Chapter 1: Introduction

The rapid growth in the global population and increasing demand for comfort and luxury have led to a surge in electricity-dependent household and commercial appliances, driving energy consumption to unprecedented levels. This trend risks exacerbating environmental hazards such as global warming - a crisis further amplified by industrial practices like dumping low-grade waste heat, deforestation, mining, and ozone layer depletion. To address these challenges, sustainable power generation technologies that utilize low-grade waste heat without additional environmental harm have emerged as critical solutions. Among these, thermodynamic cycles like the ORC stand out due to their efficiency in converting low and medium-temperature heat sources, including renewable energy and industrial waste heat, into electricity. Unlike traditional steam Rankine cycles, ORC systems excel at low-temperature applications, making them ideal for waste heat recovery. However, widespread adoption of ORC technology faces barriers such as low thermal efficiency, high cost-to-power ratios, and technological immaturity compared to established cooling/heating systems. A key limitation is the inherently low temperature lift of low-grade heat sources, which restricts heat recovery performance. Consequently, advancing ORC systems through modifications to enhance efficiency and validating these improvements through targeted experimentation is urgently needed to unlock their full potential for sustainable energy generation.

1.1. Background and Motivation

The rapid expansion of electricity-powered residential and commercial systems, driven by population growth and the pursuit of comfort, has led to surging global energy demands. According to a Statista report by Bruna Alves, worldwide electricity consumption rose from 7,320 TWh in 1980 to approximately 27,000 TWh in 2023, fuelled by industrialization and expanded electricity access. By 2050, global electricity generation capacity is projected to exceed 14.7 terawatts [1]. In 2020, renewable energy contributed 2.8 terawatts of capacity, still lagging behind fossil fuels (4.4 terawatts), with coal and peat remaining the dominant sources [1]. China leads the adoption of renewable energy1 terawatt capacity), followed by the USA (325 GW) [1]. India ranks as the third-largest electricity producer, with an installed capacity of 404.13 GW as of July 2022, of which 39.91% (161.29 GW) comes from renewables, including solar (57.97 GW), wind (40.89 GW), biomass (10.68 GW), and hydropower (46.85 GW). Despite generating 1,598 TWh in 2019–20, India faced a 212.56 GW peak demand in January 2023, underscoring the need for expanded capacity [2]. By 2035, energy use in non-OECD countries is expected to rise by 84%, with China and India leading this surge [3]. The design and operational efficiency of thermal power plants have been optimized through innovative technologies, making them a viable solution for energy generation from high-grade temperature sources but at the cost of emission of carbon footprint [4]. The UN Agenda 2030's Sustainable Development Goals (SDGs) outline this transition to a low-carbon economy, incorporating social, economic, and environmental sustainability [5]. Harnessing low-medium grade heat sources—such as geothermal energy, solar heat, and industrial waste heat—offers significant potential. Industrial processes discard 20–50% of energy as waste heat, with 18–30% recoverable for power generation. Thermodynamic cycles, particularly the organic Rankine cycle (ORC), are preferred for large-scale applications due to their efficiency and adaptability. While traditional steam Rankine cycles excel above 340–370°C, ORC systems (Figure 1.1) use organic fluids to efficiently convert lower-temperature waste heat into electricity. ORC technology is already operational globally, with installations in the USA, Canada, Italy, Austria, Germany, and others, demonstrating its feasibility for diverse energy recovery applications. ORC technology is commercially utilized in sectors worldwide, with prominent manufacturers like Turboden (Italy) and Ormat (USA). However, no significant research or commercial development has occurred in India.

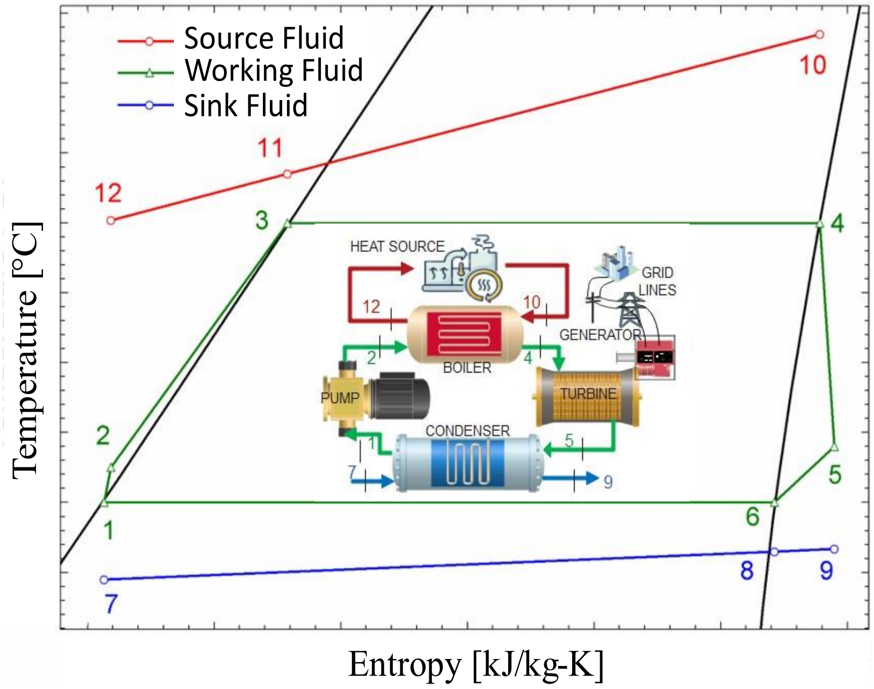

Figure 1.1. Layout and temperature-entropy diagram of waste heat recovery ORC

While attempts to use imported ORC technology have faced challenges, developing indigenous ORC systems, particularly for Nuclear Power Plants, offers a cost-effective solution for converting waste heat into electricity. This initiative can significantly boost the Indian economy, reduce coal dependency, and improve air quality, delivering health benefits to the public. The present study aims to accelerate ORC technology deployment, with recommendations to the Government of India through BRNS (Board of Research in Nuclear Sciences) for nationwide adoption and public benefit.

1.2. Literature Reviews

1.2.1. Power Cycles for Low-Medium Grade Heat Recovery

Waste heat recovery (WHR) improves energy efficiency across industries, reduces environmental impact, and cuts fuel costs, especially in fossil fuel systems. WHR approaches include heat-to-heat, heat-to-work, and heat-to-power conversions, though efficiency decreases with each conversion due to thermodynamic losses. Low-grade waste heat, often rejected by conventional power plants, can be utilized through advanced energy conversion technologies and optimized heat exchangers or fluids to enhance performance. There are a variety of methods for producing electricity from renewable heat sources, but heat engine-based power production systems are typically favoured for large-scale applications due to their adaptability and higher efficiency [6–8]. If solar photovoltaic panels with battery storage and organic Rankine cycle coupled with thermal energy storage are compared technically and economically, it was found that ORC offers improved reliability in power supply and can be scaled up to achieve higher efficiency. Comparison has been carried out on the basis of levelized cost of electricity (LCOE) at the same capital utilization factor to suggest the appropriate one between solar photovoltaic and thermodynamic cycles [9]. Various thermodynamic power cycles have been designed for their specific purpose and condition to produce electricity from low-medium heat sources, such as the organic Rankine cycle, supercritical CO_2 Rankine cycle, Kalina cycle, organic flash cycle (OFC), and trilateral flash cycle (TFC) [10–13]. ORC was developed in the early 19th century with unique qualities to utilize low and variable-temperature heat sources and it reached a sizable niche market in the power sector of the twenty-first century as it is simple, inexpensive, and compact [10]. Kalina cycle was developed in the early 1980s, and it has been cited as one of the options that better fit the heat transfer curves of the heat source and the heat recovery system [11]. However, the Kalina cycle's layout is somewhat more complicated due to the additional separators and heat exchangers, which also come at an added expense. In order to recover heat from low-temperature sources, it was observed that the Kalina cycle is a very inefficient one and suggested OFC for power generation instead of ORC and Kalina cycle [12]. Ho et al. [13] investigated 10 different siloxanes and aromatic hydrocarbons as suitable working fluids for the comparison of OFC and ORC’s and results revealed that aromatic hydrocarbons were more suitable due to their higher power output and simpler turbine designs, and both cycles possess comparable utilization efficiencies. Some studies were performed to suggest better cycle and system performance among the OFC and ORC, such as net power production, thermal and exergy efficiencies, and exergy destruction ratios at each component of the systems [14]. TFC is a modified ORC in which the organic working fluid is heated to saturation liquid condition under high pressure rather than boiled [15]. Under the same operating conditions, the TFC system may recover more waste heat than the ORC [16]. It was discovered that the TFC Power production is greater than the ORC's by 14% to 29% for the same low to medium heat and heat sink conditions if the heat source temperature is just below 100°C [17,18]. Transcritical CO_2 Rankine cycle is also used for low-temperature heat sources and it provides better temperature glide in the evaporator section [19,20]. CO_2 transcritical power cycle and Kalina cycle were compared, and it was found that the Kalina cycle shows a lower cost per net power and better economic performance [21]. The advantage of OFC is a close match between the heat transfer curves [22]. CO_2 transcritical cycle and OFC were compared using R245fa and R600 and observed that CO_2 cycle produces slightly higher per unit work and better exergy efficiency; besides, OFCs can provide an economically better solution. However, R245fa may lead to some environmental impact due to its higher GWP and there is the chance of explosion with R600 OFC [23]. Another study showed the comparison of transcritical reheat CO_2 cycles to the ORC and the Kalina cycle and deduced that the transcritical CO_2 cycle has the largest net power production and the economic performance is between the Kalina cycle and the ORC [24]. When OFC, ORC and TFC were compared to recognize the potential solutions for low-grade heat recovery, then it was investigated that TFC obtains the largest net power output (13.6 kW) at the evaporation temperature of 152°C, which is 37% higher than that of ORC (9.9 kW) and 58% higher than that of OFC (8.6 kW) [25]. When selecting a working fluid for power cycles, factors like thermodynamic properties, stability, compatibility, safety, environmental impact, cost, availability, and regulations must be carefully considered. Environmentally friendly fluids, including hydrofluoro-olefins (HFOs), are increasingly used in ORC and OFC systems. HFOs offer advantages over conventional refrigerants like HCFCs and HFCs, including lower global warming potential, higher energy efficiency, and improved safety.

While research on their properties, flammability, and oil compatibility is ongoing, their favourable thermodynamic and environmental characteristics have garnered significant attention [26]. Many refrigerants were simulated as working fluids in ORC, including toluene, R123 [27–32], R134a [33], R245fa [34–37]. HFE-7000, HFE-7100, n-pentane and isopentane [38], R245fa/isopentane and R123/R245fa. Zeotropic refrigerant mixtures, composed of two or more refrigerants with different boiling points, are used to tailor working fluid properties for specific system designs. Properly mixed zeotropic fluids improve critical temperature, pressure, boiling point, flammability, ozone depletion, and global warming potential. Unlike pure refrigerants, zeotropic mixtures evaporate and condense over a temperature range, offering advantages like better temperature glide, enhanced capacity, and increased energy efficiency [39–41].

Despite extensive research on waste heat recovery cycles such as the ORC, OFC, TFC, Kalina, and transcritical CO_2 cycles, a clear consensus on the optimal system for low-grade heat recovery remains elusive. While each cycle offers unique benefits, trade-offs exist in terms of net power output, thermal and exergy efficiency, and economic performance. Moreover, existing studies often focus on individual aspects like working fluid selection or component design, with limited comprehensive comparisons under uniform conditions. There is also a need to further assess environmentally friendly fluids and zeotropic mixtures, highlighting an important research gap for integrated, multi-criteria optimization studies.

1.2.2. ORC modification

Within the last few years, many ORC modifications have been investigated. Safarian and Aramoun [42] presented three modified organic Rankine cycles (incorporating turbine bleeding, regeneration and both of them) and showed that the ORC integrated with turbine bleeding and regeneration has the highest thermal and exergy efficiencies. Research has been done to determine the best-performing combination of regenerative ORC with both an open-feed liquid heater and an internal heat exchanger [43]. According to some research, the ORC combined with turbine bleeding and regeneration has the maximum thermal and exergy efficiency. Internal heat exchangers, bleed turbines and turbine bleeding/regeneration are also incorporated into ORC to study the effect of thermal and environmental [44]. Various working fluids are also being studied with modified ORC to see the effect [45]. Kheiri et al. [46] analysed four modifications of ORC integrated with an ejector and reported a thermal efficiency improvement in the range of 13-19%. Chen et al. [47] studied vapor-liquid ejector-modified ORC using various working fluids. Haghparast et al. [48] introduced the ejector in

ORC to lower the turbine exit pressure driven by a second-stage evaporator and got improved power generation. Oyekale et al. [49] studied the modified hybrid ORC plant and concluded that 60% of irreversibility cost rates could be minimized by proper optimization of each system component. Tashtoush and Algharbawi [50] did a parametric study and optimization of the organic Rankine cycle with two turbines and an ejector. Zhang et al. [51] found that the use of an ejector in ORC power plant at different equipment locations will increase the net power production. Jafary et al. [52] proposed two novel ORCs with a solar-powered system (one with an internal heat exchanger and the other with a mixture heater) and analysed the overall energy and exergy efficiencies. Saini et al. [53] studied the thermodynamic and economic performances of an ejector-enhanced ORC and reported cost reduction, efficiency enhancement and CO_2 emission saving. Yu et al. [54] proposed recuperative transcritical ORC and found better thermodynamic performance. Surendran et al. [55] analysed the effect of using the ejector on increasing the work output. Li et al. [56] reported the enhancement of energy performances by coupling the ejector in an organic Rankine flash cycle driven by geothermal energy. They have also found that the ejector-enhanced system is better in terms of exergy efficiency and levelized energy cost [57].

Recent research on ORC modifications has explored turbine bleeding, regeneration, and internal heat exchangers, with some studies reporting that ejector integration can improve thermal efficiency by 13–19% and boost net power output. However, there remains a significant gap in fully optimizing ejector-driven ORC systems. In particular, comprehensive evaluations of ejector positioning, operating conditions, and their effects on exergy efficiency and cost performance are limited, underscoring the need for further investigation into these configurations for enhanced low-to-medium grade heat recovery.

1.2.3. Experimental Studies of ORC

Comparative studies suggest that ORC with dry fluids is optimal for low-to-medium temperature applications when techno-economic factors are considered [58]. The basic differences in the experimental analyses on ORC are in terms of component (pump, expander, evaporator, condenser and working fluids) types [27–38,59,60]. Pump used is mainly a multi-stage centrifugal pump, magnetic gear pump, plunger pump, piston pump and diaphragm pump. Heat exchangers (condenser and evaporator) used are mainly plate, fin-tube and shell-tube types (plate heat exchanger is generally preferred for liquid secondary fluid and others are preferred for gaseous secondary fluid). Expander may be of two-types: turbine (radial turbine) and positive displacement machines. As the experimental ORC setups reported in the open literature are of small capacity (power output was limited to 10kW), the positive displacement machines were used in most of the experimental studies. Hence, the expanders used are mainly scroll expanders [28,30,35,36], screw expanders [29,33,60], rolling piston expanders [34] and vane expanders [38]. Redial turbines, axial turbines, and impulse turbines are also used as expanders in some experimental studies of ORC [27,31,37]. The optimized parameters used inlet temperatures, inlet pressure, heat load and outcome parameters behaviour are considered to maximize the output [61,62]. It has been concluded from the study that 6 system parameters, including temperature and pressure at the evaporator outlet, temperature and pressure at the condenser inlet, expander shaft efficiency and working fluid pump efficiency, play important roles in the ORC net power output and thermal efficiency [63]. Some literature suggested that hermetic scroll expanders are widely adopted for small-scale ORC systems to produce electricity [64]. An ORC experimental setup using R123 as the working fluid and heat source temperature 130°C to 160°C affects in increased net work from 0.44 kW to 0.55 kW and efficiency from 6.71% to 8.72% [65]. Similar performance improvements were noted with higher cooling water flow rates [65]. Similarly, small-scale ORC experiment is performed with R123 under various cooling conditions and cooling water mass flow rate and obtained a maximum thermal efficiency of 5.30%, turbine isentropic efficiency of 75.2% at a water flow rate of 0.591 kg/s [66]. Research has emphasized the importance of selecting suitable working fluids and configurations to enhance ORC performance. It has also been validated experimentally that for low-temperature heat sources, simple ORC produces greater expander work output than complex ORC with R123 working fluid [67]. Experimental studies of a 0.3 kW micro-ORC system using R1233zd-E as the working fluid, featuring a likely world's smallest scroll expander, revealed optimum power generation and thermal efficiency of 0.266 kW and 7%, respectively when compared with other small-scale ORC systems [68]. The study reveals that pentane is effective working fluids, achieving net electric efficiencies ranging from 3.1% to 7.1%, across 2.7–6.0 pressure ratios in air-cooled waste heat systems [69]. Liu et al. [70] explored the effects of different working fluid charge levels on key system parameters under off-design conditions, concluding that overcharging the working fluid slightly enhances expander output power. The volumetric expanders are a good option for small to medium-sized ORC systems because of their inexpensive cost, slow rotation speed, and two-phase operation capability. The most common types of volumetric expanders are scroll expanders [71], vane expanders [72], screw expanders [73], and piston expanders [74] are used in ORC for power generation. Experimental studies have been performed on many types of volumetric expanders and a study shows that up to 77% isentropic expander efficiency can be obtained with a scroll expander of R245fa working fluid [75]. Many experimental studies showed that a scroll expander is the best choice for small-scale power generation and the evaporator's inlet and outlet condition are critical parameters and its fluctuations are hard to maintain at steady-state conditions and give direct fluctuation results on expander inlet mass flow rate [71,76]. It has been proven that the maximum net power output condition will be achieved at the saturated vapor state of the expander inlet [77]. So, to find the optimum condition of maximum net power output, a separator is required before the expander inlet to get the pure vapor at saturated vapor condition to generate maximum power. Liang and Yu [77] conducted a lab-scale investigation of an ORC system and revealed that maintaining a superheat degree of zero at the expander inlet yielded optimal performance, with a maximum electric power output of 0.61 kW and a thermal efficiency of 4.09% at a heat source temperature of 96.8°C. Some studies investigated the experimental parametric study of pressures, temperatures, and mass flows and projected them as performance indicators on net power output and cycle efficiency [78,79]. Zhou et al. [80] found that cycle efficiency, expander output power and exergetic efficiency increase with the evaporating pressure and heat source temperature, while the superheat degree of the working fluid has negative effects on system performance. At the optimized condition the maximum cycle efficiency and net output power of the expander are 8.5% and 645 W, respectively, with R123 working fluid [80]. Wang et al. [40] established a small-scale ORC experimental apparatus utilizing a scroll expander to investigate the thermodynamic performance under varying turbine inlet pressures, rotational speeds, and cooling water flow rates. Their findings indicated that both thermal and exergy efficiencies increased with higher turbine inlet pressures and cooling water flow rates at R245fa, R141b working fluid. Feng et al. [81] experimentally examined the effect of pump outlet pressure, expander inlet temperature and mass flow rate on net power output and thermal efficiency and found that the net power production shows an increasing trend as the mass flow rate rises, whereas the thermal efficiency produces a smooth tendency. Wronski et. al. [82] have done the experiment at evaporation temperatures ranging from 125 °C to 150 °C and condensation temperatures ranging from 20 °C to 40 °C and found maximum net power 2.5 kW of electricity with an isentropic efficiency of approximately 70%. Bademlioglu et al. [83] numerically analyzed the factors influencing system performance using the Taguchi and ANOVA methods, concluding that the evaporator and condenser temperatures, as well as turbine efficiency, significantly affected system thermal efficiency, however, $PPTD_{evap}$, $PPTD_{con}$ and pump efficiency were least effective. Tauveron et al. [84] validate optimization models for both the ORC's condenser and evaporator application when hot and cold source temperature variation occurs, along with experimentally validating that 50% reduction in the power output associated with a 20°C increase in the cold source temperature. There is less work done on life cycle assessment (LCA) on ORC scroll expander-based experimental setup. Some researchers have done LCA on ORC using R134a and R1234ze [85]. Some experiments have been performed on R245fa working fluid at the superheated state of distributed power plants of 1-2 kW and managed to get the thermal efficiency of range 5-7% [79,86]. Hijriawan et.al [87] produce power from ORC experimental setup at 10 °C condenser temperature by employing R134a working fluid but at higher pressure. For the easy comparison of experimental ORC cycles following Table 1.1 is drawn which has main focus on components, fluids, power output, thermal efficiency along with type of ORC (saturated/superheated).

Table 1.1. Literature review of experimental ORC’s

Year & Authors	Working Fluid	Expander	Condenser, Cooling Fluid	Pump	Evaporator, Heating Fluid	Capacity	Cycle Efficiency	Configuration
2013 Zheng et. al [74]	R245fa	Rolling-piston expander	Plate heat exchanger, water	Diaphragm metering pump	Plate heat exchanger, water	0.35 kW	5%	NA
2014 Zhang et. al [29]	R123	Single-screw expander	Multi-channel parallel type, Forced air	Multistage centrifugal pump	Spiral-tube	10.38 kW	6.48%	NA
2015 Miao et.al [30]	R123	Scroll	Plate heat exchanger, water	Piston pump	Tube-in-tube, oil	4 kW	6.39%	Superheated ORC

2016 Lei et.al [60]	R123	Single screw expander	Finned air condenser, air	Multistage centrifugal pump	Shell and tube, NA	8.35 kW	7.98%	Superheated ORC
2017 Li et.al [37]	R245fa	Turbo expander	Finned-tube condenser, forced air	Variable speed pump	Plate heat exchanger, thermal oil	NA	3.44%	Superheated ORC
2017 Pang et.al [32]	R245fa, R123 and their mixtures	Scroll	Plate heat exchanger, Water	Plunger	Plate heat exchanger, Oil	1.56 kW (1:0)，1.66 kW (2:1)	4.4%	Superheated ORC
2017 Shao et.al [66]	R123	Radial inflow expander	Brazed plate heat exchanger, Water	Diaphragm pump	Brazed plate heat exchanger, Thermal oil	1.24 kW	5.2%	Superheated ORC
2018 Zhao et.al [88]	R123	Single screw expander	Shell and tube, Water	Rotary pump	Shell and tube, Oil	3.27 kW	3.04%	NA
2019 Wronski et.al [89]	n-pentane	Reciprocating piston	Brazed plate heat exchan	Air-driven piston pump	Brazed plate heat exchanger, Oil	2.5 kW	~14%	NA

			ger, Water					
2020 Usmaan et.al [86]	R245fa	Scroll	Brazed plate heat exchanger, Water	Screw type pump	Brazed plate heat exchanger, Water	0.967 kW	7.36%	Superheated ORC
2021 Li et.al [90]	R245fa	Scroll	Plate heat exchanger, Oil	Piston pump	Plate heat exchanger, Water	1-2 kW	4.9% - 5.7%	Superheated ORC
2022 Hijriawan et.al [87]	R134a	Scroll	Spiral tube-type, Water	Scroll compressor	Spiral tube-type, Refrigeration system	584.5 W	3.17%	Superheated ORC

Based on the above literature review, experimental studies were performed mostly at the expander inlet superheated state (although it produces less expander power output when compared with saturated vapor state at the same expander inlet pressure). To the best of the author's knowledge and literature review, no experimental study was performed on R601a (isopentane) working fluid despite having numerically proven great potential in waste heat recovery. No previous ORC experimental study optimizes the condition for maximum power output and experimentally validated it with data driven numerical analysis along with prediction of ORC performance. The previous experimental studies also lack in comprehensive parametric analyses involving simultaneous variations in heat load, source fluid flow rate, and sink fluid inlet temperature.

1.2.4. Case study of NPP

Nuclear power plants generally have 33-35% efficiency and dispose 60% of waste heat into nearby waterbeds and air. In some cases where disposed waste heat can be used for fish farming, farm cultivation and desalination purposes but in most cases, these are disposed of in the environment due to the remote location of NPP's (Nuclear power plants) site [91]. Heat is released from the condensation of steam into a heat sink (i.e., seas, lakes, and air) [92]. There are several techniques for waste heat utilization from NPP [93]. Indian NPP having 300-MWe AHWR releases its waste heat from the main condenser, MHT (main heat transport) purification system and heat exchangers of moderator cooling system and feed water system make ideal NPP site to study the waste heat utilization for power generation [93,94]. However, several experimental and numerical studies showed the potential of ORC technology to harness power from a range of low-medium grade waste heat sources [89]. ORC system's performance is highly dependent on the working fluid used, heat source, and heat exchanger technology [95]. ORC is well-suitable with solar thermal-based collector technologies and has been demonstrated to be a dependable technology capable of efficiently trans forming low-to-medium-level heat sources into useable uses [96]. Despite having some limitations with ORC technology, environmental benefits and payback period also play a crucial role in decision-making [97]. On the other hand, NPP produces no direct CO_2 emission and if ORC is combined with NPP, then no significant effect in CO_2 emission will obtain. Nanofluid has recently emerged as an improved heat transfer fluid for WHR [98]. Nanoparticles enhance thermal conductivity in base fluids by creating nanofluid, resulting in a higher heat transfer rate. Hence, the overall performance of WHR system will be enhanced by using nanofluids. Plate heat exchangers with improved thermal conductivity of nanofluids experience faster heat transfer rates [99].

Despite extensive research on ORC systems for low and medium-grade waste heat recovery, significant gaps remain in harnessing nuclear power plant waste heat, particularly moderator and MHT purification system heat. Nuclear plants typically operate at 33–35% efficiency and discharge about 60% of their heat into the environment. While some waste heat is used for secondary applications, much is wasted due to remote locations. There is a clear need to design and optimize ORC systems operating at source temperatures of 60–70°C and sink temperatures around 30°C, potentially incorporating nanofluids, plate heat exchangers, and scroll expanders to efficiently generate electricity and reduce cooling losses.

1.3. Research Gaps

Based on the above literature reviews, the author found below research gaps.

- No study compares all the low-medium grade heat recovery power cycles on the basis of thermodynamic, economic, environmental and technical perspectives.

- No technical and economic comparison was made between the heat recovery power cycle and solar P-V photovoltaic panels with battery storage for better selection.
- A comparative study based on energy, exergy, economics, and environmental factors of ejector-enhanced novel ORC modifications is missing in a single platform.
- The optimum ratio of an azeotropic mixture of working fluid and novel working fluids analyses is missing in numerical studies as well as experimental studies.
- No such economic model for the power cycle was used in literature, which can fulfill the interest of the consumer as well as the industry simultaneously.
- Experimental parametric performances of ORC were missing for simultaneous variation of heat load, source fluid flow rate and sink fluid inlet temperature.
- The lack of separators to ensure saturated vapour at the expander inlet hinders accurate net power output calculations in an experimental study.
- Comparative experimental analyses of volumetric expanders under diverse conditions are insufficient, and sensitivity studies on system performance parameters are limited.
- ORC's experimental study contains various research gaps, like life cycle assessment (LCA), working fluid development, system stability, and design optimization. Conventional and Machine learning-based optimization and prediction of performance parameters of ORC experimental data is missing.
- No real application-based feasibility analyses of case studies have been done using numerical and experimental validation along with estimated capability for power generation from waste heat sites.
- A complete 4E study and the effect of hot oil-based nanoparticle performance on ORC working fluid is missing at a case study of a real waste heat recovery site.

1.4. Objectives and Novelty

The author identified the objectives below based on the research gaps mentioned above.

- Six thermodynamic power cycles (ORC with dry fluid, ORC with wet fluid, CO_2 Rankine cycle, Kalina cycle, OFC and TFC) have been compared on energy, exergy, economic and environmental basis to select the best power cycle for waste heat recovery. Parametric and techno-economic analyses have been performed for all cycles to generate the maximum power from low-medium grade heat sources.
- Comparative studies of two novel ejector-coupled advanced ORCs have been proposed to further enhance the performances of output parameters and complete 4E analyses at

optimized conditions have been done. A new economic model has also been introduced for consumer and manufacturer benefits.

- A lab-scale experimental ORC setup using isopentane (R601a) has been developed and various parametric performances have been analysed. A tailor-made separator has been fabricated and installed to get a saturated vapor condition at the turbine inlet. RSM-ANOVA has been used to optimize and predict performance parameters.
- A feasibility analysis, along with a complete thermodynamic and economic analysis has been done on the Indian nuclear power plant site for potential power generation and waste heat recovery. ORC parametric study (variations of condenser temperature and cold fluid inlet temperature) was taken in the case study. The performance of a dry ORC power cycle using nanofluid as hot fluid with various organic working fluids has been analysed for a real waste heat recovery site.

The novelties of the present study are as follows: (i) 4E analysis and techno-economic comparison of all possible thermodynamic power cycles have been conducted for the low-medium grade waste heat recovery, (ii) Two novel ejector-enhanced ORCs have been presented, followed by 4E analysis, to generate maximum power, (iii) A novel combination of scroll expander with isopentane working fluid is tested with ORC experimental setup under various operating conditions, (iv) Tailored made separator has been used in the ORC experimental setup, which plays an essential role for more power generation and (v) A feasibility study, along with parametric analyses, has been done to implement ORC technology for waste heat recovery from Indian nuclear power plant.

1.5. Thesis structure

The present thesis has been organized into seven chapters.

Chapter 1 includes the background and motivation, literature reviews, research gaps, thesis objective and novelty.

Chapter 2 contains the identification and comparison of low-medium waste heat source-based thermal power cycle. In this chapter, six possible waste heat recovery cycles (Dry ORC, Wet ORC, CO_2 Rankine cycle, Kalina cycle, Organic flash cycle and Trilateral flash cycle) were studied to find the best possible cycle.

Chapter 3 provides the numerical analysis of two novel ejector-enhanced ORC. The influence of different working organic fluids on the cycle is also analysed in each modification to draw maximum work output.

Chapter 4, includes a detailed design and development of the lab-scale ORC setup by including component details, fabrication process, and sensors used. The effect of heat load, the volume flow rate of hot fluid and cold fluid inlet temperature were simultaneously studied. Optimization and prediction are also done to find out the best condition at which both net power and thermal efficiency are maximized.

Chapter 5 consists of a detailed case study of an Indian nuclear power plant. A feasibility analysis has been done to find out the location of the waste heat source for maximum power generation at maximum profit. The effect of using nano-oils as heat source fluid for the ORC is also investigated.

Chapter 6 concludes the significant findings of the present investigation and possibilities for future work.