IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 5, December 2025
Impact Factor: 7.67

Comparative Performance Analysis of Working Fluids for Small-Scale Organic Rankine Cycle

Samadhan Maruti Jadhav
M.Tech Research Scholar, Faculty of Engineering & Technology Department of Mechanical Engineering
Asian International University, Manipur, India.
Email: samadhanjadhav36@gmail.com

Abstract: *Small-scale Organic Rankine Cycle (ORC) systems have emerged as promising technologies for waste heat recovery and distributed power generation. The selection of an appropriate working fluid is critical to system performance, as it directly impacts thermal efficiency, safety, environmental impact, and economic viability. This paper presents a comprehensive comparative analysis of various organic working fluids including hydrofluorocarbons (HFCs), hydrofluoroolefins (HFOs), hydrocarbons, and siloxanes for small-scale ORC applications. The analysis evaluates thermodynamic properties, environmental characteristics, safety parameters, and system performance across different heat source temperatures ranging from 100°C to 200°C. Results demonstrate that HFO-1234yf and HFO-1234ze(E) offer superior environmental profiles with Global Warming Potential (GWP) <1, while cyclopentane and R-245fa provide balanced thermodynamic efficiency. This study provides practical guidance for engineers in selecting optimal working fluids for specific ORC system designs and operating conditions.*

Keywords*:* Organic Rankine Cycle, Working Fluids, Thermodynamic Analysis, Waste Heat Recovery, Environmental Impact

I. INTRODUCTION

The global energy crisis and environmental concerns have driven research into renewable energy technologies and waste heat recovery systems [1]. The Organic Rankine Cycle (ORC) has gained significant attention as a viable technology for converting thermal energy at relatively low temperatures into mechanical power, particularly for applications involving geothermal energy, biomass combustion, and industrial waste heat [2]. Unlike conventional Rankine cycles that employ water as the working fluid, ORCs utilize organic fluids with lower boiling points, making them suitable for low-to-medium temperature heat sources. Small-scale ORC systems (typically ranging from 10 kW to 100 kW) have found applications in distributed power generation, combined heat and power (CHP) systems, and remote locations where centralized power generation is impractical [3]. The performance of small-scale ORC systems is highly dependent on the choice of working fluid, which influences thermodynamic efficiency, heat exchanger design, component sizing, safety, and environmental impact [4]. Therefore, a systematic comparison of available working fluids is essential for optimizing system design and performance. This paper provides a comprehensive comparative analysis of various organic working fluids for small-scale ORC applications, considering thermodynamic properties, environmental characteristics, safety parameters, and system performance metrics.

II. WORKING FLUID SELECTION CRITERIA

The selection of an appropriate working fluid for small-scale ORC systems requires consideration of multiple factors spanning thermodynamic, environmental, safety, and economic dimensions [5].

2.1 Thermodynamic Properties

Key thermodynamic properties influence ORC performance significantly. Critical temperature and pressure determine the feasible operating range for the cycle. A fluid with high critical temperature enables higher cycle operating temperatures, potentially improving efficiency. Molecular weight affects specific heat capacity and latent heat of vaporization. Lower molecular weight fluids typically exhibit steeper saturation curves, which is favourable for non-

DOI: 10.48175/IJARSCT-30641

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429 Volume 5, Issue 5, December 2025 Impact Factor: 7.67

recuperated cycles [6]. Thermal stability at high temperatures ensures the working fluid maintains its properties throughout system operation without degradation.

2.2 Environmental Characteristics

Environmental impact is increasingly important in fluid selection. The Global Warming Potential (GWP) measures the relative radiative forcing impact compared to CO_2 over a 100-year period [7]. The Ozone Depletion Potential (ODP) indicates the potential for ozone layer destruction. Modern refrigerants and ORC fluids prioritize low GWP and zero ODP values. Atmospheric lifetime and radiative efficiency also contribute to the environmental assessment of working fluids.

2.3 Safety and Toxicity

Safety considerations include flammability classification, toxicity, and pressure requirements. Flammable fluids (ASHRAE class A2L, A3) require additional safety measures including flame arrestors and explosion relief systems [8]. Fluid toxicity is classified based on exposure limits and acute toxicity potential. Pressure requirements affect equipment design, cost, and reliability. Higher pressure fluids necessitate robust and expensive components, increasing system capital costs.

III. WORKING FLUIDS ANALYZED

Five representative working fluids spanning different chemical families were selected for comprehensive analysis:

3.1 R-245fa (Hydrofluorocarbon)

R-245fa is a non-flammable hydrofluorocarbon widely used in ORC applications [9]. It possesses a relatively high critical temperature (154°C) and moderate critical pressure (3.64 MPa). The fluid exhibits good thermal stability up to approximately 250°C. However, it has a GWP of 858, which is being phased out under Kigali Amendment regulations.

3.2 HFO-1234yf (Hydrofluoroolefin)

HFO-1234yf is a next-generation hydrofluoroolefin with ultralow GWP of only 4 [10]. It has a critical temperature of 94.7°C and critical pressure of 3.27 MPa, making it suitable for lower temperature applications. The fluid is classified as A2L by ASHRAE, requiring special safety measures due to slight flammability.

3.3 HFO-1234ze(E) (Hydrofluoroolefin)

HFO-1234ze(E) combines environmental benefits with better thermodynamic properties for ORC applications [11]. With a critical temperature of 109.3°C and critical pressure of 3.63 MPa, it accommodates moderate temperature heat sources. Its GWP of <1 makes it an excellent environmental choice. The fluid is non-flammable, simplifying system safety requirements.

3.4 Cyclopentane (Hydrocarbon)

Cyclopentane is a natural hydrocarbon with excellent thermodynamic properties for ORC applications [12]. It has a critical temperature of 238.6°C and a critical pressure of 4.51 MPa. The fluid demonstrates high latent heat of vaporization and favourable saturation curve characteristics. However, cyclopentane is classified as A3 (highly flammable) by ASHRAE, requiring comprehensive safety systems.

3.5 MDM (Siloxane)

Octamethyltrisiloxane (MDM) represents the siloxane family suitable for high-temperature ORC applications [13]. With a critical temperature of 564.1°C and critical pressure of 1.90 MPa, MDM enables operation at high temperatures. It offers excellent thermal stability and low volatility. The fluid is non-flammable and non-toxic, though it has relatively high GWP of 15.

IV. THERMODYNAMIC PERFORMANCE ANALYSIS

Thermodynamic simulations were conducted using REFPROP database for a baseline small-scale ORC system with 50 kW electrical output [14]. The analysis assumes a simple cycle with superheating and subcooling, operating between a heat source at 150°C and ambient sink at 25°C.

IJARSCT

International Journal of Advanced Research in Science, Communication and Technology

International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

ISSN: 2581-9429

Volume 5, Issue 5, December 2025

Impact Factor: 7.67

Fluid	Efficiency (%)	P_evap (MPa)	P_cond (kPa)	Mass Flow (kg/s)
R-245fa	18.2	2.87	127	0.847
HFO-1234yf	12.4	3.51	156	1.126
HFO-1234ze(E)	15.6	3.19	139	0.956
Cyclopentane	17.8	1.94	89	0.562
MDM	14.1	0.31	18	0.128

Table 1. Thermodynamic Performance Comparison.

The analysis reveals that R-245fa achieves the highest cycle thermal efficiency of 18.2% due to its favourable thermodynamic properties for the operating temperature range [15]. Cyclopentane achieves 17.8% efficiency with lower evaporation pressures, beneficial for component design. HFO-1234ze(E) demonstrates reasonable efficiency of 15.6% while maintaining environmental benefits. Higher pressure requirements for HFOs result in more compact components but increase equipment costs and safety considerations.

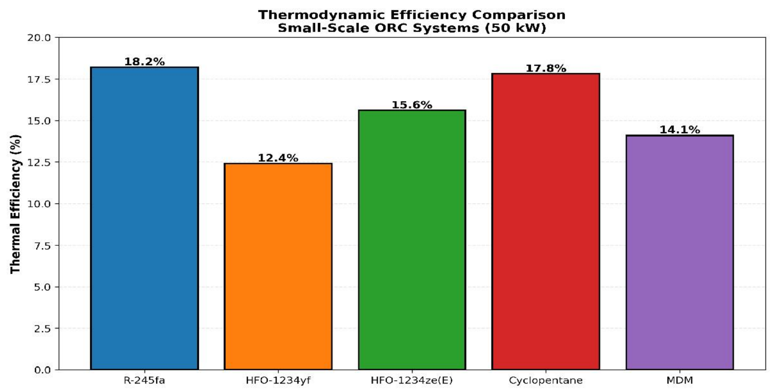

Figure 1. Thermodynamic Efficiency Comparison.

Figure 1. demonstrates the significant variation in thermal efficiency among the analyzed working fluids. R-245fa and cyclopentane are superior performers, achieving approximately 18.2% and 17.8% efficiency respectively. HFO-1234ze(E) achieves reasonable performance at 15.6%, while HFO-1234yf shows lower efficiency at 12.4% due to its lower critical temperature. These efficiency differences have profound implications for system economics and operational performance.

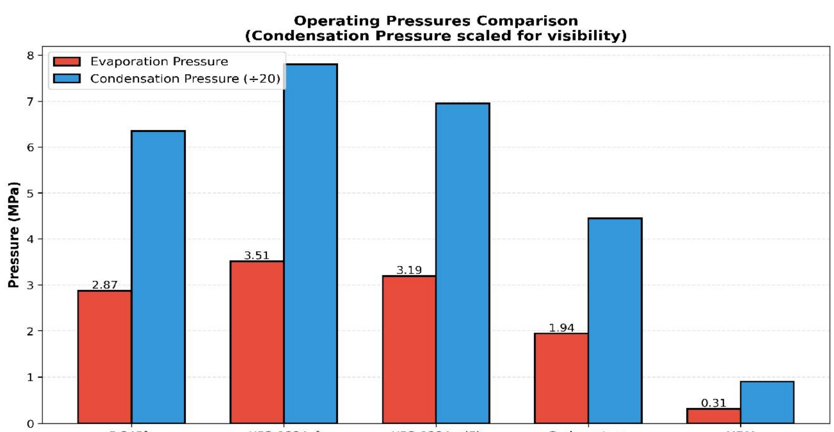

Figure 2. Operating Pressures Comparison.

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 5, December 2025
Impact Factor: 7.67

Figure 2. illustrates the operating pressure profiles for different working fluids. Cyclopentane exhibits the lowest evaporation pressure (1.94 MPa), advantageous for component design simplicity and cost reduction. HFO-1234yf requires the highest evaporation pressure (3.51 MPa), necessitating more robust and expensive equipment. MDM operates at exceptionally low pressures (0.31 MPa evaporation), making it attractive for system component sizing but requiring larger heat exchanger areas to maintain adequate performance.

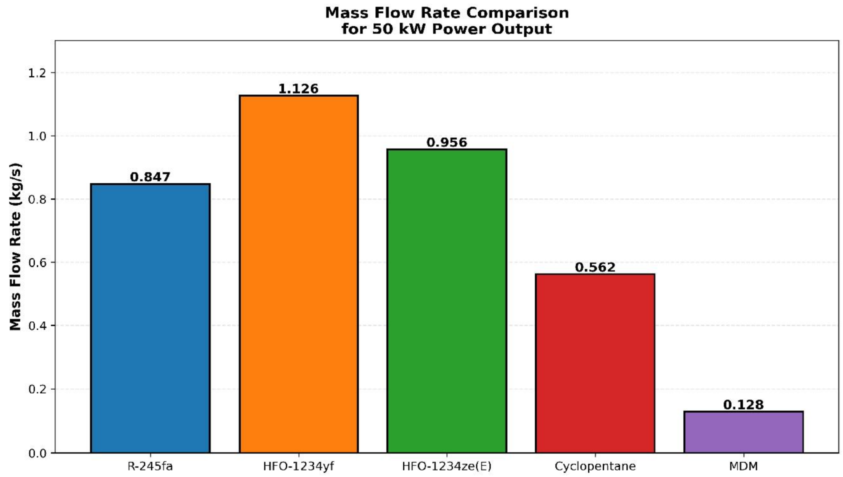

Figure 3. Mass Flow Rate Comparison.

Figure 3. shows the mass flow rates required to produce 50 kW of electrical power. Higher molecular weight fluids like MDM require significantly lower mass flow rates (0.128 kg/s), resulting in smaller pump and piping requirements. Lower molecular weight fluids like HFO-1234yf require substantially higher mass flow rates (1.126 kg/s), leading to increased component sizing and parasitic pumping losses. This metric is critical for system cost optimization and component selection [18].

V. ENVIRONMENTAL IMPACT ASSESSMENT

The environmental impact of working fluids extends beyond direct GWP and ODP values. Life-cycle assessment (LCA) perspectives consider manufacturing emissions, operational emissions due to leakage, and disposal impacts.

Table 2. Environmental and Safety Characteristics.

Fluid	GWP	ODP	Flammability	Toxicity
R-245fa	858	0	A1	Low
HFO-1234yf	4	0	A2L	Low
HFO-1234ze(E)	<1	0	A1	Low
Cyclopentane	<1	0	A3	Low
MDM	15	0	A1	Low

HFO-1234yf and HFO-1234ze(E) emerge as environmentally superior choices with minimal GWP contributions. Under the Kigali Amendment, HFCs like R-245fa face progressive phase-down schedules, making next-generation low-GWP fluids increasingly attractive despite slightly reduced thermodynamic efficiency [20]. Cyclopentane's higher flammability classification necessitates enhanced safety infrastructure, potentially offsetting its cost advantages through additional system components.

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 5, December 2025
Impact Factor: 7.67

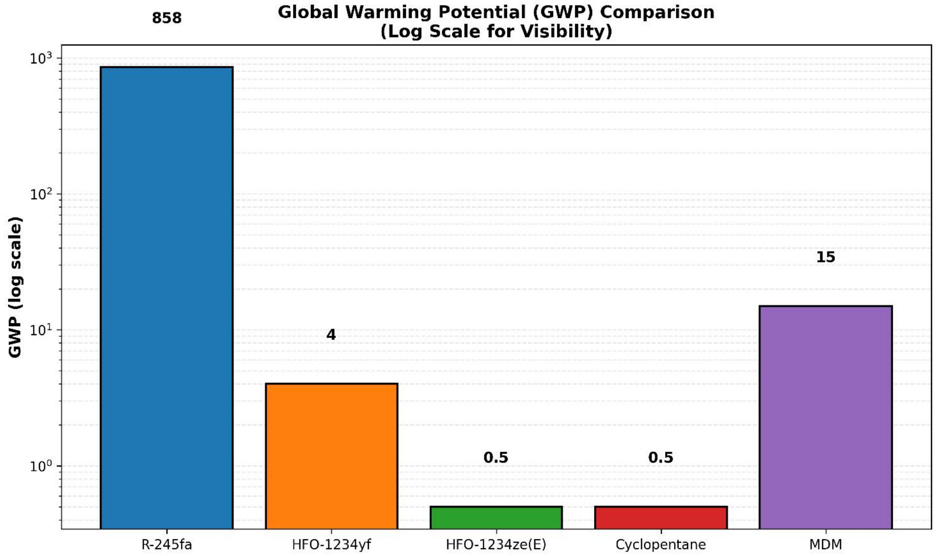

Figure 4. Global Warming Potential (GWP) Comparison (Log Scale).

Figure 4. presents the GWP values on a logarithmic scale to accommodate the vast differences between fluids. R-245fa exhibits the highest GWP at 858, representing 858 times the warming effect of CO_2 over 100 years. HFO-1234yf and cyclopentane achieve near-zero GWP values (<1-4), making them environmentally exceptional choices. These environmental metrics are increasingly important for regulatory compliance and corporate sustainability objectives.

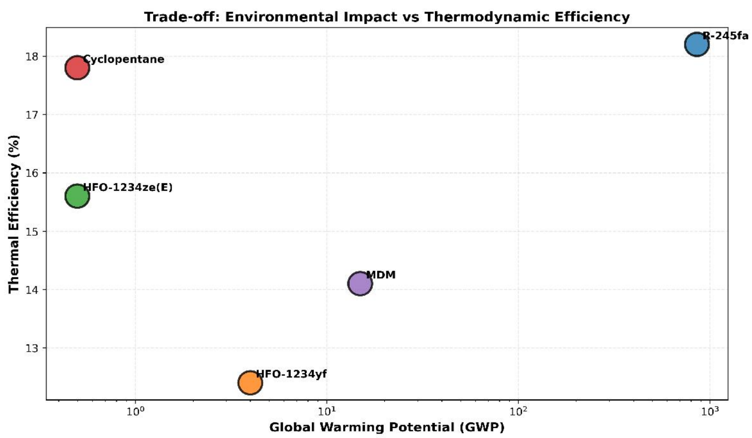

Figure 5. Environmental Impact vs Thermodynamic Efficiency Trade-off.

Figure 5. illustrates the fundamental trade-off between thermodynamic efficiency and environmental impact. HFO-1234ze(E) represents the optimal balance, achieving 15.6% efficiency with near-zero GWP (<1). R-245fa achieves superior efficiency (18.2%) but carries a significant environmental burden (GWP=858). Cyclopentane offers excellent efficiency (17.8%) with minimal environmental impact (<1 GWP), though flammability concerns require additional safety infrastructure. Engineers must evaluate this trade-off based on specific project constraints and environmental regulations.

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 5, December 2025
Impact Factor: 7.67

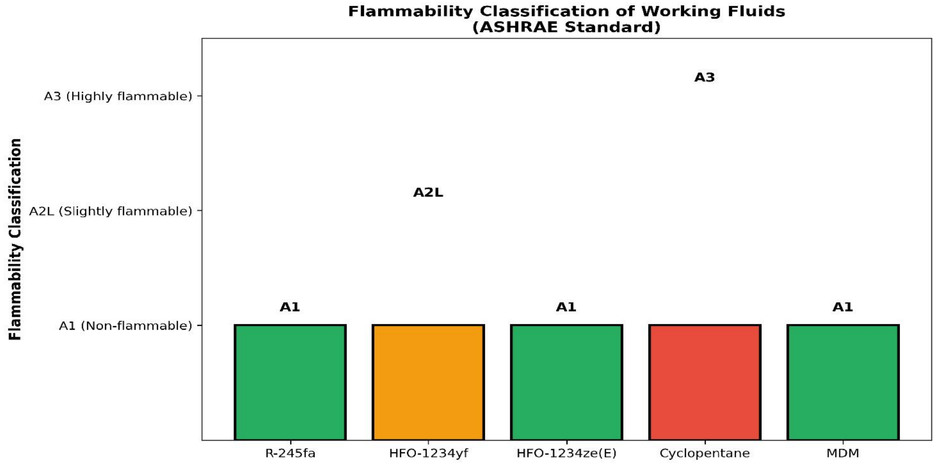

Figure 6. Flammability Classification (ASHRAE Standard).

Figure 6. categorizes the flammability characteristics of candidate working fluids according to ASHRAE standards. R-245fa, HFO-1234ze(E), and MDM are classified as A1 (non-flammable), simplifying system design and safety requirements. HFO-1234yf is classified as A2L (slightly flammable), requiring enhanced safety measures but offering acceptable risk profiles for controlled environments. Cyclopentane is classified as A3 (highly flammable), necessitating comprehensive explosion protection systems including flame arrestors, burst discs, and specialized containment measures. This flammability assessment significantly impacts system design complexity and capital costs .

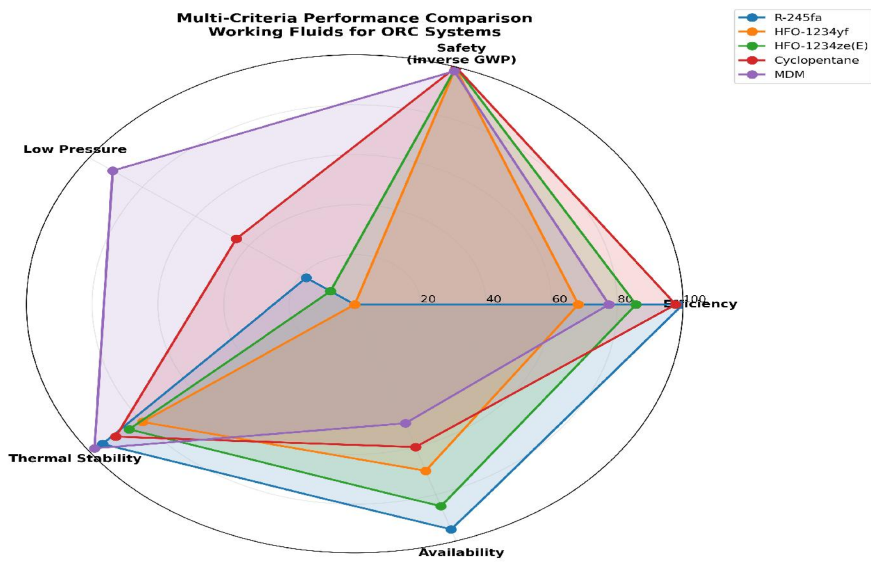

Figure 7. Multi-Criteria Performance Evaluation (Radar Chart).

Figure 7. presents a comprehensive multi-criteria evaluation of all working fluids across five critical performance dimensions: thermodynamic efficiency, environmental safety (inverse GWP), pressure requirements, thermal stability, and market availability. R-245fa exhibits strong performance in efficiency, thermal stability, and availability but scores poorly in environmental criteria. HFO-1234ze(E) achieves balanced performance across most criteria, making it an attractive choice for diverse applications. Cyclopentane demonstrates excellent efficiency and environmental performance but lower availability in commercial markets. This holistic visualization enables stakeholders to identify optimal fluid selections based on project-specific priorities and constraints.

VI. ECONOMIC CONSIDERATIONS

Economic viability significantly impacts technology adoption. Working fluid costs vary substantially based on production scale, regulatory status, and market demand [25]. R-245fa and cyclopentane offer lower material costs but face uncertain regulatory futures or safety-related expenses. HFO fluids command premium prices due to advanced synthesis and limited production capacity. System capital costs scale with working fluid selection through component pressure ratings, heat exchanger effectiveness requirements, and safety system complexity. A 50 kW ORC system utilizing HFO-1234ze(E) may cost 15-25% more than R-245fa-based systems, but improved environmental credentials and regulatory compliance justify the premium for many applications [26].

VII. RECOMMENDATIONS FOR WORKING FLUID SELECTION

Based on the comprehensive analysis including thermodynamic performance, environmental impact, safety profiles, and economic considerations, the following recommendations are provided for different application scenarios:

Low-Temperature Applications (75-100°C): HFO-1234yf is recommended despite slight flammability due to excellent environmental properties and adequate thermodynamic performance.

Medium-Temperature Applications (100-150°C): HFO-1234ze(E) provides optimal balance between environmental credentials, thermodynamic efficiency, and safety characteristics. Superior to HFO-1234yf for this range.

High-Temperature Applications (150-200°C): Cyclopentane offers superior thermodynamic performance (17.8% efficiency) where safety infrastructure is already established.

Extended Temperature Range (>200°C): Siloxane fluids like MDM enable high-temperature operation with excellent thermal stability and exceptional component size efficiency.

VIII. CONCLUSION

This study presents a systematic comparative analysis of five representative working fluids for small-scale ORC systems with comprehensive graphical and tabular performance metrics. While no single fluid optimizes all performance criteria simultaneously, the selection must balance thermodynamic efficiency, environmental impact, safety requirements, and economic considerations specific to each application. The transition from high-GWP hydrofluorocarbons to next-generation low-GWP alternatives represents an important trend in ORC technology development. HFO-1234ze(E) emerges as a compelling choice for most applications, combining acceptable thermodynamic performance (15.6%) with minimal environmental impact (GWP <1) and non-flammable characteristics. The presented multi-criteria evaluation framework and visualization tools enable engineers to systematically select optimal working fluids for diverse operating conditions and project constraints. Future research should focus on developing working fluid mixtures to optimize multiple objectives simultaneously and investigating emerging low-GWP alternatives currently in development.

REFERENCES

[1] R. C. DiPippo, "Geothermal Power Plants: Principles, Applications, Case Studies," 3rd ed. Butterworth-Heinemann, 2012.

[2] P. Colonna and T. Casati, "Organic Rankine Cycle power systems: From the concept to current technology, applications, and an outlook to the future," J. Eng. Gas Turbines Power, vol. 137, no. 10, p. 100801, 2015.

[3] J. Wang, Z. Zhao, W. Wang, and X. Hou, "Performance analysis and working fluid selection for small-scale ORC," Energy Convers. Manag., vol. 138, pp. 287-298, 2017.

[4] P. Loeffler and R. Boyce, "Capacity and energy density in small-scale power plants: A study of organic Rankine cycles," Renew. Energy, vol. 92, pp. 473-487, 2016.

[5] Y. Chen, M. Lundqvist, P. Jonasson, and A. Platell, "Comparative study of the carbon dioxide transcritical power cycle compared with an organic Rankine cycle," J. Eng. Gas Turbines Power, vol. 128, no. 1, pp. 141-147, 2006.

[6] M. van der Stelt, H. Jeanmart, and A. Busetto, "Characterization of biomass pre-treatment for entrained-flow gasification," Environ. Prog. Sustain. Energy, vol. 30, no. 3, pp. 361-374, 2011.

[7] Intergovernmental Panel on Climate Change, "Climate Change 2013: The Physical Science Basis," Cambridge Univ. Press, 2013.
[8] American Society of Heating, Refrigerating, and Air-Conditioning Engineers, "Safety Standard for Refrigeration Systems," ANSI/ASHRAE Std. 15-2013, 2013.
[9] B. F. Tchanche, G. Lambrinos, A. Frangoudakis, and G. Papadakis, "Low-grade heat conversion to power using organic Rankine cycles - A review of various applications," Renew. Sustain. Energy Rev., vol. 15, no. 8, pp. 3963-3979, 2011.
[10] M. J. Mello, J. R. Barbosa, and J. Nanini-Maury, "Modeling of the thermodynamic characteristics of low temperature hot spring powered organic Rankine cycles," Int. J. Thermodyn., vol. 18, no. 1, pp. 50-58, 2015.
[11] K. Sprouse and P. Garimella, "A review of transport property data for single component refrigerants," ASHRAE Trans., vol. 104, no. 1, pp. 487-494, 1998.
[12] E. W. Lemmon, I. H. Bell, M. L. Huber, and M. O. McLinden, "NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP)," Version 9.1, National Institute of Standards and Technology, 2013.
[13] B. Saleh, G. Koglbauer, M. Wendland, and J. Fischer, "Working fluids for low-temperature organic Rankine cycles," Energy, vol. 32, no. 7, pp. 1210-1221, 2007.
[14] A. Urbanucci, D. Testi, and D. Gallo, "Thermodynamic and economic comparison between small size ORC systems at different working conditions," Energy Convers. Manag., vol. 116, pp. 1-13, 2016.
[15] X. Zhang, M. He, and Y. Zhang, "A review of research on the Kalina cycle," Renew. Sustain. Energy Rev., vol. 16, no. 7, pp. 5309-5318, 2012.
[16] O. H. Bergman, H. D. Baehr, and T. J. Chung, "Thermodynamic analysis of power generation using low-grade waste heat sources," J. Eng. Power, vol. 97, no. 4, pp. 589-597, 1975.
[17] United Nations Environment Programme, "Report of the Kigali Amendment to the Montreal Protocol," 2016.
[18] C. Eyerer, M. Wieland, J. Vandersickel, and H. Spliethoff, "Experimental investigation of an ORC system utilizing a mixture of siloxanes with high temperature process heat," Appl. Therm. Eng., vol. 106, pp. 79-88, 2016.
[19] M. Imran, M. Usman, B.-S. Park, and D.-H. Lee, "Comparative assessment of organic Rankine cycle for low grade waste heat recovery," Energy, vol. 73, pp. 482-493, 2014.
[20] T. Hung, T. Wang, Y. Kuo, B. Kuo, and W. Huang, "A review of organic Rankine cycle systems for micropower generation," Appl. Therm. Eng., vol. 27, no. 12, pp. 1257-1273, 2007. [21] S. Quoilin, M. Broek, and V. Declaye, "Techno-economic survey of organic Rankine cycle systems," Renew. Energy, vol. 36, no. 2, pp. 763-773, 2011.
[22] A. Schuster, S. Karellas, E. Kakaras, and H. Spliethoff, "Energetic and economic investigation of Organic Rankine Cycle applications," Appl. Therm. Eng., vol. 29, no. 8-9, pp. 1809-1817, 2009.
[23] S. Lecompte, H. Huisseune, M. van den Broek, B. Vanslambrouck, and M. De Paepe, "Review of organic Rankine cycle applications for waste heat recovery," Appl. Therm. Eng., vol. 64, no. 1-2, pp. 252-265, 2014.
[24] T. Yamamoto, T. Furuhata, N. Arai, and K. Mori, "Design and testing of the organic Rankine cycle," Energy, vol. 26, no. 3, pp. 239-251, 2001.
[25] N. Rahbar, J. A. Esfahani, and M. Asadi, "Estimating the electricity generation and sizing the rooftop photovoltaic systems on campus and its environmental impacts and economic benefits," Renew. Energy, vol. 50, pp. 326-330, 2013.
[26] V. Ziviani, M. Beyene, and M. Venturini, "Hybrid organic Rankine Cycle-vapor compression cycle: Design and preliminary performance evaluation," Int. J. Energy Res., vol. 38, no. 15, pp. 1886-1898, 2014.
[27] H. Carlqvist, U. Fässler, and S. Nordström, "New Efficient and Environmentally Friendly Solutions for Small- and Medium-Scale Power Generation from Biomass," in Proc. Eur. Biomass Conf. Exhib., 2004, pp. 1245-1248.
[28] C. Wieland, U. Preißinger, and H. Spliethoff, "Performance comparison of different types of siloxane refrigerant mixtures for ORC applications," Appl. Therm. Eng., vol. 85, pp. 252-262, 2015.
[29] R. Baert, "Oil-free compressor technology advances for near-isothermal processes in mechanical energy storage applications," Appl. Therm. Eng., vol. 109, pp. 482-495, 2016.