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Review

A comprehensive review of organic Rankine cycles

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Abstract: Climate change is one of the main issues that humanity is currently facing due to carbon dioxide emissions caused by the use of fossil fuels. Organic Rankine cycles may play an important role in reducing these emissions since they can be operated by using industrial waste heat of renewable energies. The present study presents a comprehensive bibliographic review of organic Rankine cycles. The study not only actualizes previous reviews that mainly focused on basic cycles operating on subcritical or supercritical conditions but also includes the analysis of novel cycles such as two-stage and hybrid cycles and the used fluids. Recuperative and regenerative cycles are more efficient than reheated and basic single-stage cycles. The use of two-stage cycles makes it possible to achieve higher thermal efficiencies and net power outputs of up to 20% and 44%, respectively, compared with those obtained with single-stage cycles. Theoretical studies show that hybrid systems, including Brayton and organic Rankine cycles, are the most efficient; however, they require very high temperatures to operate. Most organic Rankine cycle plants produce net power outputs from 1 kW up to several tens of kW, mainly using microturbines and plate heat exchangers.

Keywords: Microturbines, organic Rankine cycles, polygeneration, power production, waste heat recovery.

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1. Introduction

Climate change is a huge problem humanity faces due to carbon dioxide (CO_2) emissions to the atmosphere. Most emissions are due to the consumption of fossil fuels. According to the International Energy Agency (IEA), in 2021, 36.3 gigatons of CO_2 were released into the atmosphere [1]. On the other hand, according to the report "Waste Heat Recovery: Technology and Opportunities in U.S. Industry" [2], just in the United States, the amount of unrecovered waste heat at temperatures lower than 150°C was 75 x 10^9 kW per year. According to the Oak Ridge Laboratory, the largest waste heat sources for most industries are exhaust gases produced by burners, furnaces, dryers, heaters, and heat exchangers using liquids at high temperatures [3]. To reduce the consumption of fossil fuels and diminish CO_2 emissions, many studies have been carried out on the study and development of organic Rankine cycles (ORC). These cycles are similar to Rankine cycles, but they utilize an organic fluid instead of steam and their capacities are considerably lower, typically varying from 20 kW to 200 kW. Besides, the operating temperatures generally do not exceed 150°C; hence, they are typically used to recover industrial waste heat or with renewable energies such as geothermal or solar.

In the last few years, some bibliographic reviews have been realized regarding ORCs. Park et al. [4] carried out a review focusing on experimental ORCs performance. The authors analyzed and reported the most relevant data on prototypes, systems developed, and trends. Tartière and Astolfi [5] analyzed the market evolution and its applications, mainly focusing on waste heat recovery. They also analyzed the future perspectives and market growth potential. Pethurajan et al. [6] carried out a bibliographic review on the selection of the turbine for ORCs, and its applications when used as topping o bottoming cycles. On the other hand, Ahmadi et al. [7] and Haghighi et al. [8] carried out bibliographic reviews of geothermal ORCs. Both papers focused on the analysis of a basic ORC, an ORC with a recuperator, and a regenerative ORC for electricity production. The paper published by Haghighi et al. [8] focused mainly on the modeling and optimization of ORC using a considerable number of different working fluids reporting values of energy and exergy efficiencies, while the paper published by Ahmadi et al. [7] additionally analyzed economic indexes such as the electricity production cost and the levelized cost of electricity, besides they compared the results with other conventional power generation systems. Moreover, Wieland et al. [9], also presented the recent advances and future perspectives for ORCs from the market perspective. Although these bibliographic reviews include different topics, they mainly focused on basic ORCs, including extra heat exchangers to recover heat, reducing the heat supply to the generator. The present bibliographic review not only updates the state of the art of basic ORCs operating on subcritical or supercritical conditions but also includes the analysis of novel ORC such as two-stage ORC, hybrid systems, and polygeneration systems composed of ORC and one or more different technologies to produce at least two different outputs. The analysis includes systems driven by geothermal energy, solar energy, and waste heat recovery produced from engines or industrial processes. The bibliographic review also includes an analysis of the different working fluids used in the different types of ORCs.

This document is structured as follows: the next section describes the basic ORC, its main modifications, and the primary substances utilized as working fluids. The third section presents the bibliographic review of single-stage systems, including their thermo-economic and life cycle analysis. The fourth section describes the cycle configurations of recuperative, regenerative, and reheated ORCs, the comparison among them, as well as the advantages they offer in terms of energy. This section also describes the supercritical cycles. The fifth section is related to novel designs of two-stage ORC, in which, at least two heat supplies are driving the system. The sixth section summarizes the hybrid cycles, these are cycles in which an ORC is integrated as a topping or bottoming cycle to increase the power production or energy/exergy efficiency. Next, a discussion section is presented where the most outstanding reviewed papers are summarized and compared to each other. Finally, the conclusions section as well as the future directions of the research on ORCs are addressed.

2. Description of Organic Rankine Cycles

A basic ORC is analogous to the steam Rankine cycle. It consists of four main components, an evaporator, an expander, a condenser, and a pump. The main difference between these two cycles is that ORCs use organic fluids instead of water as in the Rankine cycle. Another difference is that while the Rankine cycle is normally used to produce a great amount of power, the ORCs are generally used for small and medium capacities varying, in general, from just a few watts up to 200 kW, (although microturbines up to 500 kW can be found in the market). Because of the low capacity production, ORCs are normally operated using renewable energies such as solar or geothermal, or industrial waste heat.

Figure 1 shows a basic ORC. As can be seen, liquid in saturated conditions (1) is pumped increasing its pressure to the evaporator (2) where it is evaporated by supplying energy in the form of heat. Then, the working fluid leaving the evaporator (3) enters the expander reducing its pressure (4) and producing an amount of mechanical work and electricity by using a generator. The organic fluid leaving the expander passes through a condenser, where it is liquefied (1) repeating the cycle. This ORC is sometimes called single-pressure or single-stage ORC because it uses only one evaporator.

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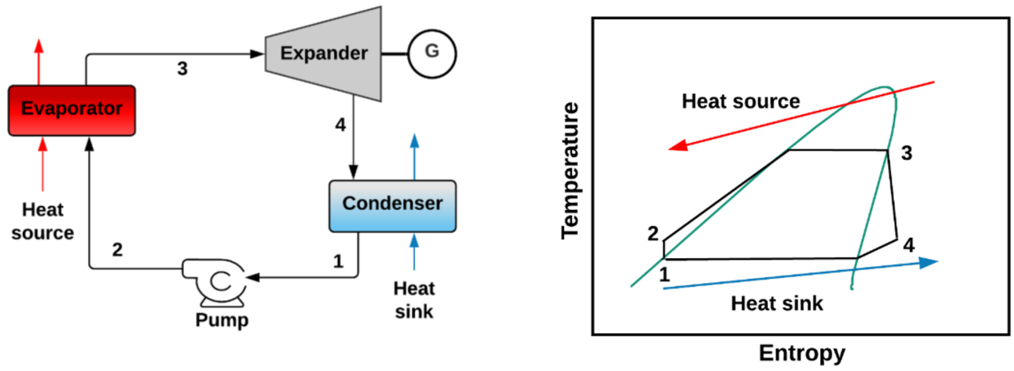
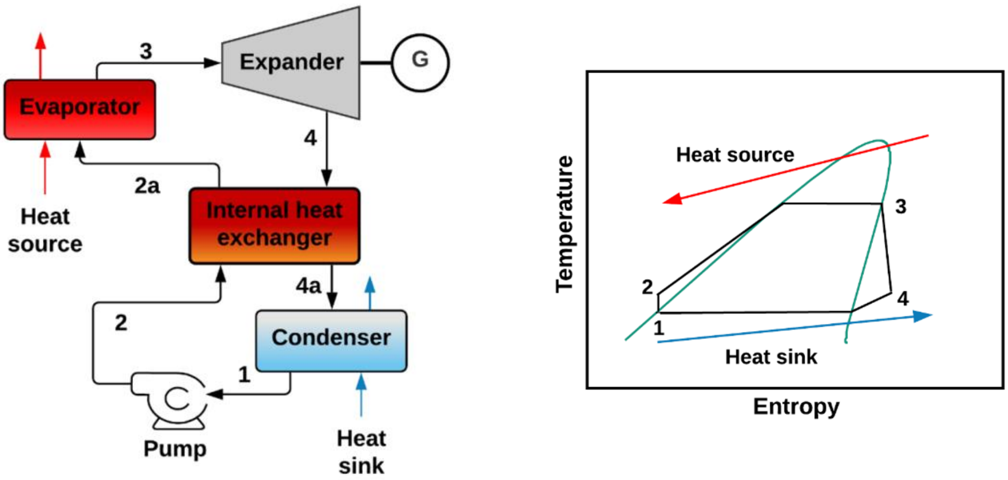


(a) (b)

Figure 1. Basic ORC (**a**) Schematic diagram; (**b**) T-s diagram.

To reduce the heat supplied to the evaporator and increase the efficiency of the system, heat exchangers can be added to the basic cycle. Some of the most well-known ORC configurations are the recuperative, the regenerative, and the reheated cycles.

Figures 2 and 3 show schematic and T-s diagrams of a recuperative and a regenerative ORC, respectively. Both cycles search to reduce the heat supplied to the evaporator increasing the system's efficiency. In the recuperative cycle an extra heat exchanger called a "recuperator" is used to preheat the working fluid going to the evaporator to reduce the heat load, while in the regenerative ORC, a working fluid's bled is made at an intermediate pressure on the expander which is mixed in an open heat exchanger, or sometimes called a regenerative tank, to preheat the working fluid coming from the condenser.



(a) (b)

Figure 2. Recuperative ORC (**a**) Schematic diagram; (**b**) T-s diagram.

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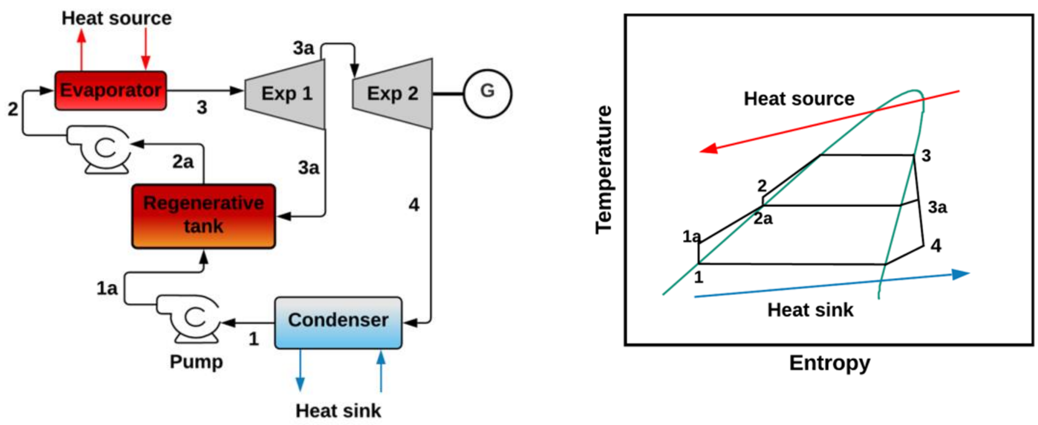
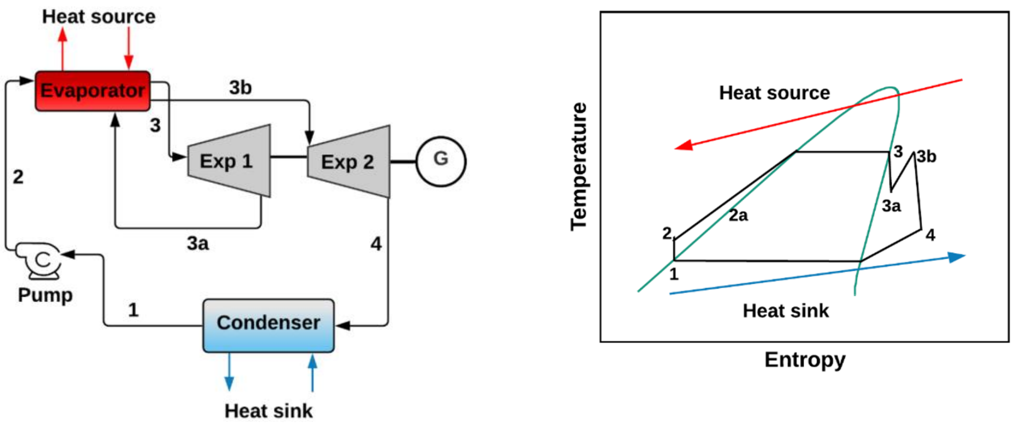


(a) (b)

Figure 3. Regenerative ORC (**a**) Schematic diagram; (**b**) T-s diagram.

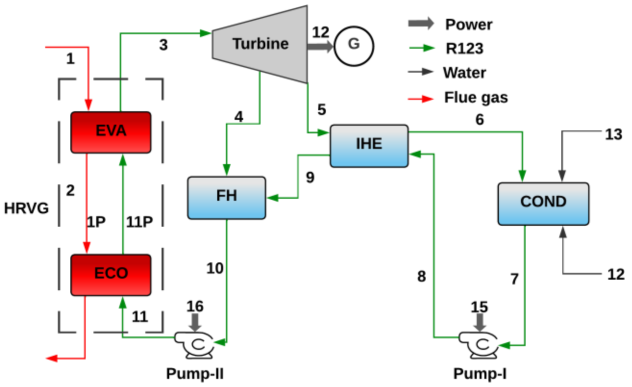
In a similar way to the regenerative cycle, in the reheated ORC, a bled of the working fluid is made at an intermediate pressure but instead of using an additional heat exchanger to preheat the liquid before entering the evaporator, the superheated working fluid is reheated in the evaporator before entering the second expander as can be seen in Fig. 4. In this case, the purpose of the modification is not to decrease the heat supplied to the evaporator but to increase the system efficiency by increasing the power production.



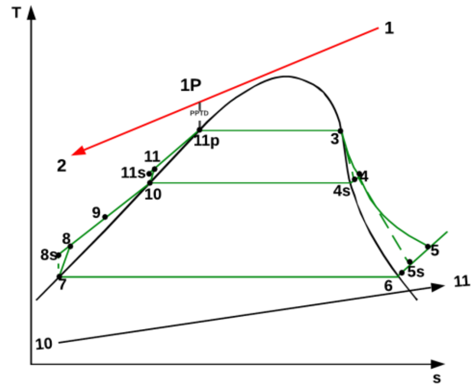
(a) (b)

Figure 4. Reheated ORC (**a**) Schematic diagram; (**b**) T-s diagram.

Another configuration of interest to be analyzed is the combination of a recuperative and a regenerative cycle, which offers the advantages of both cycles previously described, this configuration is shown in Fig. 5.



(a)



(b)

Figure 5. Recuperative-regenerative ORC (**a**) Schematic diagram; (**b**) T-s diagram.

2.1 Working fluids for ORC

Although most of the previous papers compared the performance of the basic ORC using different working fluids, there are some studies mainly focused on finding the best working fluids from the thermodynamic point of view. Zhang et al. [10] analyzed fifty-seven fluids. The analysis was made based on the working fluids' saturated vapor curves which were divided into wet, dry, and isentropic as shown in Fig. 6. According to the authors, the triangle formed by the critical point and the liquid and vapor points in saturated conditions at the turning point, significantly impact the system performance. The highest efficiencies were obtained using working fluids with turning points higher than 200°C and triangle areas lower than 6 kJ/kg. The R123 was the best fluid at temperatures lower than 130°C, achieving a value of 17.5%. At temperatures between 130°C and 230°C, the highest efficiencies were obtained with hexane, R113, and isobutane, reaching efficiencies of 22%, 21.5%, and 20%, respectively, and at temperatures around 330°C, the best working fluids were toluene and benzene with efficiencies of 29% and 28.5%, respectively.

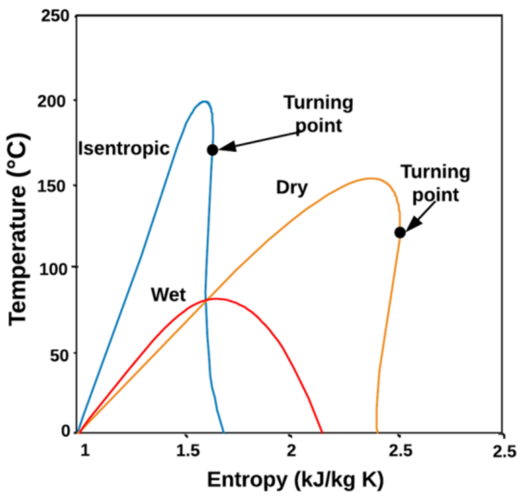


Figure 6. Saturated vapor curves for wet, dry, and isentropic working fluids.

Györke et al. [11] and Imre et al. [12] proposed a new method to determine the best working fluids for low-temperature applications. The method was based on the development of a correlation related to the molar isochoric specific heat capacity of saturated vapor states. They concluded that if the molar isochoric heat capacity of the saturated vapor phase of a fluid was smaller than 80 J/(mol·K) at a temperature 0.74 times the critical temperature, then the fluid was most likely a wet fluid, but if the heat capacity values were higher than this limit, the fluids were most likely dry or isentropic.

Györke et al. [13] proposed a new classification to determine the best fluids considering different thermodynamic characteristics such as the possibility to achieve total evaporation by adiabatic expansion or to end in a two-phase state. With these considerations, the authors proposed eight novel fluid categories instead of just three as proposed by Zhang et al. [10]. In the search for the best working fluid, Wang et al. [14] proposed a method to select a zeotropic mixture for ORC with varying heat source temperatures, i.e., when the ORC is used as a bottoming cycle in a hybrid configuration. The authors found that, for temperatures around 225°C, the zeotropic mixtures benzene/m-xylene and cyclopentane/toluene obtained the highest performance. Regarding the proposed method, it was found it was more effective when the heat source temperature varied together with the ambient temperature because the net power and exergy efficiency improved up to 22% in winter, but that enhancement was just 6.8% in summer. Blondel et al. [15] also studied the use of zeotropic mixtures (Novec649 and HFE7000) as working fluids in ORC. The authors proposed some two-phase semi-empirical heat transfer correlations (in evaporation and condensation) and evaluated the influence of the heat sources (at high and low temperatures) on the cycle performance. The authors found that zeotropic mixtures of HFE type with low glide values, do not favor a better performance than the pure fluids.

Yang et al. [16] presented a study of the relationship between critical and boiling temperatures for more than 250 working fluids. The results showed that at temperatures between 150°C and 200°C, the strong relationship between the maximum net power and the critical temperature was not affected by the reduced boiling temperature. However, at temperatures between 250°C and 300°C, working fluids with reduced boiling temperatures higher than 0.7 exhibited maximum net power even at optimum critical temperatures. Li et al. [17] proposed a new model to determine the best fluid based on a parameter defined as equivalent hot side temperature. This parameter was obtained as the ratio of the isentropic fluid expansion to the entropy change of the whole cycle. For more than half of the working fluids, the relative error was within ±0.6%. Dai et al. [18] performed a study using diverse hydrocarbons operating at four different heat sources. The propyne, cis-butene, iso-hexane, and cyclohexane achieved the highest energy efficiencies with values of 12.12%, 16.58%, 19.16%, and 21.43% driven by geothermal energy, solar energy, engine waste heat energy, and high-temperature solar energy, respectively. Luo et al. [19] developed a methodology using neural networks to improve the correlation of working fluid properties and evaluate the performance of basic ORC. It was found that with the proposed methodology, the average deviation of the ORCs efficiency was between 26% and 81% lower than by using other methods.

Fan et al. [20] proposed a method to directly correlate some working fluid's properties with the performance of an ORC. This method, based on the fluid's thermal properties, represents a more adequate criterion for the selection of the appropriate working fluid in an ORC and represents a better alternative to the limited selection criterion only based on the critical temperature. Moreover, the proposed method allows to identify the applicable range of different types of working fluids as a function of the heat source temperature. On the other hand, Zhang and Li [21] studied the super dry working fluids used in regenerative ORC for medium and low heat source temperatures. According to the authors, distinguishing between a "super dry fluid" and a "dry fluid" can be done through the area of a curved triangle in the zone of superheated vapor in a temperature-entropy diagram: a super dry fluid has an area greater than 25 kJ/kg, while a dry fluid has an area between 5 kJ/kg and 25 kJ/kg. The authors determined each fluid's optimal extraction pressure and temperature according to the power output and thermal efficiency.

Some researchers have focused on the assessment of the environmental impact of the working fluids, such as the case of Bianchi et al. [22], who estimated the greenhouse effect of two pure fluids and four mixtures used to replace the HFCs in organic Rankine systems in the scale of kW. The method utilized considers direct and indirect emissions. The authors validated their model with experimental data and found that indirect emissions of hydrofluoroolefins may lead to higher CO_2 emissions regarding the use of R134a as the working fluid. Since parameters like emission factors, fluid leakage rate, and R134a concentration can affect significantly the environmental evaluation, the authors also analyzed and discussed them. A complete review of low global warming potential (GWP) working fluids in ORC applications is presented by Bahrami et al. [23]. Some methodologies and criteria for the working fluid selection, as well as alternative working fluids such as hydrocarbons, hydrofluorochemicals, and mixtures, are included there.

3. Single-Stage ORC

As previously mentioned, there are different configurations of single-stage ORC, and all of them have been analyzed from different points of view by diverse authors. Therefore, the present section has been divided accordingly to each of these configurations. Additionally, this section includes some studies regarding supercritical ORCs.

Nurhilal et al. [24] realized the modeling of a geothermal organic Rankine cycle (G-ORC) using R601. At a temperature of 165°C, the energy efficiency was 14.61%. Herath et al. [25] realized a similar study but using other fluids. The highest efficiency was 18.5% at 194 °C using benzene. This efficiency was higher than that reported by Nurhilal et al. [24] but required higher temperatures. Yadav and Sircar [26] modeled a similar system, but using R600, R600a, R134a, and R245fa. The highest efficiency of 8% was achieved using R134a. Wang et al. [27] modeled an ORC using the hydrofluoroethers at temperatures varying from 67°C to 112°C. The highest energy and exergy efficiencies were 12.2% and 52%, respectively using HFE700.

Sakhrieha et al. [28] modeled an ORC driven with solar and geothermal energies at 60°C in Jordan. From sixteen working fluids, it was found that the R600, R32, R290, and R410a were the best. Acar and Arslan [29] performed a similar analysis using R600a but included a storage tank. The energy and exergy efficiencies decreased with the integration of solar energy. The maximum energy and exergy efficiencies were 14.56% and 71%, respectively. Bademlioglu [30] carried out the exergy analysis of a G-ORC using R123, R152a, R245fa, and R600a. The best working fluid was R123, achieving a maximum exergy efficiency of 57%. Yamankaradeniz et al. [31] analyzed the variation of the evaporator effectiveness in a G-ORC and found that the energy and exergy efficiencies increase up to 6.87% and 6.21%, with the increment of the effectiveness.

Calise et al. [32] investigated the impact of the heat transfer correlations for boiling processes in determining the evaporator area used in an ORC. They found that the net power output (per square meter of heat exchanger) considerably varies depending on the correlation used to determine the heat transfer coefficient in the evaporator. Read et al. [33] modeled the same system but compared the results using a microturbine and a twin-screw expander using correlations derived from operational data of a real ORC. The results showed that the ORC performs similarly using either type of expander. Invernizzi et al. [34] studied a modified ORC including a flashing tank and a mixing chamber, as shown in Fig. 7. It was found that the use of water/organic fluid mixtures was convenient in terms of system performance and turbine design.

On the other hand, Sun et al. [35] proposed to improve the performance of a basic ORC through the implementation of a vacuum condensation process. The results showed that, for some working fluids, the exergy efficiency of the cycle was increased by almost 8% just by reducing the condensation pressure from 0.1 to 0.001 MPa; however, some other working fluids had different optimal condensation pressures and the cycle efficiencies turned to decrease when the pressures approached 0.001 MPa.

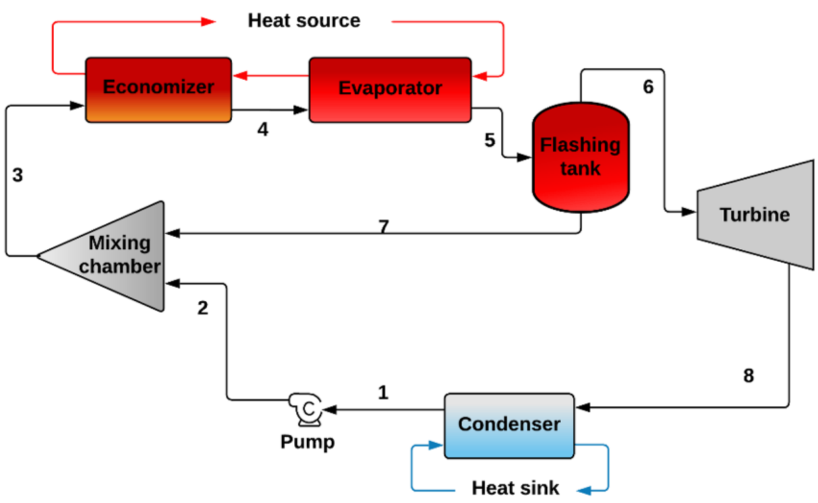


Figure 7. Thermodynamic ORC using a flashing tank and a mixing chamber, proposed by Invernizzi et al. [34].

Other studies have been realized searching the system's optimization. In this regard, Serafino et al. [36] performed a robust optimization of G-ORC. With the optimization, the power output was increased by 1.5%, and the required heat exchanger area was reduced by 34%. Huster et al. [37] used artificial intelligence and found that the net power could be increased by 4% after optimization. Khosravi et al. [38] also used artificial intelligence to model a basic ORC using different working fluids. The highest efficiencies close to 16% were achieved using R161. Some studies have focused on the implementation of ORC to improve the performance of other systems, like internal combustion engines. Such is the case of Neto et al. [39], who proposed to use a single-stage ORC coupled to a stationary diesel engine to take advantage of the exhaust gases of the latter to produce power. The study focused on parametric and economic analyses for determining the optimal operating point from these perspectives. It was found the proposed configuration increases the power produced and the thermal efficiency while reducing fuel consumption, and thus, the system's contribution to pollution. Another study on the integration of an ORC and an internal combustion engine was carried out by Ping et al. [40], who studied the dynamic correlation between the operating parameters and the performance of the coupled system under driving conditions. The authors proposed a model to assess and optimize the performance of the coupled system under different complex driving cycles. Some parameters as the speed of the expander and pump in the ORC, as well as the exhaust valve timing and the change of the cooling water temperature in the internal combustion engine, directly affect the system's performance parameters. According to the results, another key parameter affecting the system performance under dynamic conditions is vehicle speed.

3.1. Thermoeconomic and life cycle analysis of ORC

Other studies have focused on the thermoeconomic analysis of ORCs. Khosravi et al. [38] reported the Levelized Cost of Energy (LCOE) for an ORC operating with nine different working fluids, finding that a minimum LCOE of 0.09928 USD/kWh was obtained by using R1234yF. Dai et al. [18] performed a similar study but using hydrocarbons. The lowest energy costs were determined for propyne, pentane, cyclohexane, and cyclohexane, which were 1.46 USD/kWh, 1.28 USD/kWh, 1.05 USD/kWh, and 0.95 USD/kWh, respectively. Sun et al. [41] carried out a thermo-economic evaluation varying the evaporator pinch point temperature difference. It was found that a lower pinch point temperature difference causes a higher turbine output but increases the heat transfer area required by the heat exchangers as well as the investment costs. At 150°C the payback period (PBP) of just the ORC was about 4 years, while at 100°C, the PBP was 8.9 years. If a drilling cost of 500 USD/m was added to the total system costs, the PBP varied from 5.26 to 12.86 years. Mustapić et al. [42] analyzed a Geothermal ORC (G-ORC) in the city of Karlovac, Croatia using diverse fluids. The authors reported a net power index, which is the inverse of the electricity production cost. The lowest values were 0.3361W/€ (0.397 W/USD) and 0.3375 W/€ (0.398 W/USD) using n-pentane and isopentane, respectively. Kyriakarakos et al. [43] realized a similar study but on the Greek island of Milo and compared their results with other renewable technologies. It was found that the Geothermal ORC had better performance than configurations using solar photovoltaic and wind turbines.

Usman et al. [44] performed a study of a G-ORC cooled by air and by using a cooling tower operating with R245fa and R1233zde. It was found that the R1233zde had the potential to replace the R245fa at temperatures higher than 145°C. The ORCs using cooling towers were a better alternative for dry and hot climates, while the systems cooled by air could be a better alternative for cold and humid weather. Oyewunmi and Markides [45] performed a thermoeconomic study operating with seven different zeotropic mixtures and compared the results to those achieved using pure working fluids. Although by using the zeotropic mixtures higher efficiencies were reached, the system operating costs with pure n-pentane and R245fa were 14% lower. Yaïci et al. [46] analyzed a solar ORC operating with twelve zeotropic mixtures. The highest efficiencies were obtained using mixtures involving R245fa. The R245fa/propane mixture had the highest sustainability index with a minimum cost of electricity of 0.15 USD/kWh. Baral [47] modeled an ORC installed in Nepal, driven with geothermal and solar energies using R134a and R245fa. It was found that the LCOE was 0.17 USD/kWh with R134a and 0.14 USD/kWh with R245fa. Ergun et al. [48] carried out an exergoeconomic study of a G-ORC in Turkey. The lowest electricity production cost was 7.96 USD/GJ (0.0287 USD/kWh).

Oyekale et al. [49] performed an exergoeconomic assessment of a hybrid ORC cogeneration plant, using solar energy and biomass. The economic performance was assessed at a component level using the conventional specific exergy costing (SPECO) approach. The criteria for the exergoeconomic evaluation were: the exergy destruction cost rate, the exergoeconomic factor, and the relative cost difference. The system's exergy efficiency was 11%, while the electricity cost was between 10.5 c€/kW and 12.1 c€/kW, depending on the exergoeconomic approach adopted. Recently, Wang et al. [50] performed the multi-objective optimization of an ORC used in geothermal applications. For that purpose, four objective functions were selected: net power output, total product unit cost, greenhouse gas emissions, and ecological life cycle cost. The authors found that R134a showed very attractive thermodynamic and sustainable performances, while R600a had better performances from the economic and environmental aspects when the ORC operates driven by a heat source temperature at 393.15 K.

On the other hand, some studies of ORCs have focused on life cycle analysis. Zhang et al. [51] carried out a study using R134a. The energy yield ratio and the energy sustainability index, were 197.52 and 3.97, respectively. The results showed that the sustainability of the ORC system was less than power plants using wind, hydro, and geothermal energies but considerably higher than plants using fossil fuels. Li [52] performed an investigation of the environmental impact using diverse fluids. Working fluids with low GWP could reduce the emissions to the ambient between 50% and 84%, compared to fluids with high GWP. The analysis reported that R600 and R123 were the best working fluid at low heat source temperatures, while toluene was the best fluid at high temperatures. Yi et al. [53] reported that high condenser and evaporation temperatures and relatively high pinch point temperature differences are beneficial to minimize the environmental impacts.

4. Recuperative, Regenerative, Reheated, and Supercritical ORCs.

Regarding recuperative ORCs, Algieri and Šebo [54] analyzed a system using isobutane, isopentane, and R245ca. The maximum thermal efficiency was 12% for the basic cycle and 14% for the recuperative using R245ca. The thermal efficiencies were always higher with the recuperative ORC than with the basic cycle. Canbolat et al. [55] modeled a recuperative cycle using dry fluids. The highest energy and exergy efficiencies were 16.7% and 60%, respectively using R245fa. Zhang et al. [56]

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analyzed the performance of the same system but using R245fa, R1234ze(Z), R601a, and R600a. The results showed that the highest exergy efficiencies were obtained using R600a reaching values around 34.01%. Proctor et al. [57] modeled a recuperative ORC using n-pentane. The model was validated against the plant data obtaining a maximum power output deviation of 0.24%. Uusitalo et al. [58] analyzed the performance of the same system operating with diverse hydrocarbons, siloxanes, and fluorocarbon fluids. The authors concluded that, in general, the efficiencies were higher at higher fluid critical temperatures, if the evaporation pressure was slightly lower than the critical pressure. Ali et al. [59] modeled the same system using thirty-three working fluids. At a heat source temperature of 90°C, the highest thermal efficiencies were obtained with RC318 and R227ea, with values around 6.5%. At temperatures of 170°C, the highest efficiencies were obtained with R123, R236ea, and R114 with values of 19.5%, 15.6%, and 15.3%, respectively. From the exergy analysis, it was determined that more than 50% of the exergy destroyed in the system occurred in the evaporator. These results are in concordance with those published by other authors [18,30,48].

Pezzuolo et al. [60] developed a tool for fluid selection. Eighty fluids were analyzed at 170°C. The maximum thermal efficiencies are around 25.6%. were obtained with benzene, toluene, and cyclopentane. Agromayor and Nord [61] modeled the same cycle. Eighty fluids were first analyzed, but after considering safety and environmental aspects, twenty-nine were selected at temperatures between 100°C and 250°C. The exergy efficiency strongly depends on the choice of the working fluids for a basic ORC but not for the recuperative cycle. The efficiencies of the recuperative ORC were, in general, higher than those obtained with the basic ORC which is in concordance with the results published by Algieri and Šebo [54]. Regarding thermoeconomic studies, Huster et al. [62] analyzed a recuperative ORC using isobutane. The LCOE varied between 0.04 USD/KWh and 0.06 USD/kWh. Preißinger and Brüggemann [63] compared the performance of a recuperative cycle using alkylbenzenes, alkanes, and siloxanes, and found that the best working fluid was the hexamethyl-disiloxane with a PBP lower than 5 years. Heberle et al. [64,65] realized a similar study but for a system driven with solar and geothermal energy over a whole year in Turkey. The lowest electricity cost was 0.145 USD/kWh, while Ahmadi et al. [66] reported that, for their analysis, the cost was 0.3 USD/kWh. On the other hand, Stoppato and Benato A. [67] reported the life cycle analysis of a recuperative ORC driven by biomass using R123, R245fa, and R1233zd. According to the authors, the use of R1233zd guarantees the same system performance as using the other fluids but with a considerably lower impact on the environment. Lu et al. [68] analyzed the performance of a basic and a recuperative ORC using the zeotropic mixtures. The highest power and thermal efficiencies were 36.36 kW and 11.11%, respectively using R245fa/R600a. It was observed that the thermal efficiencies were higher with the recuperative than with the basic ORC, as it was reported by Algieri and Šebo, J. [54] and Agromayor and Nord [61]. Tiwari et al. [69] modeled the same ORC using the zeotropic mixture R600/R601 driven with solar energy. The results showed that the thermal and exergy efficiencies were 12.3% and 58.2%, respectively. Van Erdeweghe et al. [70] realized a thermoeconomic study of a G-ORC, and found that the system was not economically feasible to be installed in Belgium; however, the system would have a more favorable economic situation in a country with higher brine temperatures or higher cost of electricity, e.g., higher than 70 EUR/MWh (79.5 USD/MWh).

4.1. Comparison between recuperative, regenerative, and reheated ORCs

Imran et al. [71] analyzed the theoretical performance of a regenerative G-ORC and compared the results with a basic ORC and a recuperative ORC using R600, R600a, R601, R601a, R245fa, and SES36. The best fluid was R245fa for all the configurations. The energy and exergy efficiencies were the highest with the recuperative and regenerative cycles, but the specific costs were also the highest. Using the R245fa, the maximum exergy efficiency and the minimum cost for the regenerative cycle were 55.93% and 0.2567 USD/MWh, respectively. Similar results were also found by other authors [72–74]. From the exergy analysis, it was found that the exergy destruction was lower in the recuperative and regenerative cycles compared to the basic and reheated ORCs [73,74]. Yang and Yeh [75] reported the results of the thermoeconomic optimization of a reheated G-ORC. The authors analyzed six working fluids with low global warming potential. It was found that the minimum costs were obtained with R600, followed by R600a.

More recently, Nondy and Gogoi [76] compared different configurations, including basic, recuperative, regenerative, and recuperative-regenerative ORC (Figs. 1-3,5) from the exergoeconomic point of view. Their analysis considered a multi-objective optimization to improve the performance of each configuration using the exergy efficiency and the system cost as the objective functions. The authors found that under optimal conditions, the recuperative-regenerative configuration shows the best performance, followed by the regenerative, and the recuperative systems. Zhar et al. [77] also analyzed and compared three ORC configurations: basic, reheated, and regenerative cycles, operating with four different working fluids, from the energy, exergy, and economic perspectives. In this case, the regenerative cycle showed the best energy efficiency, regardless of the working fluid.

Javed and Tiwari [78] also compared the basic, recuperative, and regenerative cycles from the energy and economic perspectives, using Toluene, Nonane, Decane, and Dodecane. This study proved that, under ideal operative conditions, the regenerative cycle operating with Toluene showed the best performance obtaining a maximum first-law efficiency of 37.01%.

4.2. Supercritical ORC

A cycle is supercritical if the maximum pressure is higher than the critical pressure as shown in Fig. 8.

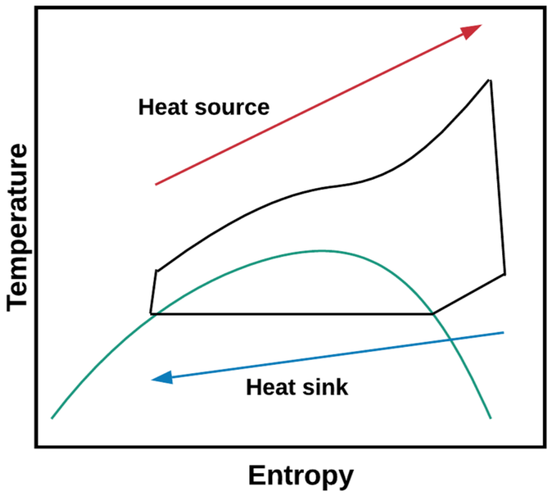


Figure 8. T-s diagram of a supercritical ORC.

Liu et al. [79] analyzed the performance of a supercritical G-ORC using diverse fluids with critical temperatures ranging from 66.0°C to 113.3°C. The highest efficiency (11.18%) was obtained with R152a which had the highest critical temperature. The authors also analyzed a subcritical ORC using zeotropic mixtures and found that the thermal efficiencies were around 3.8% higher using zeotropic mixtures, as it was reported by Oyewunmi and Markides [45]. Manente et al. [80] analyzed the same cycle and compared the results with a subcritical ORC. The results showed that, on average, the supercritical ORC produced up to 20% more power than the subcritical ORC. The highest exergy efficiency values, around 46%, were obtained with supercritical cycles using R1234yf, R134a, and R1234ze(E). Chagnon-Lessard et al. [81] optimized a supercritical G-ORC using 36 working fluids. The results were summarized in charts and a correlation that may be used as efficient tools for designing optimal geothermal power plants. Moloney et al. [82] analyzed a supercritical G-ORC with a recuperator using twenty fluids. The highest energy and exergy efficiencies were 16.2% and 52.3% using R1233zd(E).

Erdogan and Colpan [83] compared the performance of a supercritical ORC with a recuperator with a subcritical ORC. It was found that 44.12% more power was produced with the supercritical than with the subcritical ORC. Lukawski et al. [84] performed a similar study using thirteen different fluids and found that supercritical cycles achieved thermal and exergy efficiencies of up to 17% compared to subcritical ORCs. Song et al. [85] analyzed the same cycle using fifty-two different fluids at four typical temperatures. It was found that at a specific heat source temperature, the energy efficiency increases with the increment of the critical fluid temperature and decreases with increasing fluid dryness. Wang et al. [86] theoretically compared the performance of a basic and a supercritical G-ORC operating with thirty fluids being the best R134a, R32, R600a, and R22. From the comparison with subcritical ORCs, for all the working fluids, on average, the energy efficiencies were around 14.5%, while for supercritical ORCs, the efficiencies were around 17.2%. Cakici et al. [87] analyzed the same system, driven with geothermal and solar energy using R134a, R124, R142b, R227ea, and isobutane. The maximum energy and exergy efficiencies were 12% and 45%, respectively, using R134a.

5. Two-Stage ORC

Currently, there is a great variety of two-stage ORC configurations (sometimes called double-pressure ORC), but all of them have in common that the heat is supplied to the working fluid at two pressure levels to increase power production and/or system efficiency.

Sun et al. [88,89] compared the performance of a two-stage ORC as shown in Fig. 9 using R21, R114, and R245fa. This configuration is also known as a conventional two-stage ORC. Using R245fa, the highest power and exergy efficiencies were 818.6 kW and 5.85%. These values were higher than those obtained, with the basic ORC reaching values of 735.1 kW and 5.28%, respectively. Manente et al. [90] modeled a similar system but the working fluid leaving from the low-pressure turbine (LPT) was again reheated. The analyzed fluids were R134a, isobutane, isopentane, and cyclopentane. When the critical temperature was close to the heat source inlet temperature, the efficiencies of the proposed cycle were up to 29% higher than a basic ORC. At 150°C, the thermal efficiencies varied between 10.3% and 11.1% for all the fluids, while at 200°C, the efficiencies varied between 14% to 15.5%. Wang et al. [91] performed a thermoeconomic evaluation of the same configuration but using R1233zd as a working fluid. The electricity production costs ranged from 0.041 to 0.056 USD/kWh at evaporator temperatures from 140°C to 180°C.

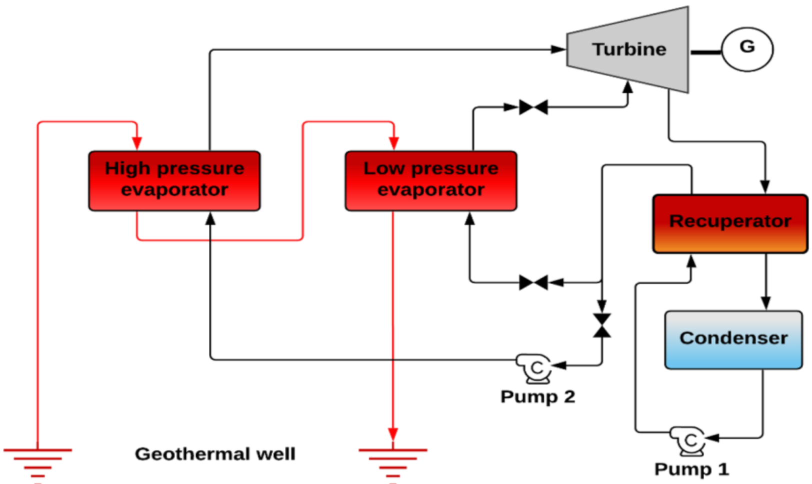
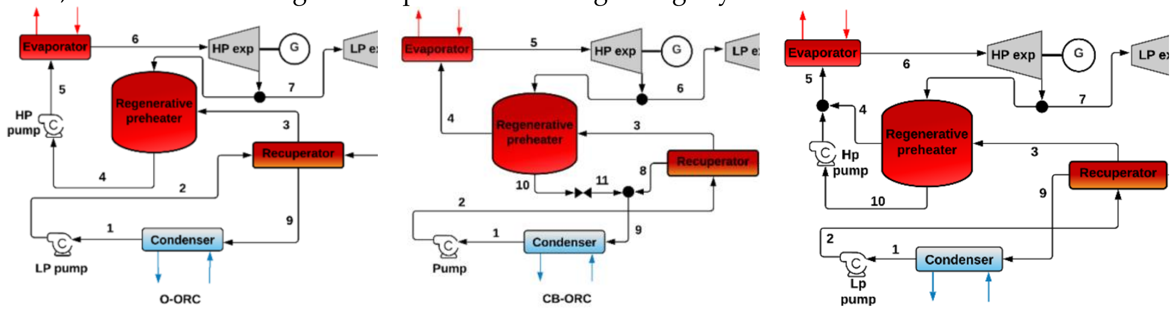


Figure 9. Thermodynamic two-evaporator ORC using a recuperator proposed by Sun et al. [88.]

Fontalvo et al. [92] compared the performance of a two-stage ORC, with a basic and a regenerative ORCs, operating with 2,3,3,3-Tetrafluoropropene (R1234yf), (trans-1,3,3,3-Tetrafluoropropene) R1234ze(E), and (cis-1,3,3,3-tetrafluoroprop-1-ene) R1234ze(Z). Unlike the cycle proposed by Sun et al. [88], the proposed cycle has two pumps at the exit of the condenser. One pumped the working fluid to the LPE, while the other pumped the fluid to the HPE. The highest energy efficiency was 18% using R1234ze(E). It was concluded that the proposed cycle increased the power by 20% compared to the basic ORC. The minimum electricity production cost was 0.3 USD/kWh with a PBP of 8 years. Similar values were also found by Ahmadi et al. [66]. Braimakis and Karellas [93] performed the optimization of three different configurations of ORCs with and without regeneration as shown in Fig. 10. For the non-regenerative cycles, the thermal efficiencies were 20.9%, 20.53%, 19.94%, and 18.02%, for the CF-ORC, O-ORC, CB-ORC, and ORC, respectively. The efficiencies for the three proposed configurations increased by around 15% when regeneration is included. These results showed that regeneration is essential in ORCs, and its effect could be even more important that the development of more sophisticated ORCs. The same authors [94] performed the exergy optimization of a two-stage ORC integrated by two-single ORCs using diverse fluids. The proposed system could achieve exergy efficiencies up to 25% higher than basic ORCs. At temperatures lower than 150°C, the exergy efficiencies varied between 20% and 30%, and were very similar for all the fluids; however, at temperatures close to 300°C, the highest exergy efficiencies were around 50% using cyclopentane, cyclohexane, and toluene. Liu et al. [95] performed an exergy analysis of the same cycle using R600, R600a, R601a, and R245fa as working fluids. The highest exergy efficiency of 41% was obtained using R600a, which was 9.4% higher compared with a single-stage cycle.



(a) (b) (c)

Figure 10. Double-stage regenerative ORC configurations with (**a**) Open preheater; (**b**) Closed preheater with backward bleed condensate circulation; (**c**) Closed preheater with forward bleed condensate circulation [93].

Li et al. [96,97] and Wang et al. [98] modeled a two-stage ORC as shown in Fig. 11 driven with geothermal energy operating with R245fa. The system was modeled at temperatures between 65°C and 100°C. The highest energy and exergy efficiencies were 9.2% and 42%, respectively, at a heat source temperature of 100°C.

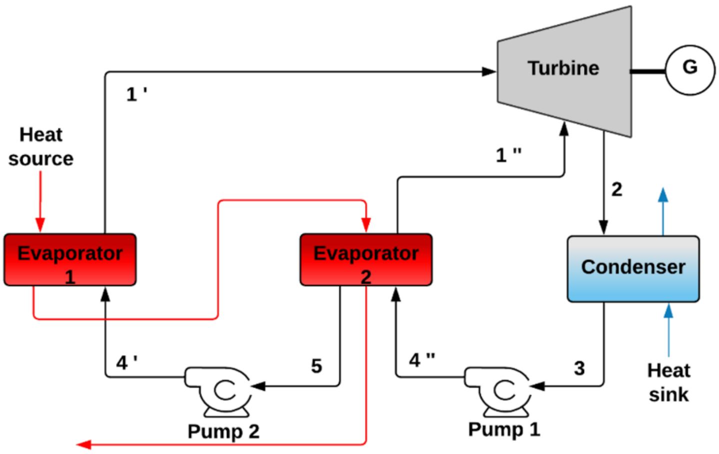
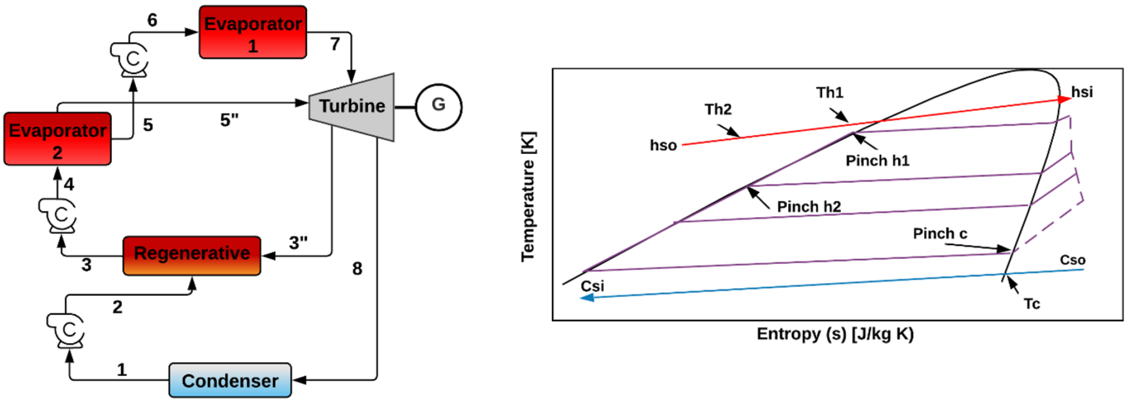


Figure 11. Thermodynamic two-stage evaporator ORC proposed by Li et al. [97].

Li et al. [99] optimized a two-stage ORC using two evaporators and a preheater using nine working fluids. The highest efficiencies were 6.1% at 100°C and 13.2% at 200°C using R245fa. Wang et al.

[100] analyzed the same cycle but operating with isobutane. It was estimated an electricity production cost of 0.24 USD/kWh at 100°C and 0.14 USD/kWh at 160°C.

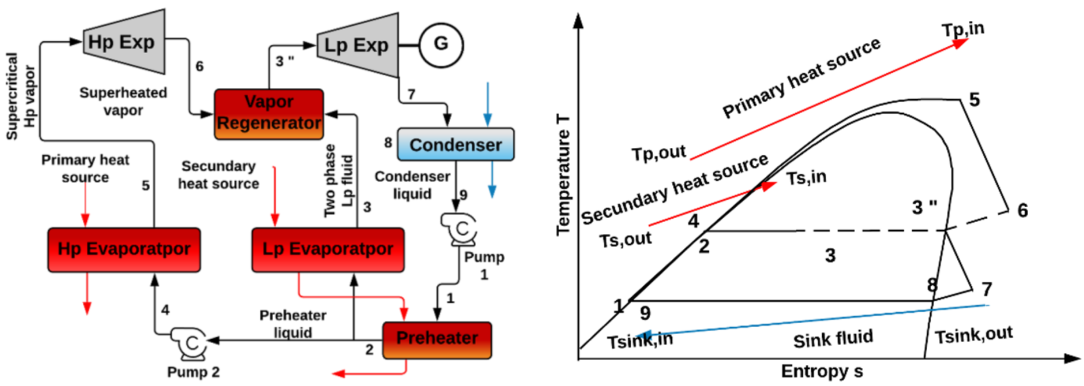
Kazemi and Samadi [101], and Samadi and Kazemi [102] proposed an ORC as shown in Fig. 12 using isobutane, R123, and isobutane/isopentane. The maximum energy and exergy efficiencies were obtained using R123 achieving values of 15.31% and 54.25%, respectively. The minimum electricity production cost was 3,500 USD/kW.



(a) (b)

Figure 12. Cycle proposed by Kazemi and Samadi [101]. (**a**) Schematic diagram; (**b**) T-s diagram.

Nami et al. [103] carried out an exergy analysis of the same cycle proposed by Kazemi and Samadi [101] showing that the low-pressure evaporator, high-pressure evaporator, and condenser were the components with the highest exergy destruction, contributing with the 38.11%, 29.98%, and 15.93%, respectively. Luo et al. [104] analyzed the performance of a two-stage ORC using a condenser with liquid separation operating with the zeotropic mixture R245fa/R365mfc. Although the system has only two evaporators due to the change in the boiling point of the zeotropic mixture, the system could operate at multiple pressures, closely matching the temperature of the heat source. The net power produced was between 13.05% and 26.18% higher than a basic ORC using the same zeotropic mixture. The use of the condenser with liquid separation leads to an increase of up to 8.22% compared to a traditional ORC. Zhou et al. [105] analyzed a two-stage ORC where the vapor at the exit of the high-temperature ORC mixed with the vapor of the low-temperature evaporator before entering the low-pressure turbine. The maximum energy and exergy efficiencies were 18.33% and 62.37%, respectively. Surendran and Seshadri [106] proposed a transcritical regenerative two-stage ORC as shown in Fig. 13 using cyclopentane driven by waste heat at two different temperature levels. The power outputs were 23% and 16% higher compared with a basic and a conventional two-stage ORC, respectively.



(a) (b)

Figure 13. Cycle proposed by Surendran and Seshadri [106]. (**a**) Schematic diagram; (**b**) T-s diagram

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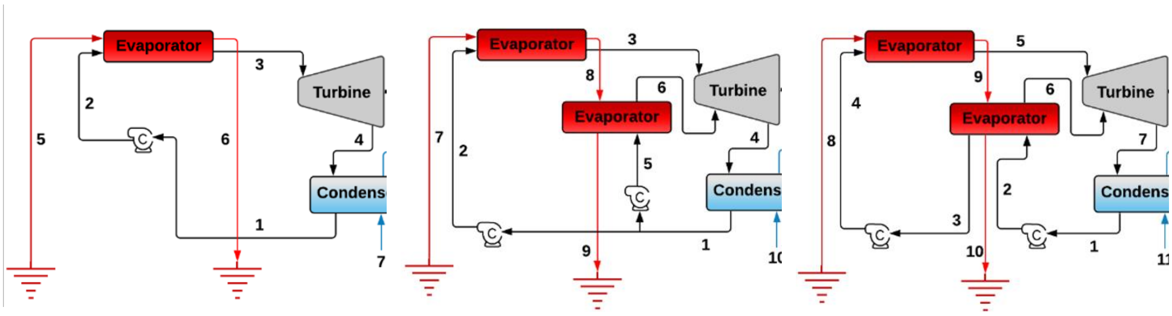
Li et al. [107] modeled an ORC with two evaporators, a high-pressure turbine, and a low-pressure turbine. The results showed that, in general, the ORC driven by the dual-level heat sources, improved the system performance compared with a single-level heat source. Heberle et al. [108] performed a life cycle assessment of a two-stage ORC. In the analysis, the authors considered the substitution of R245fa and R134a by working fluids with low environmental impacts such as R1233zd and R1234yf. It was found that the exergy efficiency decreases by 2%, but the global warming impact reduces by 78% using R123zd instead of R245fa. Sadeghi et al. [109] compared the performance of three different configurations of ORC powered by geothermal energy operating with ten zeotropic mixtures. The analyzed configurations were a basic ORC, a parallel two-stage ORC, and a series two-stage ORC as shown in Fig. 14. Using zeotropic mixtures instead of a pure fluid, such as R245fa, leads to an efficiency increase of about 25% in the three ORC configurations. Additionally, it was reported that the series two-stage ORC was the most efficient configuration. The highest energy and exergy efficiencies achieved by the series two-stage ORC were 9.79% and 57.5%, respectively.



(**a**) (**b**) (**c**)

Figure 14. Configurations analyzed by Sadeghi et al. [109] (**a**) Simple ORC; (**b**) Parallel two-stage ORC; (**c**) Series two-stage ORC.

Chagnon-Lessard et al. [110] compared the theoretical performance of four different ORC configurations: a subcritical ORC, a transcritical ORC, a subcritical two-stage ORC, and a transcritical two-stage ORC using twenty different fluids. In general, the highest efficiencies were obtained using the transcritical two-stage ORC. Wang et al. [111] compared the performance of a two-stage in-series ORC with a dual-level heat source, with a similar system but operating only with one heat source. The results showed that the electricity production cost and PBP were always lower with the two-stage ORC with a dual-level heat source. The minimum values were 0.084 USD/kWh and 1.71 years, respectively. Recently, Wang et al. [112] analyzed the exergy performance and fluid selection of a dual-loop ORC, shown in Fig. 15, driven by flue gas at 300°C. The authors conducted a multi-objective optimization with exergy efficiency, payback period, and annual CO_2 emissions reduction as the objective functions. It was found that using a zeotropic mixture instead of a pure fluid as the working fluid can benefit the system's performance, however, the optimal mass fraction in the mixture depends on each performance parameter and is different for every loop in the ORC. Moreover, the authors found that the use of optimal mixtures affect significantly the exergy efficiency and annual emissions reduction but does not have an important effect on the payback period.

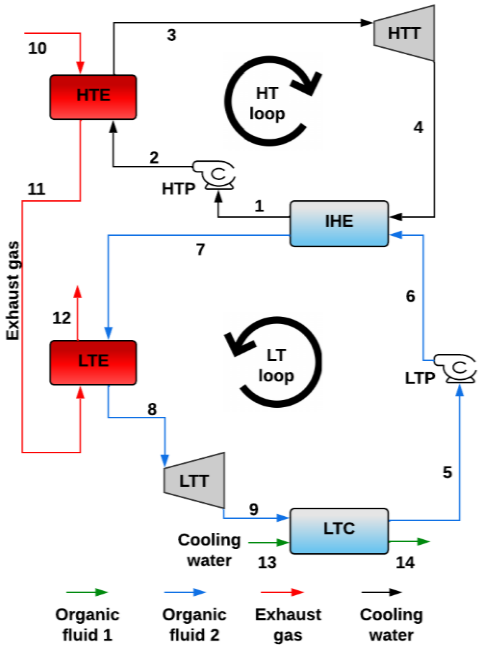


Figure 15. Schematic diagram of the two-stage ORC proposed by Wang et al. [112].

6. Hybrid ORC

Hybrid ORCs are considered as those systems integrating at least two different technologies to produce one or more different outputs.

Najjar and Qatramez [113] modeled a hybrid system consisting of a single flash geothermal cycle operating a steam turbine and an ORC using n-butane, isobutane, R11, and R123. The highest energy efficiency of 18.76% and net power output of 24,887 MW were obtained with R11. Matuszewska and Olczak [114] proposed a hybrid cycle integrating an ORC using R245fa, R1233zd(E), and R600, and a Brayton cycle operating at about 550°C. The heat delivered by the Brayton cycle gas turbine was used to preheat the brine coming from a geothermal well. The highest thermal efficiencies were achieved using R1233zd(E), reaching values up to 19.20% higher in comparison with a basic ORC. Yağlı et al. [115] proposed the adaptation of an ORC to improve the performance of a gas turbine located in a wood production facility. The study analyzed eight different working fluids. The parametric optimization of the cycle required increasing the turbine inlet pressure from 10 to 35 bar. Benzene was the best working fluid in the pressure range of 10 to 25 bar (at the inlet of the turbine), while R123 showed the highest performance for pressures between 25 and 35 bar. For this fluid, the highest values were: 1076.76 kW, 21.1%, and 47% for power production, and thermal and exergy efficiencies, respectively.

Mokarram and Mosaffa [116] proposed a cycle integrating a steam turbine and a transcritical G-ORC using R245fa. The system produced 7.2% more power compared to a similar cycle operating in subcritical conditions. The maximum energy and exergy efficiencies were 14.66% and 55.15%, respectively, with a LCOE of 0.2018 USD/kWh. Li et al. [117] proposed a cooling, heating, and power G-ORC as shown in Fig. 16 using twenty zeotropic mixtures. At a heat source temperature of 90°C, the highest net power output, cooling capacity, and exergy efficiencies were 92 kW, 2450 kW, and 0.62%, respectively, using R141b/R134a.

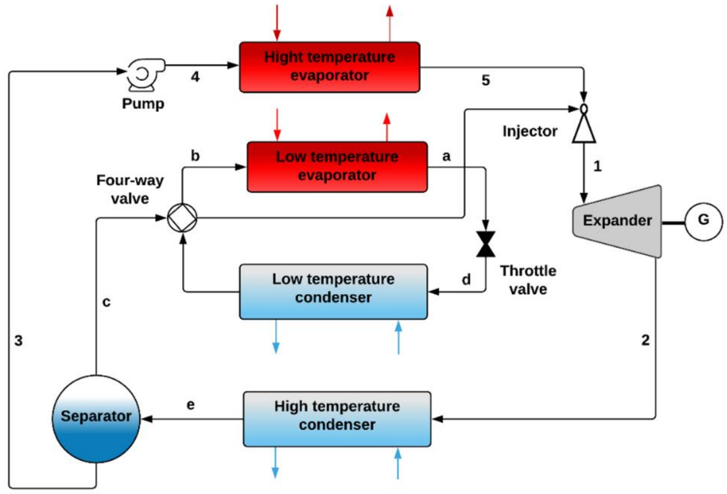


Figure 16. Schematic diagram of the hybrid system proposed by Li et al. [117].

Sun et al. [118] modeled a two-stage G-ORC recovering the residual heat of an absorption cooling system (ACS) for the simultaneous production of power and cooling. Compared to a two-stage ORC, the system enhances the net power output by 10%. Ehyaei et al. [119] proposed a similar system but using R134a. The use of the ACS increased the energy efficiency from 9.3% to 47.3%. The system's minimum electricity cost was 3.3 USD/MWh. Leveni and Cozzolino [120] carried out an energy and exergy analysis of the same system producing a net power of 5 kW obtaining an exergy efficiency of 40.98%. Wang et al. [121] proposed a similar system but, in this case with an eject-compressor cooling system (ECS). The highest energy and exergy efficiencies were 18.16% and 59.16%, respectively, at a geothermal brine temperature of 190°C. Jafary et al. [122] also studied the integration of a trigeneration system for the production of combined cooling, heating, and power (CCHP) utilizing a double-effect absorption cooling system as the bottoming cycle of an ORC driven by a solar power plant with parabolic trough collectors (PTC). The authors analyzed two configurations for the power system: the first one considered an internal heat exchanger while the second one was a regenerative system. The analysis reported a better performance from the energy and exergy perspective for the first configuration.

Jiménez-García et al. [123], also investigated the simultaneous production of power and cooling by the coupling of an ORC and a double-effect absorption cooling system, from the first law of thermodynamics perspective. The authors analyzed the system performance using four working fluids for the organic cycle (benzene, toluene, cyclohexane, and methanol) and the ammonia-lithium nitrate mixture for the absorption cycle. They found that, for a wide range of operating conditions, the cooling load was much higher than the power production. Under the operating conditions analyzed (heat source temperature from 160-220°C), the best system performance was obtained with benzene, achieving an energy utilization factor of 0.854 and a maximum exergy efficiency of 39.8%.

Lizarte et al. [124] analyzed the performance of an ORC and a cascade compressor cooling system (CCS) to produce cooling at temperatures between -55°C and -30°C. The power produced by the ORC was used as the input power of the cooling cycle. The highest COP and exergy efficiencies were 0.79 and 31.6%, respectively. A similar study was realized by Li et al. [125] but instead of producing cooling, the system was proposed for power and space heating. The system was modeled for a period of up to 20 years. The annual average COP was 3.8. Marty et al. [126] presented the optimization of a G-ORC using R245fa for the simultaneous production of power and district heating. The geothermal fluid was split into two lines, one used for the ORC and the other used for the district heating network.

Maali and Khir [127] analyzed the optimal operation of an ORC operating with solar and geothermal heat sources, from the energy and exergy perspectives. The analysis was performed considering the conditions of two typical days (summer and winter) in Tunisia. The main sources of irreversibilities were the steam generator, the air-cooled condenser, and the turbine. The power plant performance was optimized by applying a linear regression analysis to relate the volume flow rate and temperature of the heating fluid with solar radiation. The authors found that in winter, an increment from 55 to 75°C in the geothermal water temperature can improve the plant's exergy efficiency by about 4.35%. However, in summer, this parameter did not affect significantly the system performance.

Boukelia et al. [128] also analyzed the integration of solar and geothermal heat sources for electricity production, but considering two production levels: one of them was composed of a parabolic trough solar power plant and a Rankine cycle, while the other was a geothermal power plant using an organic Rankine cycle. For that purpose, the authors performed the design and thermo-economic analyses including nine organic fluids finding that this configuration raised the power generation by 19.36% regarding the stand-alone solar plant. They also found that wet fluids were more convenient than dry ones. Thus, the best fluids in this configuration were: ammonia, R32, R290, and R143a. Javanshir et al. [129] proposed a system integrated by an ORC and a CCS, as shown in Fig. 17. The system was analyzed using R134a, R22, and R142a. The highest energy and exergy efficiencies were 27.2% and 57.9%, respectively, which were obtained using R143a. The electricity production cost was 60.7 USD/GJ.

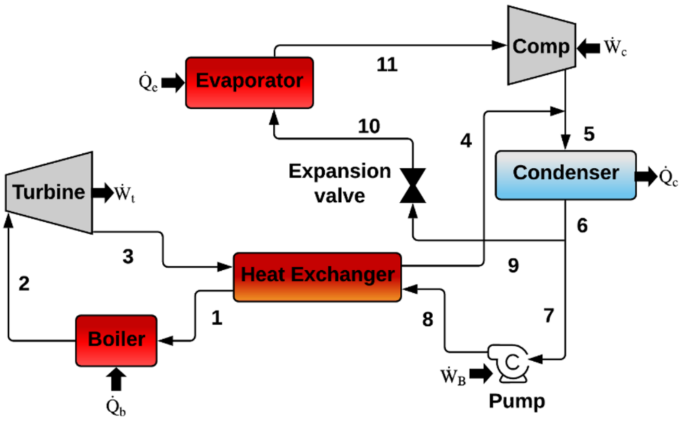


Figure 17. Schematic diagram of the hybrid system proposed by Javanshir et al. [129].

Pashapour et al. [130] proposed a system integrated by a Brayton cycle, an ORC, and an ACS for the simultaneous production of power, heating, and cooling as shown in Fig. 18. The highest exergy efficiency was 50.65%, while the maximum COP was 0.5. Although this system achieved high exergy efficiency, it requires many components and very high operating temperatures close to 1250°C.

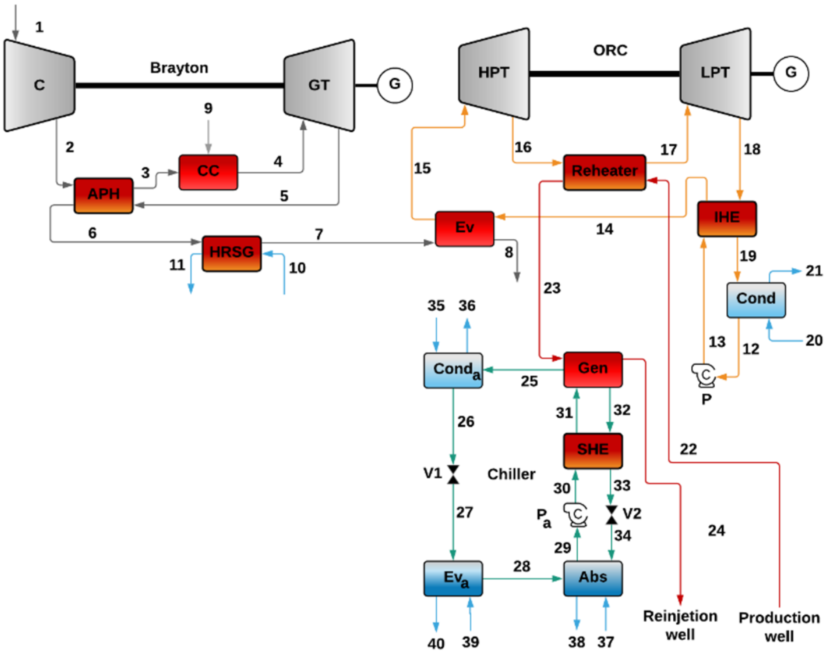


Figure 18. Schematic diagram of the hybrid ORC Pashapour et al. [130].

Sharifishourabi and Chadegani [131] proposed a system for the simultaneous production of cooling, hot water, heating, hydrogen, and power. The system was integrated by an ORC, a triple-effect ACS, a dehumidification system (DS), and an electrolyzer, all driven by solar energy. The system achieved an energy utilization factor of 0.39, a COP of 1.34, an energy efficiency of 14.4%, and an exergy efficiency of 26%. Lee et al. [132] proposed the integration of an organic Rankine cycle-direct expansion cycle (ORC-DEC) and a proton-exchange membrane fuel cell (PEMFC), for power production in a liquid hydrogen-fueled ship. The authors analyzed the cycle and the assessment results showed that the proposed system can achieve up to 221 kW of additional power, achieving energy and exergy efficiencies of up to 40.5%, and 43.5%, respectively. The authors also found that the best working fluid for the considered application was propane.

Geng et al. [133] and Wang et al. [134] analyzed a G-ORC integrated into a desalination system. The variation of the zeotropic mixture composition could significantly improve the net power and the thermal efficiency of the ORC. The highest thermal exergy efficiencies were 13.3% and 51.5%, respectively.

Gholamian et al. [135] optimized a hybrid system integrating a basic G-ORC and a proton exchange membrane electrolyzer to produce power and hydrogen simultaneously. Among others, the R114 was the best fluid. The maximum exergy efficiency was 21.9%, which was 12.7% higher than that obtained using just the basic ORC. Recently, Azad et al. [136], analyzed the integration of a two-stage in-series ORC and a fuel cell. This cycle utilized a proton exchange fuel cell for electricity generation, an ORC with zeotropic mixtures for power production, and a thermoelectric generator instead of a condenser in the ORC as a heat recuperator used to produce electricity and minimize heat loss. It was found that this configuration can improve the overall exergy efficiency by 1.9%.

Kaşka et al. [137] presented a cycle integrated by a G-ORC, a CCS, and a Claude cycle. The ORC was used to produce the electricity to drive the refrigeration cycle, which was used in turn to produce the cold necessary to liquefy the hydrogen through the Claude cycle. The system was modeled using R600, R600a, R123, R245fa, and R141b. The authors found that the hydrogen liquefaction cost was 39.7% lower than values reported in the literature using traditional methods. Ganjehsarabi [138] and proposed a system for the same purposes but integrating a G-ORC coupled to a proton exchange membrane electrolyzer. The exergy efficiencies were around 40% with the proposed fluids. Han et al. [139] also proposed a system for the simultaneous production of power and hydrogen. The system consisted of a steam turbine, an ORC, and a proton exchange membrane electrolyzer. The maximum energy and exergy efficiencies were 18.96% and 57.24%, respectively. They were considerably higher

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than those reported by Ganjehsarabi [138] but required higher geothermal brine temperatures. Cao et al. [140] proposed another system for hydrogen production consisting of an electrolyzer fuel cell and a two-stage ORC. The highest energy and exergy efficiencies were 12.2% and 24.7%, respectively. The minimum electricity production cost was 36.6 USD/GJ. Recently, Fallah et al. [141], performed an advanced exergy analysis of a hybrid cycle combining a supercritical CO_2 system coupled to an ORC as a bottoming cycle. In this study, the avoidable and unavoidable parts of the irreversibility were determined and accounted for. The components with the highest exergy destruction were identified as well as the avoidable amount of it, thus, the authors determined the priority components to be modified to reduce the overall exergy destruction.

7. Discussion

7.1. Basic ORC

The modeling of the basic cycles has been realized at temperatures from 60°C using fluids such as R600, R32, R290, and R410a [28], and up to 350°C using Propyne, cis-butene, iso-hexane, and cyclohexane [18]. At temperatures lower than 120°C, fluids such as R123, R134a, R600, R290, R1234yf, and R245fa have been the most efficient. The highest thermal efficiency of 14.6% was obtained using R600, followed by 12.2% using HFE7000, and 12.0% using R245fa. At temperatures between 120°C and 240°C, the highest efficiencies were achieved using benzene and methanol, achieving a thermal efficiency of 18.5%, while at temperatures higher than 240°C, a thermal efficiency as high as 29% was achieved utilizing toluene [10], followed by 21.43% using cyclohexane [18].

From the research focused on the working fluids, it was found that the dry or isentropic fluids are the best suitable to be used in microturbines since higher efficiencies could be achieved, also avoiding blade damages of the turbine caused by wet vapor [11,12]. Dry fluids with turning points higher than 200°C are the best to achieve higher efficiencies [10]. It was also found that by utilizing zeotropic mixtures, the efficiencies could be better than those achieved with pure fluids [45].

Regarding thermoeconomic studies, it was found that the payback period of G-ORCs considerably varied depending on the driven temperature and the drilling costs, since this parameter for an ORC operating at 150°C is about 4 years, while when it operates at 100°C, this parameter increases up to 8.9 years [41]. The best fluids from the thermoeconomic point of view were R1234yf and cyclohexane.

From the life cycle analysis, it was shown that although the sustainability values of the ORCs were lower than power plants using renewable energies, were considerably higher than plants using fossil fuels. From the environmental point of view, R600 and R123 were the best working fluids at low heat source temperatures, while toluene was the best fluid at high temperatures [53].

7.2. Recuperative, regenerative, reheated, and supercritical cycles

Table 1 shows the most relevant data for the recuperative, regenerative, reheated, and supercritical ORCs. The studies analyzing the working fluids found that the fluorocarbons and hydrocarbons with low critical temperatures were the best for low heat source temperatures, while the siloxanes and the hydrocarbons with high critical temperatures were the most suitable at high temperatures [58]. Diverse authors coincide that the R245fa was the most efficient fluid when compared with some hydrocarbons and other working fluids at temperatures lower than 140°C [54,71,72], but at temperatures around 170°C, the best working fluids were ethanol, benzene, and toluene with values of 24.2%, 23.2%, and 22.9%, respectively [60].

From the comparison between the different configurations of ORCs operating in subcritical mode, it was found that the efficiencies of recuperative ORCs were up to 15% higher than those of a basic ORC [54,61]. Using R245fa as working fluid and at an evaporation temperature of 130°C, the most efficient cycles were the recuperative and the regenerative ORCs achieving efficiencies of around 13.2%, while with the basic and reheated ORCs, the efficiencies were around 12% [71,73,74]. Regarding supercritical ORCs, it was found that at temperatures lower than 150°C, these cycles produced up to 20% more power than subcritical ORCs, achieving maximum power outputs of around 44.12% [80,83]. The highest exergy efficiency values, around 46%, were obtained with supercritical using R1234yf, R134a, and R1234ze(E). At temperatures between 170°C and 240°C, it was reported that the highest efficiencies were obtained with R1233zd(E), butane, isopentane, pentane, and neopentane [82]. It was found that the critical temperature and fluid dryness considerably affected the system performance. Considering not only the thermodynamic efficiencies, but also the toxicity, flammability, and environmental friendliness, the best working fluids were R134a, R600, R601, and R123, in the range from 100 up to 300°C [85]. From the exergy analysis, it was found that the maximum irreversibilities (contributing more than 50%) occurred in the evaporator, followed by the condenser, expander, and pump [59,73,74]. Finally, from the thermoeconomic studies, it was estimated that the lowest LCOE was obtained with the reheated ORC, followed by the recuperative, the basic, and the regenerative ORCs, with values of 0.26 USD/kWh, 0.28 USD/kWh, 0.29 USD/kWh, and 0.3 USD/kWh, respectively [73,74].

Table 1. Operating parameters and main results for the different configurations of ORCs.

Reference	Cycle more efficient	Conditions	Working fluid	Output	Efficiency (%)		Component with the highest irreversibilities	LCOE
					Thermal	Exergy		
Algieri and Šebo [54]	Recuperative	T_{HS}=139 °C	Isobutane, isopentane and R245ca*	4.0 kW	14.0	-	-	-
Canbolat et al. [55]	Recuperative	T_{HS}=127 °C	R142b, R227ea, R245fa*, R600 and R600a	-	16.7	60.0	Evaporator	-
Zhang et al. [56]	Superheated recuperative	T_{HS}=100 °C	R245fa, R1234ze(Z), isopentane e isobutane*	24.0 kW	26.38	34.0	-	-
Uusitalo et al. [58]	Recuperative	T_{HS}=300 °C	hydrocarbons, siloxanes and fluorocarbons	31.1 kW	25.2	-	-	-
Ali et al. [59]	Basic, Recuperative	T_{HS}=165 °C	Butane, Isobutane, Isopentane*, etc.	89.61 kW	19.83	-	Evaporator	-
Pezzuolo et al. [60]	Basic, Recuperative	T_{HS}=170 °C	benzene*, toluene, cyclopentane, etc.	4.0 MW	25.7	37.60	-	0.118 USD/kWh
Agromayor and Nord [61]	Simple, Recuperative	T_{HS}=600 °C	Alkylbenzenes, alkanes and siloxanes	550 kW	-	30.0	-	-
Lu et al. [68]	Basic, Recuperative	T_{HS}=140 °C	zeotropic mixtures R601a/R600 and R245fa/R600a	36.4 kW	11.11	-	-	-
Imran et al. [71]	Basic, Recuperative,	T_{HS}=160 °C	R600, R600a, R601, R601a, R245fa* and SES36.	68.4 kW	14.02	55.93	-	-

	Re-generative							

* Most efficient working fluid

Table 1. Operating parameters and main results for the different configurations of ORCs. Continuation.

Reference	Cycle more efficient	Conditions	Working fluid	Output	Efficiency (%)		Component with the highest irreversibilities	LCOE
					Thermal	Exergy		
Wang et al. [72]	Basic, Recuperative, Regenerative	T_{HS}=150 °C	Fourteen working fluids R245fa*	-	12.0	48.0	-	-
Li [73] and Li [74]	Basic, Regenerative, Recuperative, Reheated	T_{HS}=130 °C	Fourteen working fluids, R245fa*	-	13.2-13.8	-		0.26 USD/kWh
Yang and Yeh [75]	Reheated	T_{HS}=94 °C	R600*, R600a, R1233zd, R1234yf, R1234ze.	332.7 kW	8.29	-	-	0.3 USD/kWh
Liu et al. [79]	Basic Supercritical	T_{HS}=130 °C	R125, R218, R143a, R32, R290, R134a, R227ea, R1234ze(E), and R152a*	599.1 kW	11.18	-	-	-
Manente et al. [80]	Supercritical	T_{HS}=150 °C	R1234yf*, R134a, R1234ze (E), R1234ze (Z), R245fa, R600a	900.8 kW	10.64	-	-	-
Moloney et al. [82]	Binary, Single flash	T_{HS}=240 °C	Twenty different working fluids	150 kW	19.0	50.0	Turbine	-
Lukawski et al. [84]	Basic, Recuperative supercritical	T_{HS}=220 °C	Thirteen working fluids. R134a*	120 kW	19.0	-	-	-
Cakici et al. [87]	Recuperative	T_{HS}=160 °C	R134a*, R124, R142b, R227ea, and isobutane	5800 kW	12.0	45.0	Parabolic trough solar	-

	super-critical						collec-tors	

* Most efficient working fluid

7.3. Two-stage ORC

There are a considerable number of studies regarding two-stage ORCs proposing diverse configurations, some of them, in addition to the evaporator and condenser, include components such as a recuperator and a regenerator. The use of a regenerator proved to be very convenient since it increased up to 15% the thermal efficiencies of the analyzed configurations [93]. A great variety of working fluids have been proposed for the different configurations, but those with the highest efficiencies were R245fa, R123, R1234ze(E) cyclopentane, and isopentane.

From Table 2 it can be seen that the highest thermal efficiencies (about 18%) were obtained by Zhou et al. [105] and Fontalvo et al. [92] with a two-stage regenerative ORC operating at temperatures around 200°C. At temperatures lower than 150°C, the highest thermal efficiency (15.31%) was achieved with the system proposed by Kazemi and Samadi [101]. Some of the proposed two-stage ORCs could increase the efficiency between 10% and 20% [88,89,93–95] and the power between 13% and 26% [89,101] compared to basic cycle configuration. Regarding the cost analysis, the lowest LCOE (0.084 USD/kWh) and payback period (1.71 years) were reported by Wang et al. [111] for the system consisting of a two-stage series ORC operating with dual-level heat supply.

Table 2. Operating parameters and main results for the two-stage ORCs.

Reference	Cycle more efficient	Conditions	Working fluid	Output	Efficiency (%) Thermal	Efficiency (%) Exergy	Cost (LCOE or PBP)	Component with the highest irreversibilities
Sun et al. [88,89]	Basic, two-stage*	T_{HS}=113 °C	R21, R114, and R245fa*	818.6 kW	-	5.85	-	HPE
Manente et al. [90]	Basic, two-stage*	T_{HS}=200 °C	R134a, R1234ze (Z), isobutane, isopentane, and cyclopentane.	8573 kW	15.36	-	-	-
Wang et al. [91]	Two-stage	T_{HS}=113.8°C	R1234zd	614.27 kW	-	-	PBP=3.99	-
Fontalvo et al. [92]	Two-stage, basic, regenerative*	T_{HS}=200 °C	R1234yf, R1234ze(E)*, and R1234ze(Z).	33 kW	18.1	60.0	0.3 USD/kWh PBP=8 years	-
Braimakis and Karellas [93,94]	Basic, two basic operating in cascade	T_{HS}=100 °C	butane, pentane, cyclopentane*, cyclohexane, toluene, R134ze, and R134yf.	-	5.0	25.0	-	-
Liu et al. [95]	Basic, two basic operating in cascade	T_{HS}= 140 °C	R600, R600a, R601a, and R245fa	-	-	41.0	-	-
Li et al. [96,97]	Two-stage	T_{HS}=100 °C	R245fa	9.0 kW	9.2	42.0	-	HPE
Li et al. [99]	Basic, two-stage	T_{HS}=200 °C	R227ea, R236ea, R245fa*, R600, R600a, R601,	100 kW	13.5	-	-	-

			R601a, R1234yf and R1234ze(E),					
Wang et al. [100]	Basic, two-stage*	T_{HS}=160 °C	Isobutane	241.7 kW	11.29	-	0.14 USD/kWh	-
Kazemi and Samadi [101]	Three-pressure levels	T_{HS}=134.3°C	Isobutane and R123*	-	15.31	54.25	-	Condenser
Samadi and Kazemi [102]	Three different pressures levels	T_{HS}=124.5 °C	Isobutane, isopentane*	-	13.78	53.02	-	-
Luo et al. [104]	Basic, two basic operating in parallel*	T_{HS}=195°C	Isobutane-isopentane (0.9-0.1)	407.62 kW	-	31.77		HPE
Zhou et al. [105]	Two-stage	T_{HS}=188 °C	6 working mixtures, pentane/Cis-2-butane (0.539/0.461)*	5983.19 kW	18.43	62.96	-	HPE
Surendran and Seshadri [106]	Transcritical regenerative two-stage	T_{HS}=302 °C	Cyclopentane	349 kW	15.3	17.4	-	HPE
Sadeghi et al. [109]	Basic, two-stage parallel, series two-stage*	T_{HS}= 100 °C	R407A	940.3 kW	8.53	55.63	-	HPE
Wang et al. [111]	Two-stage series with dual-level HS	T_{HS}=104 °C	R123	78 kW	6.0	28.0	0.084 USD/kWh PBP=1.71 years	-

* Most efficient working fluid

7.4. Hybrid systems

Regarding the systems designed to produce only power, the best efficiency (19.2%) was achieved with the ORC integrated into a Brayton cycle [114]; however, the heat source temperature required was more than 300°C higher than that in the cycles integrated into a steam turbine.

As for the systems integrating ORCs and cooling systems, the best was the one proposed by Wang et al. [121], using an eject-compressor cooling system. This system achieved an exergy efficiency of 59.16% operating at 190°C, followed by the one proposed by Javanshir et al. [129] reaching a value of 57.9%.

In relation to the systems to produce three or more useful outputs, the one with the highest exergy efficiency was the one proposed by Han et al. [139], achieving an exergy efficiency of 57.1%. However, for the same purposes, the system proposed by Kaska et al. [137] reached the lowest LCOE of 0.0247 USD/kWh.

8. Conclusions

As can be seen from the literature reviewed, there is a great interest in studying and developing ORCs. Many studies have been focused on modeling using a great variety of fluids and configurations such as regenerative, recuperative, and reheated in the case of single-stage cycles, operating either in subcritical or supercritical modes. Also, many studies have been realized proposing diverse

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configurations of two-stage ORCs to increase the system's efficiency, power output, or both. Also, hybrid cycles have been proposed by combining ORCs with other technologies such as gas, steam turbines, cooling systems, and electrolyzers. These hybrid cycles can produce just power, power and cooling, and even hydrogen and desalinization, among other products.

Respecting theoretical studies, it was reported that at temperatures lower than 120°C, the highest thermal efficiencies were achieved with R123, R1233zd(E), R134a, R600, R290, R1234yf, and R245fa, while at higher temperatures the benzene, the methanol, the toluene, and the cyclohexane were the best. From the economic point of view, the best fluids were R1234yf and cyclohexane, but from the environmental point of view, the R600, R601, R123, and R134a were the best at low heat source temperatures and toluene at high temperatures.

Regarding the comparison of different configurations of single-stage cycles, it was reported that the most efficient were both, the recuperative and regenerative systems, achieving thermal efficiencies up to 15% higher than those reached with basic cycles. Supercritical cycles could produce up to 20% more power compared to subcritical cycles. From the studies proposing different configurations of two-stage ORCs, it is difficult to establish which is the most efficient, since the diverse authors chose different working fluids and operating conditions; however, in most of the studies, the authors reported that the thermal efficiencies could be up to 20% higher and the power up to 44% higher compared to single-stage cycles. From the studies related to hybrid systems, it was found the most efficient were those integrating Brayton cycles; however, these systems require operating temperatures around 300°C higher than the system integrating a steam turbine.

As can be seen from the literature reviewed, in recent years a great number of studies related to organic Rankine cycles have been proposed. Some of the studies have focused on integrating organic Rankine cycles into other conventional cycles such as binary geothermal cycles or Bryton cycles, while many other studies integrate new components to the basic cycle to make them more efficient or well for polygeneration purposes producing two or more outputs such as power and cooling, power and heating, and power and hydrogen among other outputs. However, most of the studies realized on new cycles are theoretical, and none of them report the performance of modified cycles that are not regenerative or recuperative. This shows, that there is still an important gap between the new configurations proposed theoretically and the development of experimental prototypes. This could be for different reasons, such as systems complexity, investment cost, and technological aspects. Nevertheless, this gap is in general normal in the development of thermodynamic cycles and other technologies, so it is expected that in the forthcoming years, new prototypes emerge based on some of the new theoretical cycles proposed.

9. Future directions

To date, in the literature, it is possible to find a large number of studies focused on the optimization of organic cycles from the perspective of first and second laws of thermodynamics, for basic and more complex cycles. The present review work condenses what is considered the most outstanding studies that, through multiple and varied strategies, have dedicated their efforts to the proposal and analysis of modifications of the simplest cycles to improve their theoretical performance. Based on the observed trends, the authors believe that future research on organic Rankine cycles could lean toward the trends mentioned below:

1. **Simulation of dynamic systems:** some recent studies on energy systems, including ORCs, have proposed dynamic models that consider the transient behavior of the main operating parameters. Thus, the theoretical performance predicted by such numerical models is more realistic than that corresponding to steady-state models. In the case of hybrid cycles, as mentioned previously, a large number of studies are related to the use of solar energy without thermal energy storage, which implies that the temperature of the energy source is highly dependent on time. This is an example where dynamic numerical simulation models should be used. Similar to the heat

supply temperature, many other parameters of a variant nature should be analyzed from the dynamic perspective.

2. **Validation of proposed models:** to date, the vast majority of studies on organic cycles found in the literature have not been validated experimentally. This implies that there is a huge number of cycles with extremely attractive performance parameters; however, in the case of advanced cycles with multiple components, there is no certainty of their operational viability, neither for technical issues in real environments, nor economic ones. A major experimental research effort on such systems should be carried out in the short and medium term.
3. **Characterization of working fluids:** a large number of theoretical studies consider the use of new working fluids, particularly of zeotropic mixtures, whose properties in many cases are defined, either in the different specialized software or through semi-empirical correlations. However, it is sometimes difficult to find the thermophysical properties of such substances in the ranges required for organic cycles. For these reasons, it is considered necessary that shortly, there will be more research on the properties of new working fluids in the operating ranges of interest.
4. **Cogeneration systems:** the results of the analyses of hybrid systems described in this review, in general, predict a better performance of the systems in which the ORCs are integrated. For this reason, future proposals for systems simultaneously producing several useful energy effects, particularly those of an experimental nature, should be encouraged.
5. **Multi-objective optimization:** Some recent research has conducted optimization studies on systems with several objective functions, which typically are energy and/or economic parameters; however, the vast majority of analyses leave aside environmental aspects, such as those related to life cycle analyses or direct and indirect emissions to the environment. It is expected that, soon, the studies on the proposed new power cycles can be complemented with analyses from an environmental approach.
6. **Supercritical ORC:** Regarding supercritical cycles, the number of studies addressing them is currently limited. Some studies (as Moloney et al. [82]), indicate that supercritical cycles can be more efficient than subcritical ones when the ORC takes advantage of a low-temperature heat source. Thus, today there is a large number of studies in the literature about the huge potential for the exploitation of this type of thermal source, i.e., some of geothermal nature. For this reason, it is desirable to intensify the research on supercritical organic systems.
7. **Cleaner production:** in recent decades, the trend towards the design and implementation of systems that efficiently take advantage of the various sources of clean energy, has been one of the priorities of research and development of energy technology. In this sense, organic Rankine systems have not been the exception. It is expected that a growing integration of ORCs will be maintained for the use of energy sources such as geothermal, solar, or even waste heat from industrial processes or from any other process suitable to be used by an organic power system.

Some other authors [142], consider that also reversible ORC-heat pump systems represent an additional field of interest to work into, as a key solution to waste heat recovery together with thermal and electrical energy storage. Also, the authors foresee potential improvements in the efficiency of ORCs, as a product of component-level research, particularly in expanders, pumps, and heat exchangers.

Nomenclature

ACS	absorption cooling system
CCS	compression cooling system
DS	dehumidification system
ECS	ejector cooling system
ExD	exergy destruction
Exp	expander
COP	coefficient of performance
G	generator
HPE	high-pressure evaporator
HPT	high-pressure turbine
HS	heat source
LPE	low-pressure evaporator
LPT	low-pressure turbine
LCOE	levelized cost of energy
ORC	organic Rankine cycle
PBP	payback period
SP	single-pressure
TP	two-pressure

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