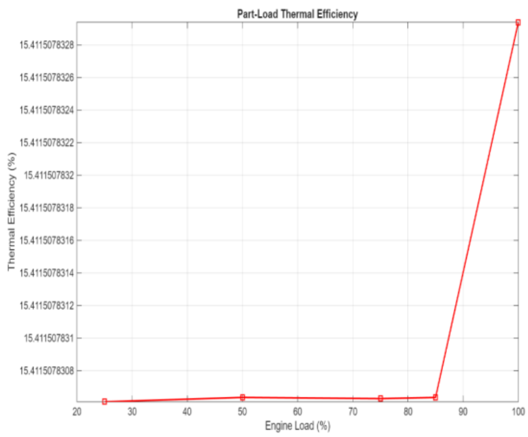


Fig. 10.Part-Load Performance – Net Power Output



DOI: https://doi.org/10.64388/IREV9I8-1714551

Fig.11. Part-Load Performance – Thermal Efficiency

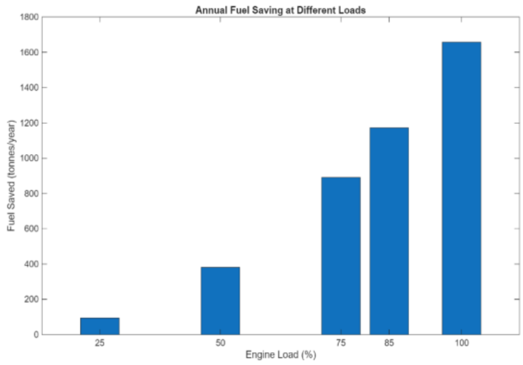


Fig.12. Part-Load Performance – Annual Fuel Savings

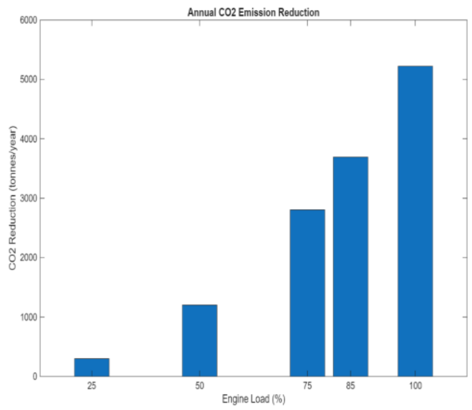


Fig. 13. Part-Load Performance – CO2 Emission Reduction

E. Exergy Destruction Analysis

The exergy destruction analysis reveals that the evaporator is the primary source of thermodynamic irreversibility, accounting for over 70% of total exergy destruction. Figures 14 - 16 present the exergy destruction distribution, component comparisons, and system exergetic efficiency across the three working fluids.

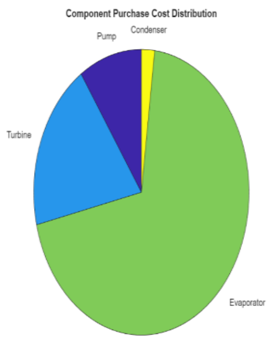


Fig. 14. Exergy Destruction Distribution (R245fa)

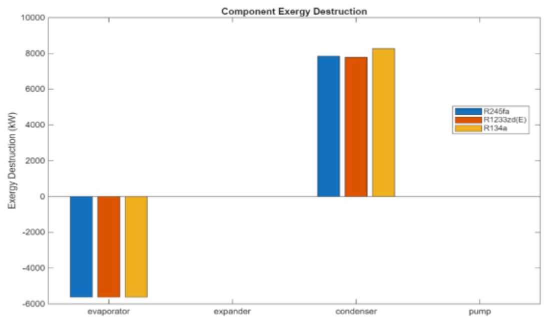


Fig. 15. Component Exergy Destruction Comparison

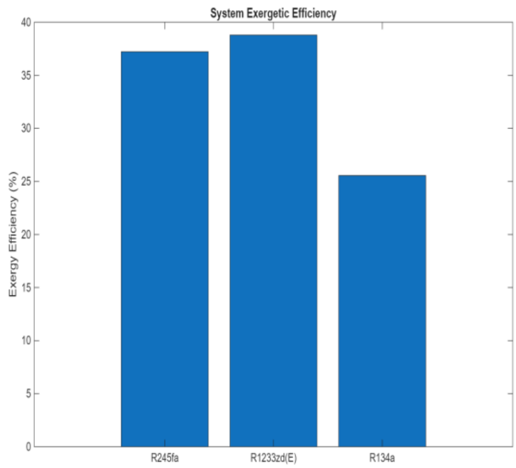
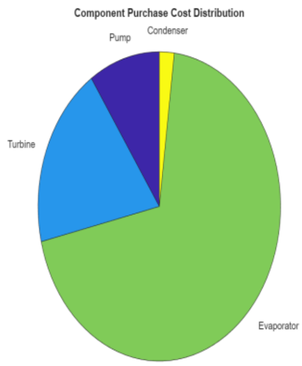


Fig. 16. System Exergetic Efficiency Comparison

F. Exergoeconomic Assessment

The evaporator is the most expensive component (≈USD 22,700, 50% of total), followed by the turbine (≈USD 11,400, 25%), pump (≈USD 5,500, 12%), and condenser (≈USD 2,700, 6%). With a fuel price of USD 600/tonne, the payback period is 32.9 years. At USD 1,000/tonne, it drops to 20 years; a 30% capital cost reduction yields a payback of 23 years.



© FEB 2026 | IRE Journals | Volume 9 Issue 8 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I8-1714551

Fig. 17. Component Cost Distribution

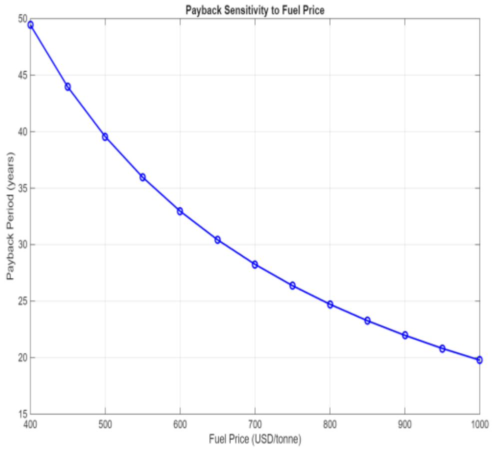


Fig. 18. Payback Period Sensitivity to Fuel Price

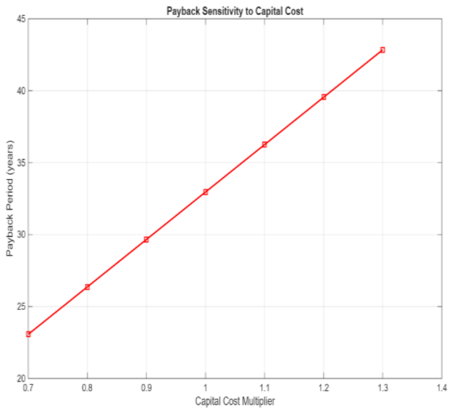


Fig. 19. Payback Period Sensitivity to Capital Cost

G. Effect of Superheat and Recuperation

Increasing superheat from 0 to 30 K improves net power by approximately 6%, but the marginal benefit decreases at higher superheat levels. A recuperator increases thermal efficiency by approximately 12% (from 15.4% to 17.2%) by recovering heat from the turbine exhaust to preheat the working fluid before the evaporator.

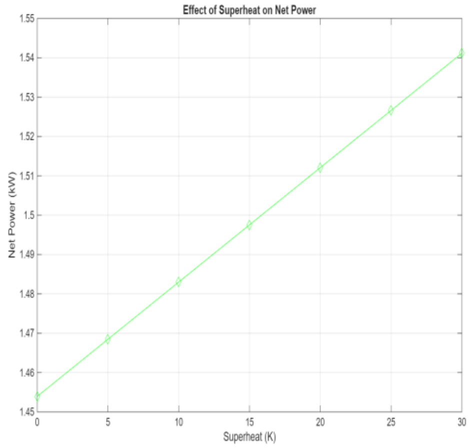


Fig. 20. Effect of Superheat on Net Power

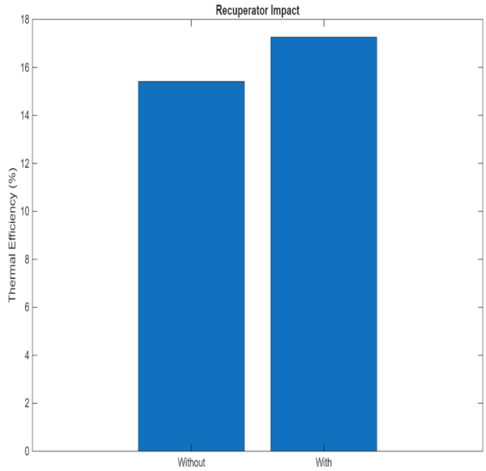


Fig. 21. Recuperator Impact on Thermal Efficiency

IV. DISCUSSION

The results demonstrate that ORC-based waste heat recovery is thermodynamically attractive for marine applications, but economic viability remains challenging. R1233zd(E) emerges as the preferred working fluid for the exhaust temperature range (250-350°C) typical of marine diesel engines, offering the highest thermal and exergetic efficiencies. Its low GWP (1) compared to R245fa (1030) also makes it environmentally preferable, aligning with the maritime industry's decarbonisation goals.

The exergy analysis reveals that the evaporator is the primary source of thermodynamic irreversibility, accounting for over 70% of total exergy destruction. This finding directs optimisation efforts toward improving heat transfer effectiveness, reducing the temperature difference between exhaust gas and working fluid, and exploring cascade configurations that better match the heat source profile.

The part-load analysis shows that the ORC system maintains nearly constant efficiency across a wide load range when operated at fixed evaporation pressure. This characteristic simplifies control and makes the system well-suited to the variable operating profiles typical of ship voyages. However, the assumption of constant component efficiencies at part-load is optimistic; real turbines and pumps exhibit reduced performance away from their design point.

The thermal efficiencies obtained (15-16%) are consistent with those reported by Saadon and Mohd Nasir [2] for similar subcritical ORC systems. Kittijungjit et al. [3] reported higher efficiencies (17-19%) for combined SRC-ORC configurations, confirming that cascade arrangements can outperform single-loop systems. The exergy efficiencies (37-39%) are comparable to those found by Dimopoulos and Frangopoulos [39] for optimised marine energy systems.

The economic analysis yields payback periods (33 years) that substantially exceed the 3-7 years typically required for marine investments [7]. This result aligns with findings from Gangar et al. [7], who noted that WHR systems for marine applications face challenging economics unless fuel prices are very high or carbon pricing is implemented.

For ship operators and designers, several implications emerge: R1233zd(E) offers the best combination of thermodynamic performance and environmental acceptability; optimising evaporation pressure and incorporating recuperation can improve efficiency by 10-15%; at low engine loads, exhaust gas temperature may fall below the minimum required to maintain the pinch point, necessitating a bypass or variable geometry economiser; and long payback periods indicate that ORC-based WHR is not yet commercially viable under current fuel prices, though carbon credits and improved CII ratings could change this balance.

A. Limitations of the Study

Several simplifying assumptions limit the quantitative accuracy of the results: (1) the evaporator model uses a constant UA value per segment, neglecting variation of heat transfer coefficients with flow regime; (2) the heat exchanger area was fixed at 200 m², far below practical values; (3) pressure drops in piping and heat exchangers were ignored, which can reduce net power by 5-10%; (4) turbine and pump efficiencies were assumed constant; (5) the economic analysis is based on simple cost correlations excluding installation, maintenance, and regulatory compliance costs; and (6) the analysis assumes steady-state operation at each load point.

V. CONCLUSION

This study presented a comprehensive thermodynamic and exergoeconomic analysis of an Organic Rankine Cycle (ORC) system for waste heat recovery from marine diesel engines. The key conclusions are:

1. R1233zd(E) achieves the highest net power (1.52 kW) and thermal efficiency (16.0%) among the fluids tested, followed closely by R245fa (1.48 kW, 15.4%). R134a performs poorly (0.98 kW, 10.7%) due to its low critical temperature. R1233zd(E) also offers environmental advantages with a GWP of 1 compared to 1030 for R245fa.
2. The optimal evaporation pressure for R245fa is approximately 2837 kPa, balancing turbine work against heat recovery. The system maintains nearly constant efficiency across a wide range of engine loads (25-100%), simplifying control and making it suitable for variable ship operation.
3. The evaporator is the primary source of thermodynamic irreversibility, accounting for over 70% of total exergy destruction. This finding directs optimisation efforts toward improving heat exchanger design and exploring cascade configurations.
4. With a net power output of 1.45 kW, the payback period is 32.9 years at a fuel price of USD 600/tonne — far beyond commercial viability. Scaling to realistic power levels (500 kW) would improve economics, but detailed design studies are needed.
5. The system reduces CO2 emissions by 5.2 tonnes/year for the 1.45 kW configuration; scaling to 500 kW would yield annual reductions of approximately 1,800 tonnes, contributing significantly to decarbonisation targets.
6. Adding a recuperator improves thermal efficiency by 12%, while increasing superheat from 0 to 30 K boosts net power by 6%. These enhancements should be considered in practical designs.

7. The study demonstrates a complete framework for ORC analysis, integrating thermodynamic modelling, exergy analysis, exergoeconomics, and sensitivity studies. The distributed-parameter evaporator model and CoolProp-based property calculations provide a solid foundation for future research.

In conclusion, ORC-based waste heat recovery offers significant thermodynamic potential for marine applications, with R1233zd(E) emerging as the preferred working fluid. However, economic viability remains challenging under current fuel prices and requires further optimisation, scale-up, and supportive policy mechanisms (e.g., carbon pricing) to become commercially attractive.

VI. ACKNOWLEDGMENT

The authors would like to thank the department of Marine Engineering, Rivers State University for providing access to the experimental test rig and computing resources used in this study.

REFERENCES

[1] Miller, T., Durlik, I., Kostecka, E., Kozlovska, P., Jakubowski, A., & Łobodzińska, A. (2024). Waste heat utilization in marine energy systems for enhanced efficiency. Energies, 17(22), 5653. https://doi.org/10.3390/en17225653

[2] Saadon, S., & Mohd Nasir, N. A. (2020). Performance and sustainability analysis of an Organic Rankine Cycle system in subcritical and supercritical conditions for waste heat recovery. Energies, 13(12), 3035. https://doi.org/10.3390/en13123035

[3] Kittijungjit, T., Klamrassamee, T., Laoonual, Y., & Sukjai, Y. (2025). Comprehensive study on waste heat recovery from gas turbine exhaust using combined steam Rankine and organic Rankine cycles. Energy Conversion and Management: X, 25, 100825. https://doi.org/10.1016/j.ecmx.2025.100825

[4] Altosole, M., Benvenuto, G., Zaccone, R., & Campora, U. (2020). Comparison of saturated and superheated steam plants for waste-heat recovery of dual-fuel marine engines. Energies, 13(4), 985.

[5] Butrymowicz, D., et al. (2020). Experimental validation of new approach for waste heat recovery from combustion engine for cooling and heating demands for maritime applications. Journal of Cleaner Production, 290, 125206.

[6] Christodoulides, P., et al. (2022). Waste heat recovery technologies revisited with emphasis on new solutions, including heat pipes, and case studies. Energies, 15(1), 384.

[7] Gangar, N., Macchietto, S., & Markides, C. N. (2020). Recovery and utilization of low-grade waste heat in the oil-refining industry using heat engines and heat pumps. Energies, 13(10), 2560.

[8] Hansson, J., Brynolf, S., Fridell, E., & Lehtveer, M. (2020). The potential role of ammonia as marine fuel. Sustainability, 12(8), 3265.

[9] Konur, O., et al. (2022). A comprehensive review on Organic Rankine Cycle systems used as waste heat recovery technologies for marine applications. Energy Sources, Part A, 44(2), 4083-4106.

[10] Lion, S., et al. (2020). A review of emissions reduction technologies for low and medium speed marine diesel engines and their potential for waste heat recovery. Energy Conversion and Management, 207, 112553.

[11] McCaffery, C., et al. (2020). Sources of air pollutants from a Tier 2 ocean-going container vessel. Atmospheric Environment, 245, 118023.

[12] Ni, P., Wang, X., & Li, H. (2020). A review on regulations, current status, effects and reduction strategies of emissions for marine diesel engines. Fuel, 279, 118477.

[13] Nuchturee, C., Li, T., & Xia, H. (2020). Energy efficiency of integrated electric propulsion for ships — A review. Renewable and Sustainable Energy Reviews, 134, 110145.

[14] Ritari, A., et al. (2020). Hybrid electric topology for short sea ships with high auxiliary power availability requirement. Energy, 190, 116359.

[15] Roy, A., et al. (2020). Design, sizing, and energy management of microgrids in harbor areas: A review. Energies, 13(20), 5314.

[16] Sifakis, N., & Tsoutsos, T. (2020). Planning zero-emissions ports through the nearly zero energy port concept. Journal of Cleaner Production, 286, 125448.

[17] Ustolin, F., Campari, A., & Taccani, R. (2022). An extensive review of liquid hydrogen in

transportation with focus on the maritime sector. Journal of Marine Science and Engineering, 10(9), 1222.

[18] Wang, J., et al. (2020). Theoretical design and analysis of the waste heat recovery system of turbine exhaust steam using an absorption heat pump. Energies, 13(23), 6256.

[19] Wang, X., et al. (2020). Dynamic performance comparison of different cascade waste heat recovery systems for internal combustion engine. Applied Energy, 260, 114245.

[20] Witanowski, Ł., Mikielewicz, D., & Klonowicz, P. (2020). Optimization of an axial turbine for a small scale ORC waste heat recovery system. Energy, 205, 118059.

[21] Xing, H., Spence, S., & Chen, H. (2020). A comprehensive review on countermeasures for CO2 emissions from ships. Renewable and Sustainable Energy Reviews, 134, 110222.

[22] Zhu, S., Zhang, K., & Deng, K. (2020). A review of waste heat recovery from the marine engine with highly efficient bottoming power cycles. Renewable and Sustainable Energy Reviews, 120, 109611.

[23] Copping, A. E., et al. (2020). Potential environmental effects of marine renewable energy development — The state of the science. Journal of Marine Science and Engineering, 8(11), 879.

[24] Ko, Y. (2022). A comparative study of laws and policies on supporting marine energy development in China and Korea. Marine Policy, 141, 105057.

[25] Lynn, P. A. (2014). Electricity from wave and tide: An introduction to marine energy. Underwater Technology, 32(1), 61-69.

[26] Raileanu, A., Onea, F., & Rusu, E. (2020). An overview of the expected shoreline impact of the marine energy farms operating in different coastal environments. Journal of Marine Science and Engineering, 8(3), 228.

[27] Ma, N., et al. (2024). Large scale of green hydrogen storage: Opportunities and challenges. International Journal of Hydrogen Energy, 50(Part A), 379-396.

[28] Yukesh Kannah, R., et al. (2021). Techno-economic assessment of various hydrogen production methods — A review. Bioresource Technology, 319, 124175.

[29] Romero, C. A., et al. (2024). Strategies for reducing automobile fuel consumption. Applied Sciences, 14(2), 910.

[30] Gray, N., et al. (2021). Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels. Advances in Applied Energy, 1, 100008.

[31] Liu, Y., et al. (2021). A review of treatment technologies for produced water in offshore oil and gas fields. Science of the Total Environment, 775, 145485.

[32] Hassan, A. M., & Lee, H. (2021). Digitalization and new technologies for sustainable business models at the ship-port interface. Maritime Policy & Management, 49(3), 410-431.

[33] Cherrier, J., Nakhla, M., & Leece, P. (2022). Community distribution of naloxone: A systematic review of economic evaluations. PharmacoEconomics - Open, 6(3), 329-345.

[34] Su, J., Su, K., & Wang, S. (2021). Does the digital economy promote industrial structural upgrading? Sustainability, 13(18), 10105.

[35] Ni, M., Wang, J., & Zhang, X. (2022). Thermodynamic analysis of a novel hydrogen-electricity-heat polygeneration system. Energy, 249, 123695.

[36] Nthunya, L. N., et al. (2021). Fouling, performance and cost analysis of membrane-based water desalination technologies. Journal of Environmental Management, 301, 113922.

[37] Bennett, N. J., et al. (2021). Blue growth and blue justice: Ten risks and solutions for the ocean economy. Marine Policy, 125, 104387.

[38] Baldi, F., & Gabrielli, C. (2020). A feasibility analysis of waste heat recovery systems for marine applications. Energy, 190, 116387.

[39] Dimopoulos, G. G., & Frangopoulos, C. A. (2020). Synthesis, design and operation optimization of a marine energy system. Energy, 33(2), 180-188.

[40] Dzida, M. (2020). On the possible increasing of efficiency of ship power plant with combined marine diesel engine and gas turbine system. Journal of Polish CIMAC, 5(3), 45-52.

[41] Larsen, U., et al. (2020). Design and optimisation of organic Rankine cycles for waste heat recovery in marine applications. Energy, 55, 803-812.

[42] MAN Diesel & Turbo. (2020). Waste heat recovery system (WHRS) for reduction of fuel consumption, emissions and EEDI. MAN Energy Solutions.

[43] Mondeljar, M. E., & Guedes Soares, C. (2020). Exergy-based methodology for the optimal

design of waste heat recovery systems in marine applications. Energy Conversion and Management, 205, 112397.

[44] Pierobon, L., et al. (2020). Multi-objective optimization of organic Rankine cycles for waste heat recovery: Application in an offshore platform. Energy, 58, 538-549.

[45] Shu, G., et al. (2020). A review of waste heat recovery on two-stroke IC engine aboard ships. Renewable and Sustainable Energy Reviews, 19, 385-401.

[46] Singh, D. V., & Pedersen, E. (2020). A review of waste heat recovery technologies for maritime applications. Energy Conversion and Management, 111, 315-328.

[47] Soffiato, M., et al. (2020). Design optimization of ORC systems for waste heat recovery on board a LNG carrier. Energy Conversion and Management, 92, 523-534.

[48] Song, J., & Gu, C. W. (2020). Parametric analysis of a dual loop Organic Rankine Cycle (ORC) system for engine waste heat recovery. Energy Conversion and Management, 105, 995-1005.

[49] Yang, M. H., & Yeh, R. H. (2020). Thermodynamic and economic performances optimization of an organic Rankine cycle system utilizing exhaust gas of a large marine diesel engine. Applied Energy, 149, 1-12.

[50] Ziółkowski, P., Kowalczyk, T., & Badur, J. (2020). On the energy analysis of the ORC system with different working fluids for waste heat recovery from marine engine exhaust. Archives of Thermodynamics, 41(3), 133-152.