Istraživanja i projektovanja za privredu
Journal of Applied Engineering Science

Review Paper

DOI:10.5937/jaes0-36319
Paper number: 20(2022)3, 1001, 957-970
www.engineeringscience.rs * ISSN 1451-4117 * Vol.20, No 3, 2022

ORGANIC RANKINE CYCLE (ORC) SYSTEM IN RENEWABLE AND SUSTAINABLE ENERGY DEVELOPMENT: A REVIEW OF THE UTILIZATION AND CURRENT CONDITIONS FOR SMALL-SCALE APPLICATION

Miftah Hijriawan[1], Dwi Aries Himawanto[1], Nugroho Agung Pambudi[2], Zainal Arifin[1,*]

[1]Graduate Program of Mechanical Engineering, Universitas Sebelas Maret, Jl. Ir. Sutami No. 36 Surakarta, Indonesia
[2]Mechanical Engineering Education, Universitas Sebelas Maret, Jl. Ir. Sutami No.36 Surakarta, Indonesia
*zainal_arifin@staff.uns.ac.id

The Organic Rankine Cycle (ORC) is a thermodynamic cycle that converts heat into mechanical energy to produce electrical power in a closed system using organic working fluids. It is also a heat recovery technology that can use heat at low temperatures and makes it a promising thermodynamic cycle with cost-effectiveness and more energy efficiency. However, the ORC system's total efficiency is determined by the compatibility of the expander characteristics and working fluid properties with the system's thermodynamic cycle parameters. This study aims to analyze using an integrative review method regarding the development of the ORC system as a heat recovery technology. The purpose of the integrative review method is to review the knowledge base, where the review is carried out critically and has the potential to conceptualize and expand the theoretical foundation developed. In this case, the first analysis is about the literature study on the parameters of the ORC system. Furthermore, the development and optimization of the ORC system are discussed further to analyze its capabilities in various applications. Work fluids, component optimizations, and system configurations have been reported for possible improvements. In addition, this ORC system can be used as a technology in developing various renewable energy sources, including solar, biomass, geothermal, and waste heat. Furthermore, this system is assessed for its environmental and economic benefits to developing its capabilities and potential. The results show that integrating the ORC system in various renewable energy sources can provide proper operation, better efficiency, and advantages such as increased power and reduced pollution.

Keywords: ORC, renewable energy, heat recovery

1 INTRODUCTION

Energy is an important topic for several studies due to global warming and increased energy demand [1]. The tendency of fuels such as kerosene, liquefied petroleum gas (LPG), gasoline, coal, petroleum, and others derived from very limited fossil fuels to finish quickly also adds to the need to focus on this concept [2], [3]. Therefore, this is led to the utilization of renewable and sustainable energy sources potential to solve the problem [4].

Most renewable energy sources with low to moderate temperatures, such as solar, geothermal, biomass, and industrial waste heat, are difficult to convert efficiently into electricity using conventional power generation. Therefore, this encourages research on several thermodynamic cycles, such as the Rankine cycle, which was widely developed [5]. The Rankine cycle, which involves isentropic compression in the pump, addition of pressure heat in the boiler, isentropic expansion in the expander, and release of pressure heat in the condenser, is suitable and can be used in steam power plants. After condensing steam, the working fluid is fed back into the evaporator to maintain a continuous cycle [6], [7]. Meanwhile, due to the Steam Rankine Cycle (SRC) limitations, the Organic Rankine Cycle (ORC) system has been developed as a solution to the use of low heat sources. Also, it has a more flexible design in several possible system configurations [8]. It has also been stated that heat from a source can be utilized at low temperatures by combining the ORC with the SRC concept and an organic working fluid with a low boiling point [9].

The ORC system is a potential method for producing electrical power from low-temperature heat sources in renewable energy applications and improving industrial energy efficiency. [10]–[12]. It is also commonly utilized due to the ease of design and operation [13], [14]. However, the system has several disadvantages currently being investigated by researchers to improve its operations. In recent years, some of the factors designed to ensure improved performance have been categorized into three: the effect of cycle configuration, the choice of operating fluid, and the system's operational working conditions [1].

Because of its simplicity and reliability, combined heat and power production (CHP) utilizing the ORC system is the most suitable and promising alternative [15]. The system can also be freely applied to several different resources, either as a stand-alone or a Combined Heat and Power Production (CHP). As a result of this article, the characteristics that affect the efficiency and performance of the ORC system in its application as a small-scale energy generator are described in this study. It also presents optimization possibilities to achieve efficiencies from the system's initial development. Furthermore, a comprehensive discussion of the integration of the ORC system in renewable and sustainable energy sources is discussed, with a focus on current conditions and future developments. In addition, an analysis of environmental and economic benefits is also explained as a consideration in the application of the ORC system.

2 ORGANIC RANKINE CYCLE PARAMETERS AND OPTIMIZATION

2.1 Parameters of Organic Rankine Cycle Performance

Several factors influence the ORC system's efficiency, including the choice of working fluids, the usage of expanders, the system's adaptability, and working circumstances. [16], [17]. The effect is both technical and economical in the developmental stages. Meanwhile, Drozdz reported that the results obtained from technical and economic optimization are different [18]. The assumption based on economic criteria shows that the optimal exploitation point is ideal in cases with stable economic parameters and changes when the parameters are dynamic. It is shown in geothermal energy sources, where the optimal pumping intensity is affected by changes in the heat unit relationship and the value of electrical energy.

Water is commonly utilized as the working fluid in SRCs that operate on a large scale with high-temperature energy sources. However, the thermodynamic nature of the steam produced requires a complicated generator scheme. At the same time, the creation of a liquid fluid during the expansion process also leads to several problems in the turbine. Therefore, water is an unsuitable working fluid for low-temperature energy sources [19].

Using organic working fluids with boiling points lower than water is promising to generate electrical energy in the ORC [20]. Moreover, the suitability of several components with the configuration of this system also provides an important role in producing optimal work from the ORC system.

The isentropic working fluid pump and expanders are considered to have no change in temperature or entropy, while the evaporator and condenser are unaffected by the operations. As a result, the following is the energy conservation relationship for each component [7], [21], [22]:

Working Fluid Mass Flow Rate (kg/s)

$$\dot{m} = \rho \, . \, v \tag{1}$$

$$\dot{m} = \frac{\dot{Q}_{evap}}{h_{eca\,p_{out}} - h_{evap\ \_in}} \tag{2}$$

Pump power (Watts), with $q = 0$

$$w_{pump\ ,in} = \dot{m} \, . \, h_{pump\ \_out} - h_{pump\ \_in} \tag{3}$$

or,

$$w_{pump\ ,in} = \dot{m} \, . \, V(p_{pump\ \_out} - p_{pump\ \_in}) \tag{4}$$

Heat Enter the Evaporator (Watt), with $w = 0$

$$Q_{evap\ ,in} = \dot{m} \, . \, (h_{eva\,p_{out}} - h_{eva\,p_{in}}) \tag{5}$$

Expander Power (Watts), with $q = 0$

$$w_{turb\ ,out} = \dot{m} \, . \, (h_{tur\,b_{in}} - h_{tur\,b_{out}}) \tag{6}$$

Heat Out on the Condenser (Watt), with $w = 0$

$$Q_{cond\ ,out} = \dot{m} \, . \, (h_{con\,d_{out}} - h_{con\,d_{in}}) \tag{7}$$

Energy Efficiency

$$\eta_{en} = \frac{w_{net}}{Q_{in}} = 1 \, \frac{Q_{out}}{Q_{in}} \tag{8}$$

where,

$$w_{net} = q_{in} - q_{out} = w_{turb\ ,out} - w_{pump\ ,in} \tag{9}$$

2.2 The Selection of Organic Working Fluid

The selection of a safe and environmentally friendly working fluid with reliable thermodynamic characteristics and suitability at a specific temperature range is necessary to obtain an optimal work cycle and system configuration [16], [23]. Moreover, the temperature range for ORC operation also influences the selection process due to the fluid's thermodynamic properties on cycle efficiency at different applied temperatures [24].

The critical temperature, critical pressure, and type of expansion of the fluid (dry or wet) are the most typical thermo-physical parameters used to determine the nature of the working fluid [25]. A high-molecular-complexity expander is utilized to lower the average temperature difference between fluids with the same critical temperature, while a heat exchanger is used to prevent exergy losses [26]. Meanwhile, a higher critical temperature also requires an expander with a low rotation speed to obtain a rate close to the optimal value [27].

Because of the vibrations of the atoms, a rise in molecular complexity usually increases the heat capacity of the molecules. As can be seen from the difference in the slope of the saturated vapor curve and the simple molecule in the T-S diagram in Figure 1, this has three main implications for the power cycle. As a result, in dry conditions, this results in an expansion. This phenomenon demonstrates how the preheating phase in evaporation and the desuperheating phase in heat loss are becoming increasingly important [19].

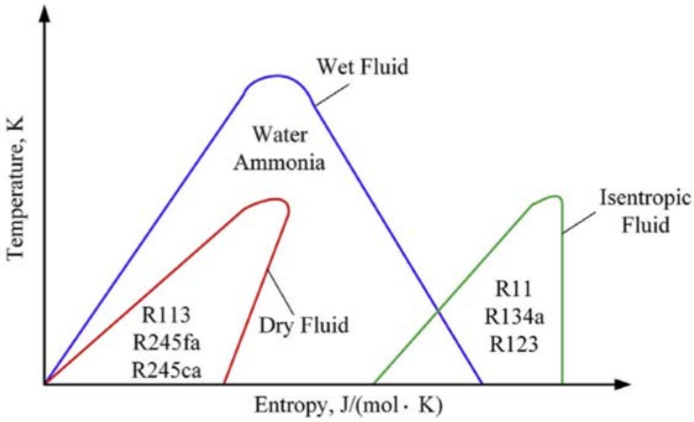


Fig. 31. The T–S diagram for wet, isentropic, and dry fluid [28], [29]

The slope of the saturation vapor curve, as shown in Figure 1, is one approach to defining organic fluids. Furthermore, dry and isentropic fluids can outperform wet fluids [1]. To achieve superior thermal performance, the ORC system with low-temperature heat requires an organic fluid with a lower latent heat of evaporation [28]. Furthermore, low-specific-volume organic fluids reduce the heat exchanger and expander size and decrease total system size and cost. [30]. As a result, to improve cycle efficiency, the fluid must reach a critical temperature close to the heat source's maximum temperature [31]. Meanwhile, a larger molecular weight can minimize the number of stages necessary for the expander, allowing for a more solid ORC design, increased mass flow and turbine performance, and lower costs [24], [32]. Because of their low critical temperature value, refrigerants are frequently used as the working fluid in waste heat recovery with low-temperature quality [33]. Most of the challenges in the design of turbines in ORC systems can be solved by using a different working fluid with a higher molecular mass and molecular complexity, lower critical pressure, and lower boiling point than water [19]. It can be seen in Table 1, which compares the three most common types of working fluids or about 80% of the most widely used in ORC systems [34].

Table 21. Properties of the three most commonly used working fluids in ORC systems [34]

Fluid (type)	T_{NBP}(K)	T_C(K)	P_C(MPa)	ODP	GWP	Safety Group^a
R134a (wet)	247.0	374.2	4.06	0	1430	A1
R245fa (dry)	288.2	427.2	3.65	0	1030	B1
R123 (dry)	300.9	456.8	3.66	0.02	77	B1

2.3 The Selection of Expander Type

While determining an expander for an ORC system, numerous criteria must be considered, including power capacity, isentropic efficiency, cost, and complexity. The parameters that can be applied to various types of expanders varied. An acceptable choice should be made based on the system's operational and working conditions [28].

It is possible to generally categorize expanders into the velocity types such as radial inflow and outflow, axial types, and volume types such as reciprocal piston, screw, and scroll expanders, as shown in Figure 2 [35], [36].

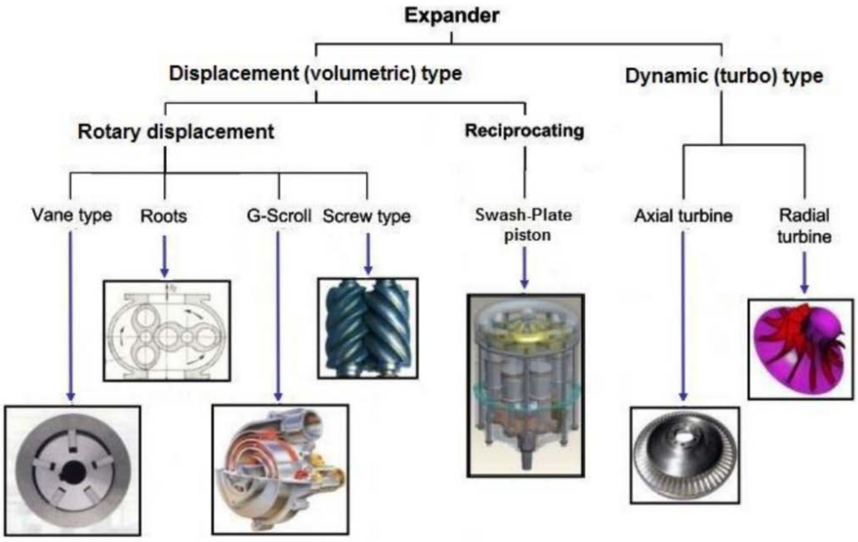


Fig. 2. Classification of Expanders for ORC Systems [37]

Turbo expanders are commonly applied in ORC systems with output power greater than 50 kW and are advantageous due to their small size, lightweight, and high efficiency. Their design and production process, on the other hand, is challenging. As a result, they have higher costs because there is a possibility of a considerable reduction in efficiency if they do not fit the design. Due to the risk of blade destruction, expander turbines cannot work in two conditions [29].

Screw expanders are best suited to output power ranges of 20-50 kW, whereas other volumetric expanders are better suited to output power ranges of 1-10 kW [10], [36]. These volumetric expanders differ from speed type expanders in that they have a lower flow rate, a higher-pressure ratio, and a lower rotational speed. Their advantage is that they can operate with the working fluid in two-phase conditions, which can occur at the end of the ORC system’s expansion process [38].

2.3.1 Reciprocating Piston Expander

It is the first type of volumetric expander developed [29]. It can produce high expansion efficiency and a volume ratio capable of reaching 10 or slightly higher [39]. The expander, however, requires a lot of bearings and intake and exit valves in its application, which makes the design complicated and expensive. Moreover, the liquid fluid in the expander cylinder can damage the component. Therefore, this expander is not recommended in the wet type of expansion [40].

2.3.2 Vane Expander

This type has a low rotational speed and volume ratio of less than 5. Its vane angle usually comes into contact with the expander casing, which means lubrication is needed to avoid damage to the working fluid. Moreover, it is important to consider its high friction wear and tear. This vane expander is very popular and widely used in industries, and its efficiency is reported to be from 30 to 40% [40]. Badr et al. reported that the vane expander’s efficiency reaches 80% in certain conditions [41].

2.3.3 Screw Expander

The screw expander does not require any valves but needs at least four bearings for two rotors that are not in contact. It means lubrication is required to guarantee a closed system in this expander [29] and is observed to have the highest lubrication requirement out of the volumetric types of the expander. It, however, needs to be operating at a high rotation (>10,000 rpm) when not lubricated to minimize losses. Therefore, it is considered inappropriate to be applied in standard generators. The volume ratio is also in the range of 5, with an efficiency of approximately 50% [39]. Meanwhile, it is possible to properly handle the humidity or liquid phase created in this expander [28], [40].

2.3.4 Scroll Expander

A scroll expander is a primary mechanism consisting of two spirals that serve as a fixed and orbiting scroll. It can be installed directly on the generator shaft to prevent additional bearings. Furthermore, the volume ratio spans from

1 to 5 [39], [42]. Even for relatively small systems (1 kW), Wang et al. and Zhou et al. showed measured efficiency of up to 83% [43], [44]. The liquid phase is not a problem for this scroll expander [40]. Due to its solid structure, reliability, fewer moving parts, lower noise and vibration, it has lately emerged as a possibility for energy generation in micro and small-scale ORC systems [45], [46].

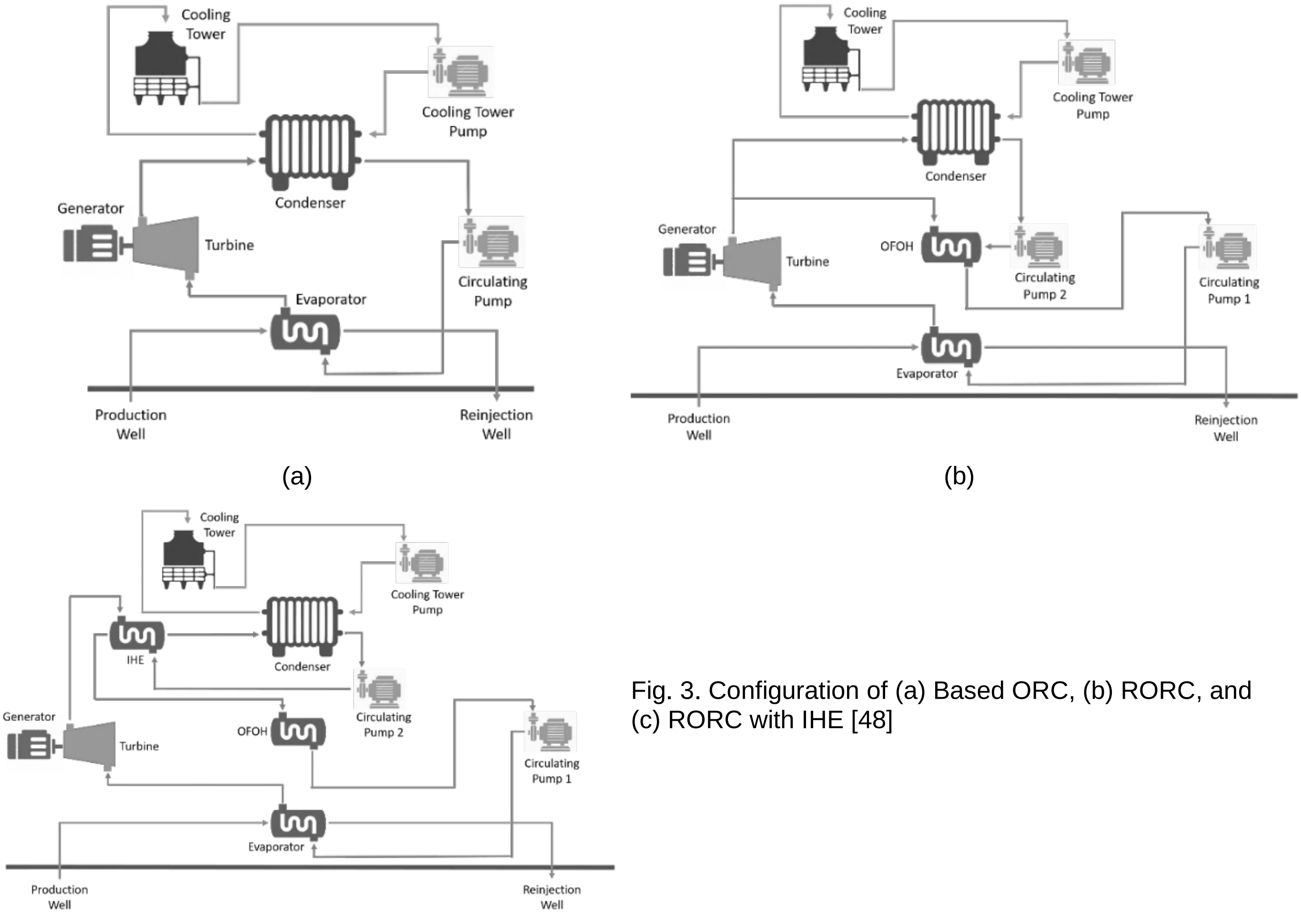
Because of these characteristics, scroll-expanders are preferred in this ORC system. Furthermore, the applicability of these properties, the nature of the working fluid, and the thermodynamic cycle parameters all affect the system's overall mechanical or energy efficiency [17]. Trans critical ORC systems with scroll expanders have been discovered by Landelle et al. to have the ability to obtain a maximum expander efficiency of up to 66.5% with a gross power production of 6 kW under supercritical entry conditions [47].

2.4 The Organic Rankine Cycle (ORC) System Configuration

The ORC system's performance is highly influenced by its configuration and installation model. Choosing the wrong design can limit the system's thermal efficiency and prevent it from utilizing heat to its full potential [48]. Based ORC, regenerative ORC (RORC), and RORC with Internal Heat Exchanger (IHE) are some of the possible configurations in this study, as illustrated in Figure 3 [22], [48].

In the ORC, efficiency can be improved by regenerating or feeding liquid heaters or operating above the critical point in the transcritical or supercritical cycle [49]. A SORC with a regenerator is known as the Regenerative Organic Rankine Cycle (RORC). This setup allows some heat to be recovered from the expander exit, reducing the requirement for a condenser. On the other hand, it may be detrimental in recovering as much heat as feasible in the regenerator [50].

The three types of configuration presented in Figure 3 show the addition of Open Feed Organic Heater (OFOH) and IHE in the RORC configuration with IHE can increase the factors affecting the performance by improving the efficiency and reducing energy loss from the cycle [48], [49], [51].



(a)

(b)

(c)

Fig. 3. Configuration of (a) Based ORC, (b) RORC, and (c) RORC with IHE [48]

3 ORGANIC RANKINE CYCLE PARAMETERS AND OPTIMIZATION

At low temperatures, the ORC characteristics produce highly efficient power. It requires a simple system configuration, and efficient expanders are very suited for most renewable energy sources, such as solar, biomass, and geothermal, or to increase industrial energy efficiency [12], [19], [52]. Figure 4 shows the application range of ORC systems based on temperature and power output which is recommended to ensure better conditions for work and efficiency.

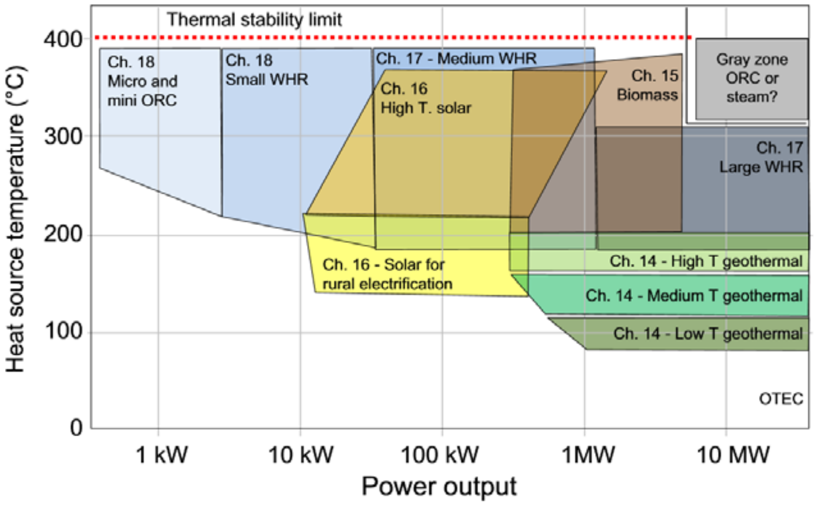


Fig. 4. An overview of ORC uses in the temperature-power output plane of heat sources [19]

The heat source providing the energy required by the ORC system also has different characteristics which significantly influence theoretical analysis and system design [53]. The ORC system overview concerning its technical utilization aspects, transformation, or energy exploitation process is presented in Figure 5 by following a possible configuration [54].

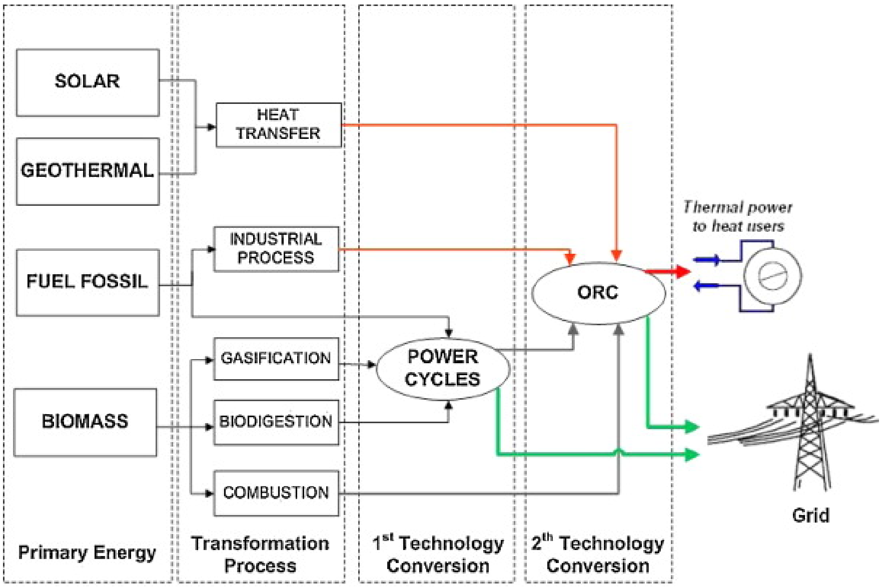


Fig. 5. An overview of ORC's potential applications by energy source [54]

3.1 Solar Energy

Solar energy-based technology has recently attracted interest in fulfilling the different energy needs of humankind [55]. Concentrated Solar Power (CSP) is a technique that employs a mirror or lens to focus sunlight on heating fluid and producing steam, which is then utilized to drive turbines and generate power in the same way as conventional power plants work [3].

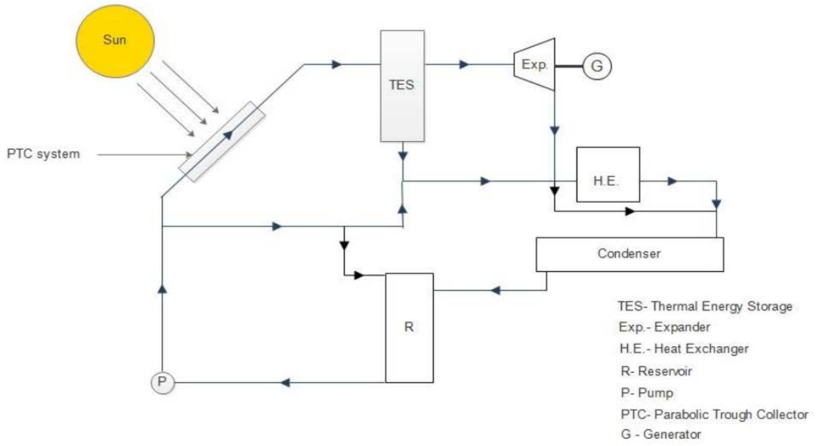


Fig. 6. ORC System Schematic Diagram with Solar Thermal Energy [37]

Figure 6 shows a block diagram of the SORC prototype, with the evaporator being a solar parabolic collector system that directly vaporizes the working fluid. To improve the present heating system, the hot steam is held in Thermal Energy Storage (TES) [15]. Furthermore, high pressure and temperature steam are directed towards the expander to generate electricity, and the low-pressure steam is cooled in the condenser after departing the expanders [37].

The heat energy from the sun is used in the Solar Rankine Cycle to heat the working fluid directly using direct vapor generation (DVG) and indirectly utilizing the heat transfer fluid (HTF) through a collector that works as an evaporator [56]. This application shows the configuration of solar energy with an ORCe using a solar thermal collector is very attractive for large capacity plants [55]. Concentrated solar collectors are commonly used for large-power capacity systems because of their high efficiency in the medium to the high-temperature range. Meanwhile, the type of collector used may impact the energy produced's efficiency [56], [57].

3.2 Biomass

Biomass is one of the most important energy sources, accounting for about 10% of global energy consumption. It comes from various industrial and agricultural operations, such as manufacturing and agricultural and forest wastes [13], [49]. Rice husks, sawdust, rice straw, and other biomass wastes are used as an alternative to fossil fuels in several underdeveloped nations [2]. The thermo-chemical and bio-chemical or biological technologies are the two basic procedures for converting these resources to energy [15], [58].

Biomass offers a lot of potential for simultaneously producing combined heat and power (CHP) [13]. It can also be used to create power in both external and internal combustion systems. The biomass is burned in a boiler for external combustion. The heat is directed into the ORC, but it must first be transformed into gas through pyrolysis or liquid biofuel in a conventional internal combustion engine. External combustion has the main disadvantage of lower conversion efficiency, whereas internal combustion has the problem of gas purification [53].

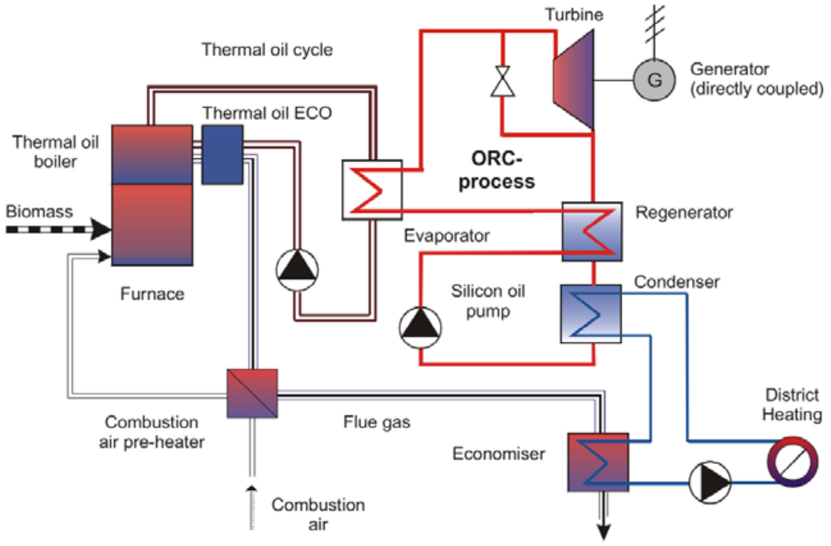


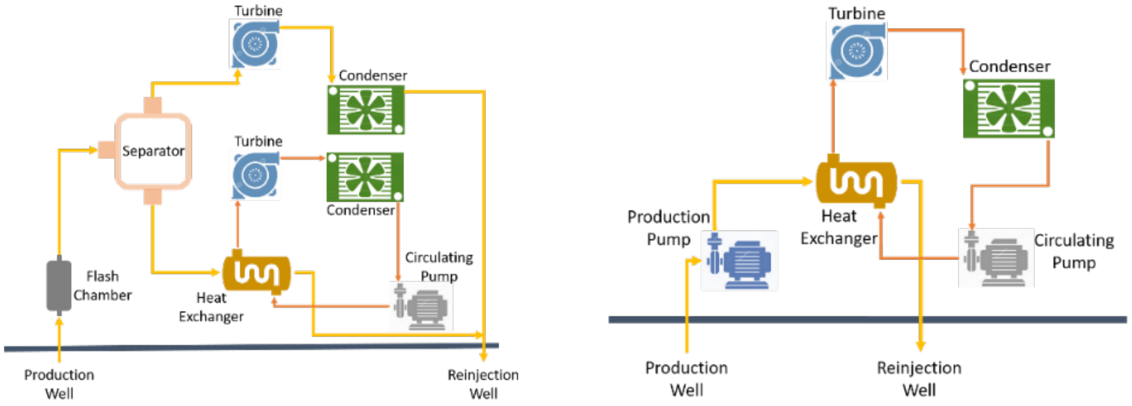
Fig. 7. The working principle of the biomass-fueled ORC process [59]

Figure 7 represents the biomass configuration with the ORC system, and the process includes using a hot oil cycle to connect the ORC system to a thermal oil boiler. This ORC system also operates in a closed cycle using silicon oil as the organic pressurized fluid, evaporated, heated by thermal oil in the evaporator, and transmitted in an axial turbine directly connected to an asynchronous generator. Furthermore, before entering the condenser, the silicone oil passes through a regenerator, and the condensation happens at a temperature that allows heat to be collected and utilized as district heat. Later in the cycle, the working fluid passes through the pump to return to the suitable pressure level [59]. Using medium heating media or thermal oil, on the other hand, has various advantages, including low evaporator pressure, insensitivity to load fluctuations, simple, and safe operation [60].

3.3 Geothermal

There are two types of geothermal energy sources. The first is hydrothermal reservoirs containing hot water or steam, immediately injected into the ORC system [61]. The second is Enhanced Geothermal Systems (EGS), which employ cold water pumped into wells drilled through shale to create hot water or steam at temperatures below 650°C [53]. Construction of new geothermal power plants in new fields and enhancing the thermal efficiency of existing power plants are two approaches to developing geothermal power plants [62], [63]. It is possible to apply the ORC technology for geothermal resources to a binary power plant system. Ormat first tested this in the early 1980s, which succeeded in developing this method as a solution for the commercial utilization of geothermal resources at low to medium temperatures. The binary power plant system, on the other hand, is currently much more similar to the ORC [25].

By employing waste brine from a separator, this binary geothermal power plant system can be applied to a flash system geothermal power plant [64]. The combination of this system can combine the two system advantages, which allows it to create an ideal cycle. This combined flash-binary geothermal power plant uses at least two turbines, making it possible to produce more power even with the same power source [7]. The configuration of the two systems is shown in Figure 8.



(a) (b)

Fig. 8. (a) Combined Flash-Binary Power Plant and (b) Binary Geothermal Power Plant [16]

However, while implementing ORC technology in a binary geothermal power plant, various factors must be considered, including the working fluid, condensation temperature and pressure, cooling media, expander technology, and cycle type [25]. Meanwhile, the integrated system performance of the supercritical ORC cycle-based hybrid system is the best, followed by subcritical ORC, single flash, dual flash, and Kalina cycle [65].

3.4 Waste Heat Recovery System (WHRS)

The development of waste heat and the lack of appropriate equipment for cost-effective usage of low-level heat are the fundamental energy inefficiencies in an industrial system [5]. The Waste Heat Recovery System (WHRS) is a cost-effective, ecologically acceptable technology for saving energy in an industry by repurposing waste heat even at low temperatures [66]. It is also proven to increase energy effectiveness and provide considerable economic benefits such as reducing fuel consumption and even CO2 production in an integrated energy generating unit with WHRS [1], [67]. It is due to the prospect of providing a profitable energy source while also lowering overall energy usage through numerous WHRS technologies to recover waste heat [68], [69].

However, it is important to note that each waste heat temperature range has a specific WHRS technology to obtain the most optimal efficiency [68]. It is also possible to use heat sources directly for energy generation needs in direct usage and heat exchangers [70]. Furthermore, the thermodynamic cycle can be used directly to recover heat from waste to generate electrical energy or improve a process's energy efficiency [71]. Through a comparative thermodynamic analysis of ORC and Kalina Cycle, Nemati et al. also stated that using thermodynamic cycles with organic working fluids offers cost-effectiveness and energy recovery approaches that are more promising for intermediate-level waste heat sources [23]. Furthermore, the ORC system is a thermodynamic cycle and WHRS technology that may use waste heat in power plants employing a variety of energy sources, including geothermal, biomass, and solar, at low temperatures (less than 100°C) [68]. The system's main advantage is converting energy that would otherwise be wasted into reusable energy. Therefore, it significantly reduces thermal pollution and fossil fuel consumption [37].

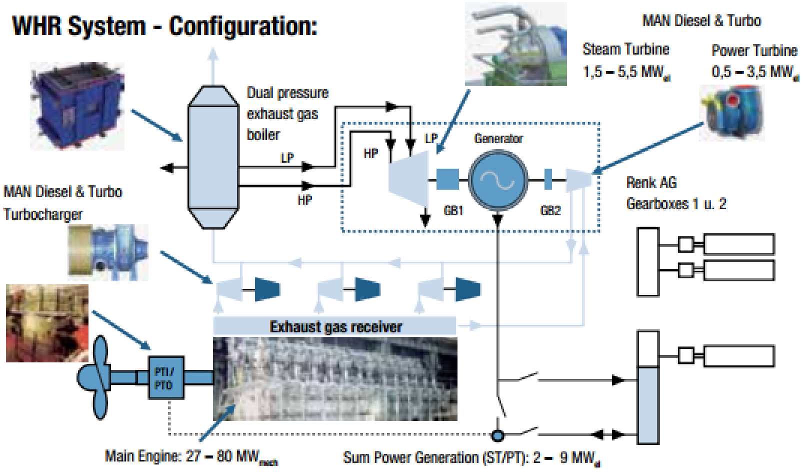


Fig. 9. WHR Working Principles [72]

Figure 9 is an example of the application of the WHRS principle to a MAN B&W low-speed diesel engine with the exhaust gas observed to be flowing pass the main turbocharger engine through the exhaust gas bypass. Therefore, this reduces the total incoming air and exhaust gas and subsequently increases the exhaust gas temperature. This further causes an increment in steam production in the boiler, which is later used in turbines to produce electrical energy. As part of the WHRS, a pressure decrease at the exhaust gas bypass can also be exploited to generate power using a secondary turbine [72].

4 ENVIRONMENTAL AND ECONOMIC BENEFITS OF ORC

The use of the ORC system needs to consider various aspects other than its work performance. Some of the elements that need to be considered in using this ORC system include environmental and economic issues. In this case, the impact of the ORC working fluid on the environment is very important. Some things that need to be considered are fluids with high Ozone Depletion Potential (ODP). In addition, organic fluorinated liquids (HFCs) should be avoided as they have a high Global Warming Potential (GWP) [6]. GWP is not only necessary for environmental concerns but also cycle efficiency. It can be seen that the working fluid with a GWP lower than 1500 can absorb more energy from the heat source to increase the cycle efficiency [13], [73].

Compared to water or steam cycles, ORC systems provide limited performance due to low to moderate operating temperature levels. However, the ORC system can convert low-grade heat input into energy at an acceptable conversion ratio [74]. In this case, the configuration of the ORC system can also play an important role in the resulting environmental impact [75]. As with the use of a recuperator which can reduce the average heat transfer temperature to the environment, it is lower and results in higher cycle thermal efficiency and reduces the resulting thermal pollution to the environment [13].

Organic fluids are expensive, so it is important to find a suitable trade-off between cost and performance. In general, the fluids used in the operation of the ORC system are fluids that have been widely used in other fields. It aims to obtain organic fluids at lower prices [10], [76]. Expanders have an important role in generating system performance. In this regard, investigations using volumetric expanders have been carried out to provide good performance at lower costs. Cost reductions for high-speed power generators with a working fluid that does not require excessively high turbine rotational speeds can increase the cost-effective capabilities of small-scale ORC units [10].

Under favorable evaporating pressure and condensing temperature conditions for a wide range of ORC applications, the specific cost per kilowatt-hour decreases as thermal efficiency increases. In addition, lower condensing temperatures or higher evaporating pressures can also lower the specific cost per kilowatt-hour. On the other hand, with a constant condensing temperature and vaporization pressure, a working fluid with a higher critical temperature can achieve a lower specific cost [51], [74], [77].

5 CONCLUSION

The ORC system is a promising technology for generating energy by utilizing heat sources at low temperatures. However, the cycle configuration, working fluid selection, and operational working conditions in the system all impact its performance. Because of its simplicity and reliability when linked with other production systems, Combined Heat and Power Production (CHP) based on a small-scale ORC system were one of the best and most promising alternatives. Meanwhile, while choosing an expander for the system, numerous criteria must be addressed, including power capacity, isentropic efficiency, cost, and complexity. However, Scroll-expanders were preferred because of their excellent efficiency, low noise and vibration levels, and great reliability. With the inclusion of OFOH and IHE in the RORC configuration, the configuration was also an important factor affecting system performance, with IHE enhancing performance and reducing the cycle’s energy loss. Furthermore, the ORC system’s properties make it ideal for most renewable energy sources, including geothermal, solar, and biomass, and it offers the industry increased energy efficiency by utilizing waste heat. The findings revealed that integrating the ORC system with various energy sources provides proper operation, improved efficiency, and multiple benefits such as increased power and reduced pollution by limiting wasted heat.

ACKNOWLEDGMENT

The Deputy for Research and Development Strengthening, Ministry of Research and Technology/National Research and Innovation Agency, has charged this research to the Budget Implementation List (DIPA) for the Fiscal Year 2021 with the title **“**Development of Passive Cooling Systems with Integration of Heat Sinks and Wind Concentrators to Improve Photovoltaic Performance-ground System” and Contract Number: 221.1/UN27.22/HK.07.00/2021.

REFERENCES

[1] Mahmoudi, A., Fazli, M., and M. Morad, R.(2018). A recent review of waste heat recovery by Organic Rankine Cycle. Applied Thermal Engineering, vol. 143, no. January, pp. 660–675, doi: 10.1016/j.applthermaleng.2018.07.136.

[2] Wijianto, Sarjito, Subroto, and Himawanto, D. A. (2018). The effect of variation number of holes on burner cap of TLUD gasification stove. IOP Conference Series: Materials Science and Engineering, vol. 403, no. 1, doi: 10.1088/1757-899X/403/1/012097.

[3] DeLovato, N., Sundarnath, K., Cvijovic, L., Kota, K., and Kuravi, S. (2019). A review of heat recovery applications for solar and geothermal power plants. Renewable and Sustainable Energy Reviews, vol. 114, no. August, p. 109329, doi: 10.1016/j.rser.2019.109329.

[4] Dincer, I. (2000). Renewable energy and sustainable development: A crucial review. Renewable and Sustainable Energy Reviews, vol. 4, no. 2, pp. 157–175, doi: 10.1016/S1364-0321(99)00011-8.

[5] Chan, C. W., Ling-Chin ,J., and Roskilly ,A. P. (2013). A review of chemical heat pumps, thermodynamic cycles and thermal energy storage technologies for low grade heat utilization. Applied Thermal Engineering, vol. 50, no. 1, pp. 1257–1273, doi: 10.1016/j.applthermaleng.2012.06.041.

[6] Caceres, I. E., Agromayor, R., and Nord, L. O. (2011). Thermodynamic Optimization of an Organic Rankine Cycle for Power Generation from a Low Temperature Geothermal Heat Source. Proceedings of the 58th SIMS September 25th - 27th, Reykjavik, Iceland, pp. 251–262, doi: 10.3384/ecp17138251.

[7] Cengel, Y. A. and Boles, M. A.. (2015). Thermodynamics An Engineering Approach, 8th ed. New York: McGraw-Hill Education.

[8] Blanquart, F. (2017). Perspectives for Power Generation from Industrial Waste Heat Recovery. KTH School of Industrial Engineering and Management.

[9] Zhang, X., He, M., and Zhang, Y. (2012). A review of research on the Kalina cycle. Renewable and Sustainable Energy Reviews, vol. 16, no. 7, pp. 5309–5318, doi: 10.1016/j.rser.2012.05.040.

[10] Tocci, L., Pal, T., Pesmazoglou, I., and Franchetti, B. (2017). Small Scale Organic Rankine Cycle (ORC): A Techno-Economic Review. Energies, MDPI, pp. 1–26, doi: 10.3390/en10040413.

[11] Shi, L., Shu, G., Tian, H., and Deng, S. (2018). A review of modified Organic Rankine cycles (ORCs) for internal combustion engine waste heat recovery (ICE-WHR). Renewable and Sustainable Energy Reviews, vol. 92, no. November 2017, pp. 95–110, doi: 10.1016/j.rser.2018.04.023.

[12] Tartière, T. and Astolfi, M. (2017). A World Overview of the Organic Rankine Cycle Market The Overview the Organic Rankine Assessing the feasibility of the heat. Energy Procedia, vol. 129, pp. 2–9, doi: 10.1016/j.egypro.2017.09.159.

[13] Rahbar, K., Mahmoud, S., Al-Dadah, R. K., Moazami, N., and Mirhadizadeh, S. A. (2017). Review of organic Rankine cycle for small-scale applications. Energy Conversion and Management, vol. 134, pp. 135–155, doi: 10.1016/j.enconman.2016.12.023.

[14] Lecompte, S., Huisseune, H., Van Den Broek, M., Vanslambrouck, B., and De Paepe, M. (2015). Review of organic Rankine cycle (ORC) architectures for waste heat recovery. Renewable and Sustainable Energy Reviews, vol. 47, pp. 448–461, doi: 10.1016/j.rser.2015.03.089.

[15] Pereira, J. S., Ribeiro, J. B., Mendes, R., Vaz, G. C., and André, J. C. (2018). ORC based micro-cogeneration systems for residential application - A state of the art review and current challenges. Renewable and Sustainable Energy Reviews, vol. 92, no. April, pp. 728–743, doi: 10.1016/j.rser.2018.04.039.

[16] Hijriawan, M., et al.(2019). Organic Rankine Cycle (ORC) in geothermal power plants. Journal of Physics: Conference Series, vol. 1402, no. 4, doi: 10.1088/1742-6596/1402/4/044064.

[17] Clemente, S., Micheli, D., Reini, M., and Taccani, R. (2012). Energy efficiency analysis of Organic Rankine Cycles with scroll expanders for cogenerative applications. Applied Energy, vol. 97, pp. 792–801, doi: 10.1016/j.apenergy.2012.01.029.

[18] Drozdz, M. (2003). An optimization model of geothermal-energy conversion. Applied Energy, vol. 74, no. 1–2, pp. 75–84, doi: 10.1016/s0306-2619(02)00133-2.

[19] Macchi, E. (2017). Theoretical basis of the Organic Rankine Cycle. Elsevier Ltd., doi: 10.1016/B978-0-08-100510-1.00001-6.

[20] White, M. T., Oyewunmi, O. A., Chatzopoulou, M. A., Pantaleo, A. M., Haslam, A. J., and Markides, C. N. (2018) Computer-aided working- fluid design , thermodynamic optimization and thermoeconomic assessment of ORC systems for waste-heat recovery. Energy, vol. 161, pp. 1181–1198, doi: 10.1016/j.energy.2018.07.098.

[21] Lukawski, M. (2009). Design and Optimization of Standardized Organic Rankine Cycle Power Plant for European Conditions. Akuyreyri: RES: The School for Renewable Energy Science.

[22] Xi, H., Li, M., Zhang, H., and He, Y. (2019) Experimental studies of organic Rankine cycle systems using scroll expanders with different suction volumes. Journal of Cleaner Production, vol. 218, pp. 241–249, doi: 10.1016/j.jclepro.2019.01.302.

[23] Nemati, A., Nami, H., Ranjbar, F., and Yari, M. (2016). A comparative thermodynamic analysis of ORC and Kalina cycles for waste heat recovery : A case study for CGAM cogeneration system," Case Stud. Therm. Eng., vol. 9, no. September pp. 1–13, 2017, doi: 10.1016/j.csite.2016.11.003.

[24] Johnson, I., Choate, W. T., and Davidson, A. (2008). Waste Heat Recovery: Technology and Opportunities in U.S. Industry. United State.: BCS Inc., Laurel, MD. doi: 10.2172/1218716.

[25] Spadacini, C., Xodo, L. G., and Quaia, M., (2017) Geothermal energy exploitation with Organic Rankine Cycle technologies. in Organic Rankine Cycle (ORC) Power Systems, Italy: Elsevier Ltd, pp. 473–525. doi: 10.1016/B978-0-08-100510-1.00014-4.

[26] Astolfi, M., Romano, M. C., Bombarda, P., and Macchi, E. (2014.) Binary ORC (organic Rankine cycles) power plants for the exploitation of medium e low temperature geothermal sources e Part A : Thermodynamic optimization. Energy, vol. 66, pp. 423–434, doi: 10.1016/j.energy.2013.11.056.

[27] Astolfi, M., M. Romano, C., Bombarda, P., and Macchi, E. (2014). Binary ORC (Organic Rankine Cycles) power plants for the exploitation of medium e low temperature geothermal sources e Part B : Techno-economic optimization. Energy, vol. 66, pp. 435–446, doi: 10.1016/j.energy.2013.11.057.

[28] Bao, J. and Zhao, L. (2013). A review of working fluid and expander selections for organic Rankine cycle. Renewable and Sustainable Energy Reviews, vol. 24, pp. 325–342, doi: 10.1016/j.rser.2013.03.040.

[29] Zhou, F., Joshi, S. N., Rhote-Vaney, R., and Dede, E. M. (2017). A review and future application of Rankine Cycle to passenger vehicles for waste heat recovery. Renewable and Sustainable Energy Reviews, vol. 75, no. January 2016, pp. 1008–1021, doi: 10.1016/j.rser.2016.11.080.

[30] Macchi, E. and Perdichizzi, A. (1981). Efficiency Prediction for Axial-Flow Turbines Operating With Nonconventional Fluids. American Society of Mechanical Engineers, vol. 103, no. 81-GT-15, pp. 5–11, 1981.

[31] Invernizzi, C., Iora, P., and Silva, P. (2007). Bottoming micro-Rankine cycles for micro-gas turbines., vol. 27, no. 1, pp. 100–110, doi: 10.1016/j.applthermaleng.2006.05.003.

[32] Stijepovic, M. Z., Linke, P., Papadopoulos, A. I., and Grujic, A. S. (2012). On the role of working fluid properties in Organic Rankine Cycle performance. Applied Thermal Engineering, vol. 36, no. 1, pp. 406–413, doi: 10.1016/j.applthermaleng.2011.10.057.

[33] Desideri, A., Gusev, S., Van Den Broek, M., and Lemort, V. (2016). Experimental comparison of organic fluids for low temperature ORC (organic Rankine cycle) systems for waste heat recovery applications. Energy, vol. 97, pp. 460–469, doi: 10.1016/j.energy.2015.12.012.

[34] Fu, B. R., Lee, Y. R., and Hsieh, J. C. (2016). Experimental investigation of a 250-kW turbine organic Rankine cycle system for low-grade waste heat recovery. International Journal of Green Energy, vol. 13, no. 14, pp. 1442–1450, doi: 10.1080/15435075.2016.1212353.

[35] Qiu, G., Liu, H., and Riffat, S. (2011). Expanders for micro-CHP systems with organic Rankine cycle. Applied Thermal Engineering, vol. 31, no. 16, pp. 3301–3307, doi: 10.1016/j.applthermaleng.2011.06.008.

[36] Alshammari, F., Usman, M., and Pesyridis, A. (2018). Expanders for Organic Rankine Cycle Technology. IntehcOpen, no. November, pp. 41–59, doi: 10.5772/intechopen.78720.

[37] Dutta, S. P. and Borah, R. C. (2018). Design of a Solar Organic Rankine Cycle Prototype for 1 kW Power Output. International Journal of Engineering Trends and Technology (IJETT), vol. 62, no. 1, pp. 23–33.

[38] Imran, M., Usman, M., Park, B., and Lee, D. (2016). Volumetric expanders for low grade heat and waste heat recovery applications. Renewable and Sustainable Energy Reviews, vol. 57, pp. 1090–1109, doi: 10.1016/j.rser.2015.12.139.

[39] Lemort, S., Guillaume, V., Legros, L., Declaye, A., Quiilin, S. (2013). A Comparison of Piston, Screw and Scroll Expanders for Small-Scale Rankine Cycle Systems. The 3rd International Conference on Microgeneration and Related Technologies.

[40] Weiß, A. P. (2015). Volumetric Expander vs. Turbine - Which is the better choice for small ORCC Plants?. in 3rd International Seminar on ORC Power Systems, vol. 1, no. October 2015, pp. 1–36. doi: 10.1017/CBO9781107415324.004.

[41] Badr, O., Probert, D., and O’callaghan, P. W. (1986). Multi-Vane Expanders as Prime Movers in Low-Grade Energy Engines. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, vol. 200, no. 2, pp. 117–125, doi: 10.1243/PIME_PROC_1986_200_017_02.

[42] Kim, H. J., Ahn, J. M., Park, I., and Rha, P. C. (2007). Scroll expander for power generation from low-grade steam source. Journal of Power and Energy, vol. 221, p. 705, doi: 10.1243/09576509JPE392.

[43] Wang, D., Ling, X., Peng, H., Liu, L., and Tao, L. (2013). Efficiency and optimal performance evaluation of organic Rankine cycle for low grade waste heat power generation. Energy, vol. 50, pp. 343–352, doi: 10.1016/j.energy.2012.11.010.

[44] Zhou, N., Wang, X., Chen, Z., and Wang, Z., (2013). Experimental study on Organic Rankine Cycle for waste heat recovery from low-temperature flue gas. Energy, vol. 55, pp. 216–225, doi: 10.1016/j.energy.2013.03.047.

[45] Song, P., Wei, M., Shi, L., Danish, S. N., and Ma, C. (2015). A review of scroll expanders for organic rankine cycle systems. Applied Thermal Engineering, vol. 75, pp. 54–64, doi: 10.1016/j.applthermaleng.2014.05.094.

[46] Emhardt, S., Tian, G., and Chew, J. (2018). A review of scroll expander geometries and their performance. Applied Thermal Engineering, vol. 141, no. June, pp. 1020–1034, doi: 10.1016/j.applthermaleng.2018.06.045.

[47] Landelle, A., Tauveron, N., Revellin, R., Haberschill, P., and Colasson, S. (2017). Experimental Investigation of a Transcritical Organic Rankine Cycle with Scroll Expander for Low - Temperature Waste Heat Recovery. Energy Procedia, vol. 129, pp. 810–817, doi: 10.1016/j.egypro.2017.09.142.

[48] Eryanto, G. et al.(2020). Analysis of organic Rankine cycle based on thermal and exergy efficiency. Journal of Physics: Conference Series, vol. 1595, no. 1. doi: 10.1088/1742-6596/1595/1/012018.

[49] Tchanche, B. F., Pétrissans, M., and Papadakis, G. (2014). Heat resources and organic Rankine cycle machines. Renewable and Sustainable Energy Reviews, vol. 39, pp. 1185–1199, doi: 10.1016/j.rser.2014.07.139.

[50] Iglesias, S.G., Ferreiro, R.G., Carbia, J.C., and Iglesias, D.G.(2018). A review of thermodynamic cycles used in low temperature recovery systems over the last two years. Renewable and Sustainable Energy Reviews, vol. 81, no. August 2017, pp. 760–767, doi: 10.1016/j.rser.2017.08.049.

[51] Li, G. (2016). Organic Rankine cycle performance evaluation and thermoeconomic assessment with various applications part II: Economic assessment aspect. Renewable and Sustainable Energy Reviews, vol. 64, pp. 490–505, doi: 10.1016/j.rser.2016.06.036.

[52] Hijriawan, M., Pambudi, N. A., Wijayahnto, D.S.,Biddinika, M. K., and Saw, B. L. H.(2021). Experimental analysis of R134a working fluid on Organic Rankine Cycle (ORC) systems with scroll-expander. Engineering Science and Technology, an International Journal, no. xxxx, doi: 10.1016/j.jestch.2021.06.016.

[53] Zhai, H., An, Q., Shi, L., Lemort, V., and Quoilin, S. (2016). Categorization and analysis of heat sources for organic Rankine cycle systems. Renewable and Sustainable Energy Reviews, vol. 64, pp. 790–805, doi: 10.1016/j.rser.2016.06.076.

[54] Vélez, F., Segovia, J. J., Martín, M. C., Antolín, G., Chejne, F., and Quijano, A. (2012). A technical, economical and market review of organic Rankine cycles for the conversion of low-grade heat for power generation. Renewable and Sustainable Energy Reviews, vol. 16, no. 6, pp. 4175–4189, doi: 10.1016/j.rser.2012.03.022.

[55] Modi, A., Bühler, F., Andreasen, J. G., and ,Haglind F. (2017). A review of solar energy based heat and power generation systems. Renewable and Sustainable Energy Reviews, vol. 67, pp. 1047–1064, doi: 10.1016/j.rser.2016.09.075.

[56] Aboelwafa, O., Fateen, S. E. K., Soliman, A., and Ismail, I. M. (2018). A review on solar Rankine cycles: Working fluids, applications, and cycle modifications. Renewable and Sustainable Energy Reviews, vol. 82, no. May 2017, pp. 868–885, doi: 10.1016/j.rser.2017.09.097.

[57] Delgado-Torres, A. M. and García-Rodríguez, L. (2012). Design recommendations for solar organic Rankine cycle (ORC)-powered reverse osmosis (RO) desalination. Renewable and Sustainable Energy Reviews, vol. 16, no. 1, pp. 44–53, doi: 10.1016/j.rser.2011.07.135.

[58] Eyidogan, M., Canka, F. K., Kaya, D., Coban, V., and Cagman, S. (2016). Investigation of Organic Rankine Cycle (ORC) technologies in Turkey from the technical and economic point of view. Renewable and Sustainable Energy Reviews, vol. 58, pp. 885–895, doi: 10.1016/j.rser.2015.12.158.

[59] Obernberger, I., Thonhofer, P., and Reisenhofer, E. (2002). Description and evaluation of the new 1,000 kWel Organic Rankine Cycle process integrated in the biomass CHP plant in Lienz, Austria. Euroheat & Power, vol. 10, pp. 1–17, [Online]. Available: http://www.turboden.eu/en/public/downloads/report_on_lienz_plant.pdf

[60] Tchanche, B. F., Lambrinos, G., Frangoudakis, A., and Papadakis, G. (2011). Low-grade heat conversion into power using organic Rankine cycles - A review of various applications. Renewable and Sustainable Energy Reviews, vol. 15, no. 8, pp. 3963–3979, doi: 10.1016/j.rser.2011.07.024.

[61] Pambudi, N. A. (2018). Geothermal power generation in Indonesia, a country within the ring of fire: Current status, future development and policy. Renew. Sustain. Energy Rev., vol. 81, no. July 2017, pp. 2893–2901, doi: 10.1016/j.rser.2017.06.096.

[62] Pambudi, N. A., Itoi, R., Jalilinasrabady, S., and ,Jaelani K. (2014). Exergy analysis and optimization of Dieng single-flash geothermal power plant. Energy Conversion and Management, vol. 78, pp. 405–411, doi: 10.1016/j.enconman.2013.10.073.

[63] Rudiyanto, B., Aries, M., Pambudi, N. A., Widjonarko, W., and Hijriawan, M. (2021). An update of second law analysis and optimization of a single-flash geothermal power plant in Dieng, Indonesia. Geothermics, vol. 96, no. March, p. 102212, doi: 10.1016/j.geothermics.2021.102212.

[64] Pasek, A. D., Soelaiman, T. A. F., and Gunawan, C. Thermodynamics study of flash–binary cycle in geothermal power plant. Renewable and Sustainable Energy Reviews, vol. 15, no. 9, pp. 5218–5223, 2011, doi: 10.1016/j.rser.2011.05.019.

[65] Li, K., Liu, C., Jiang, S., and Chen, Y. (2020). Review on hybrid geothermal and solar power systems. Journal of Cleaner Production, vol. 250, doi: 10.1016/j.jclepro.2019.119481.

[66] Reddy, C. C. S., Naidu, S. V, and Rangaiah, G. P. (2013). Waste Heat Recovery Methods and Technologies. Chemical Engineering.

[67] Changshun, Z., Gang, X. U., and Tong, L. I. U. (2013). Thermodynamic analysis of the integrated waste heat recovery system for power plant. Advanced Material Research, vol. 817, pp. 698–701, doi: 10.4028/www.scientific.net/AMR.816-817.698.

[68] Jouhara, H., Khordehgah, N., Almahmoud, S., Delpech, B., Chauhan, A., and Tassou, S. A. (2018). Waste heat recovery technologies and applications. Thermal Science and Engineering Progress, vol. 6, no. January, pp. 268–289, doi: 10.1016/j.tsep.2018.04.017.

[69] Saghafifar, M., Omar, A., Mohammadi, K., Alashkar, A., and Gadalla, M. (2019). A review of unconventional bottoming cycles for waste heat recovery: Part I – Analysis, design, and optimization. Energy Conversion and Management, vol. 198, no. June 2018, p. 110905, doi: 10.1016/j.enconman.2018.10.047.

[70] Rielly, K. O. and Jeswiet, J. (2015). Improving Industrial Energy Efficiency through the Implementation of Waste Heat Recovery Systems. Transactions of the Canadian Society for Mechanical Engineering, vol. 39, no. 1, pp. 125–136.

[71] Costiuc, I., Costiuc, L., and Radu, S. (2015). Waste Heat Recovery using Dirrect Thermodynamic cycle. Bulletin of The Transilvania University of Brasov, Series I: Engineering Sciences, vol. 8, no. 2, pp. 1–6.

[72] MAN.(2014). Waste Heat Recovery System (WHRS) for Reduction of Fuel Consumption, Emissions and EEDI.MAN Diesel Turbo, pp. 1–6.

[73] Zhai, H., Shi, L., and An, Q. (2014). Influence of working fluid properties on system performance and screen evaluation indicators for geothermal ORC (organic Rankine cycle) system. Energy, vol. 74, no. C, pp. 2–11, doi: 10.1016/j.energy.2013.12.030.

[74] Feng, Y. Q., et al.(2020). Parametric analysis and thermo-economical optimization of a Supercritical-Subcritical organic Rankine cycle for waste heat utilization. Energy Conversion and Management, vol. 212, no. March, p. 112773, doi: 10.1016/j.enconman.2020.112773.

[75] [Ochoa, G. V., Chamorro, M. V., and Silvera, O. C. (2022). Thermo-economic and sustainability assessment of two solar organic Rankine cycles in the United States. Sustainable Energy Technologies and Assessments, vol. 50, no. August 2021, p. 101758, doi: 10.1016/j.seta.2021.101758.

[76] Qiu, G. (2012). Selection of working fluids for micro-CHP systems with ORC," Renewable Energy, vol. 48, pp. 565–570, doi: 10.1016/j.renene.2012.06.006.

[77] Kumar, A. and Rakshit, D. (2021). A critical review on waste heat recovery utilization with special focus on Organic Rankine Cycle applications. Cleaner Engineering and Technology, vol. 5, p. 100292, doi: 10.1016/j.clet.2021.100292.

Paper submitted: 07.02.2022.

Paper accepted: 24.04.2022.