

Abstract

The rapid growth in population and increasing demand for comfort and luxury in daily life have resulted in a substantial rise in electricity consumption. Global electricity usage has surged from 7,320 TWh in 1980 to nearly 27,000 TWh in 2023, driven by industrialization and improved access to power worldwide. However, this demand remains heavily reliant on fossil-based energy sources, contributing significantly to environmental issues such as global warming, ozone layer depletion, and deforestation. Despite advancements in renewable energy technologies, fossil fuels still dominate electricity generation. To sustainably meet the growing energy needs, it is imperative to explore alternative, efficient, and environmentally friendly power generation technologies. The Organic Rankine Cycle (ORC) has emerged as a promising solution to harness low- and medium-temperature heat sources, including geothermal, solar, and industrial waste heat. Compared to the traditional steam Rankine cycle, ORC is better suited for low-grade heat applications, offering higher feasibility and efficiency. Studies indicate that waste heat constitutes 20–50% of industrial energy consumption, with 18–30% of this recoverable. However, challenges such as low thermal efficiency, high cost-to-power ratios, and limited technology maturity hinder widespread ORC adoption. This study focuses on improving ORC performance through numerical analysis and experimental investigation. Developing indigenous ORC systems tailored to local needs can significantly reduce reliance on fossil fuels, promote renewable energy utilization, and provide economic and environmental benefits. The outcomes aim to support ORC technology deployment in India, advance sustainable energy goals, and address the energy demand gap.

Various thermodynamic power cycles can be utilized to convert low-to-medium temperature heat (available from many sources and has huge potential) to electricity. A detailed comparison between them is essential to identify the suitable one. Hence, to fulfill this research gap, six thermodynamic power cycles (Organic Rankine cycle with dry fluid, Organic Rankine cycle with wet fluid, Transcritical CO₂ Rankine cycle, Kalina cycle, Organic flash cycle and Trilateral flash cycle) have been compared for various heat source and sink temperatures. Objective functions are power generation, efficiency, irreversibility, cost, profit, environmental benefit, techno-economic parameters, etc. The study shows that the trilateral flash cycle is best for medium heat source temperature and the CO₂ Rankine cycle for low heat source temperature. The trilateral flash cycle shows an 11.5% higher exergy efficiency and 16.16% increment in annual profit at 160°C heat source temperature compared to the organic Rankine cycle with dry fluid. A decrease in condenser temperature is more advantageous than an

increase. The study reveals that the CO₂ Rankine cycle would be advantageous for low-grade heat sources while the trilateral flash cycle for medium-grade heat sources in terms of performance, cost, design, operation and environmental benefits.

The need for organic Rankine modification by various means can be realized for low-medium grade heat recovery. Hence, two new ejector-enhanced organic Rankine cycles (EEORC-1 and EEORC-2) are presented in this study. Three new economic models (M1, M2, and M3) have been chosen to study the feasibility in the real world and ensure market entry of the technology for commercialization, leading to mutual benefit to both industries and consumers. Energy, exergy, economic and environmental performances are evaluated for various working fluids and waste heat inlet temperatures by optimizing cycle parameters to maximize net work output. Economic simulation is performed to judge the best model suitable for the minimum possible selling price along with the maximum possible profit to the industry. Results show that EEORC-1 with R123 performs best and renders a maximum 18% increment in net work output at 70 °C heat source temperature. The basic cycle has maximum thermal and exergy efficiencies of 3.8% and 40.0%, respectively at 70°C heat source temperature. M2 model is suitable for consumers as well as government and private-owned power plants. The proposed M2 economic model gives a maximum of 7.32% increment in profit by EEORC-1. Extra profit can be generated by earning more carbon credit.

A laboratory-scale ORC system is designed and developed for electricity generation from low-medium-grade heat sources. The experimentation involves component selection, fluid selection, design, fabrication and testing. A custom-designed separator has been fabricated and used to ensure saturated vapor at the turbine inlet. R601a has been used as a working fluid due to its zero ODP and negligible GWP. Parametric analyses examined the effects of heat loads (5–11.5 kW), hot fluid flow rates (40–60 L/min), and cold air inlet temperatures (29–37°C) on system performance. At 11.5 kW, the net power peaked at 0.939 kW, and cycle efficiency increased from 2.34% to 8.08%, demonstrating the benefits of optimized heat input. Exergy efficiency is found to be highest at moderate flow rates (40 L/min), with evaporator effectiveness ranging from 0.78 to 0.84. RSM-ANOVA tool has been used for simultaneous optimization of net power and cycle thermal efficiency and validated performance predictions with minimal errors (1.55% for net power, 2.01% for efficiency). Findings have been extended to analyze waste heat recovery from an Indian nuclear power plant (NPP), demonstrating the ORC system's versatility. This research offers practical insights and guidelines to enhance ORC systems for industrial waste heat recovery applications.

A feasibility study is essential before installing a power generation system to recover waste heat from nuclear power plants. Hence, nine possible waste heat locations of Indian nuclear power plants are identified and two feasible cases (case-1 and case-2) are deduced to use the organic Rankine cycle as a bottoming cycle. ORC is used for waste heat recovery from a nuclear power plant (NPP) without alteration of any existing system and components to avoid any safety issues. Energy, exergy, economic and environmental performances are evaluated for selected working fluids and given waste heat conditions for selected feasible cases. Capital investment in alternators has been correlated with the help of the available market price of alternators and applied in economic analysis. The economic study is based on Net present value, Discounted payback period, Levelized cost of energy, Internal rate of return, Profit and per unit build-up cost of ORC to suggest whether the installation is worth the venture or not. The result is compared in tabulated form for both feasible cases and different working fluids. Different working fluid behaviors are also compared to get the best working fluid. The result shows that below 41°C condenser temperature, case-2 based bottoming ORC should be the priority to install and at the availability of sufficient funds, both cases can be installed, which will cumulatively produce 499.3 kW of electricity from waste energy with a total of 204.62 thousand USD annual profit from the total capital investment of 764.96 thousand USD. For 40 years of the system's lifetime, a total of 1.392 million USD will be used if both cases are employed and the invested cost will be returned in 8.73 years.