A review of solar-driven organic Rankine cycles: Recent challenges and future outlook

Reyhaneh Loni[a], Omid Mahian[b], Christos N. Markides[c], Evangelos Bellos[d,*], Willem G. le Roux[e], Ailbakhsh Kasaeian[f], Gholamhassan Najafi[a], Fatemeh Rajaee[f]

[a] Department of Biosystem Engineering, Tarbiat Modares University, Tehran, Iran.

[b] School of Chemical Engineering and Technology, Xi'an Jiaotong University, Xi'an, Shaanxi, China.

[c] Clean Energy Processes (CEP) Laboratory, Department of Chemical Engineering, Imperial College London, London SW7 2AZ, UK.

[d] Thermal Department, School of Mechanical Engineering, National Technical University of Athens, Athens, Greece.

[e] Department of Mechanical and Aeronautical Engineering, University of Pretoria, Private Bag X20, Hatfield, 0028, South Africa.

[f] Department of Renewable Energies, Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran.

***Corresponding authors:** Evangelos Bellos (bellose@central.ntua.gr), R. Loni (rloni2017@gmail.com)

Highlights

•Solar driven organic Rankine cycles are summarized and discussed in detail.

•Concentrating and non-concentrating solar thermal systems are included.

•Parabolic trough collector is the best solar technology for power production.

•The use of solar organic Rankine cycles in polygeneration is a promising idea.

•There is a need for conducting future experimental studies in a great scale.

Abstract

The organic Rankine cycle (ORC) is an effective technology for power generation from temperatures of up to 400°C and for capacities of up to 10 MW_{el}. The use of solar irradiation for driving an ORC is a promising renewable energy technology due to the high compatibility between the operating temperatures of solar thermal collector technologies and the temperature needs of the cycle. The objective of this review paper is to present and discuss the operation principles of solar-ORC technology and the wide range of solar-ORC systems that have been studied in the literature. Various solar thermal technologies that can drive the ORC are investigated, such as the flat plate collector, evacuated tube collector, compound parabolic collector, parabolic trough collector, linear Fresnel reflectors, dish concentrators and solar towers. Both simulation studies and experimental investigations are included in the study. Hybrid systems and different thermal storage techniques are also examined in detail. Moreover, systems with ORC which produce many useful outputs such as cooling, heating and fresh water are studied because they present high sustainability indexes. The limitations of the technology are also highlighted, along with critical suggestions aimed at steering future research in this field. The final conclusions indicate that the development of trigeneration and polygeneration systems with ORC

sub-systems is a promising avenue, not only for the future development of solar-ORC technology but also for the development of renewable and sustainable energy systems in a broader context.

Keywords: solar organic Rankine cycle, solar thermal collector, concentrating solar power, renewable energy systems, polygeneration.

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Contents

1 Introduction

Renewable energy is a fast-growing and increasingly competitive alternative to fossil fuels [1]. Solar energy can be converted to electrical energy using different technologies such as photovoltaic (PV) panels or thermal power plants. Solar thermal power plants are based on thermodynamic cycles such as the Rankine cycle (RC) and the Brayton cycle, amongst others. Solar collectors deliver heat to these power cycles and can be divided into two categories, namely non-concentrating and concentrating collectors. Concentrating collectors have a small receiver aperture area relative to the concentrator aperture area, are usually used in applications with medium or high-temperature needs and have to track the sun in order to achieve proper concentration. Non-concentrating technologies can operate without tracking and can be used in low-temperature applications.

In general, power cycles can be categorised into gas/single-phase (such as Brayton) and vapour/two-phase (such as Rankine) cycles. In its simplest form, the RC consists of four basic components: a pump, an evaporator, a turbine and a condenser (see Fig. 1). The working fluid is circulated by using a pump (process 1-2), it absorbs heat at constant pressure in the evaporator (process 2-3), produces power by expansion in the turbine (process 3-4) and rejects heat at constant pressure in the condenser (process 4-1). This thermodynamic cycle can operate with various working fluids including water, organic fluids and CO_2. The working fluid has to change phase within a specific temperature range and therefore gases, such as air and nitrogen, are not used in the cycle.

The organic Rankine cycle (ORC) uses an organic working fluid. The organic fluids have lower critical temperatures than water and are therefore more suitable for low and medium-temperature heat sources such as solar systems. An important advantage of ORC systems is that they can be applied at smaller scales compared to water/steam RC systems. Besides solar energy, other renewable and sustainable energy sources can be coupled to ORC such as geothermal, biomass and industrial waste heat. Generally, the optimum temperature compatibility between these sources and organic fluids makes the use of ORC an ideal candidate for future sustainable energy systems [2].

The ORC is a developing technology mostly found in Europe, the USA, China, and Japan. There are over 25 companies that develop ORC projects with various capacities. The capacity is usually between 10 kW_{el} and 150 kW_{el} [3], while there have been cases of up to 240 MW_{el} [4]. The companies with the greater number of projects are ORMAT, Turboden, Exergy, General Electric and Turbine Air Systems [3]. The first ORCs were installed in the 1980s. In 2017, there were about 700 ORC projects worldwide with a cumulative capacity of 2.7 GW_{el}. An annual capacity increase of about 250 MW_{el} has been reported [3].

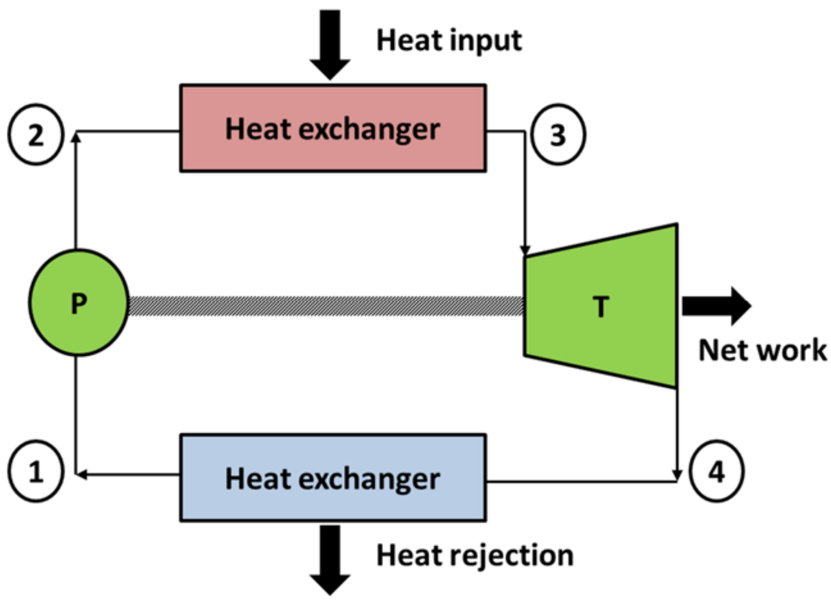
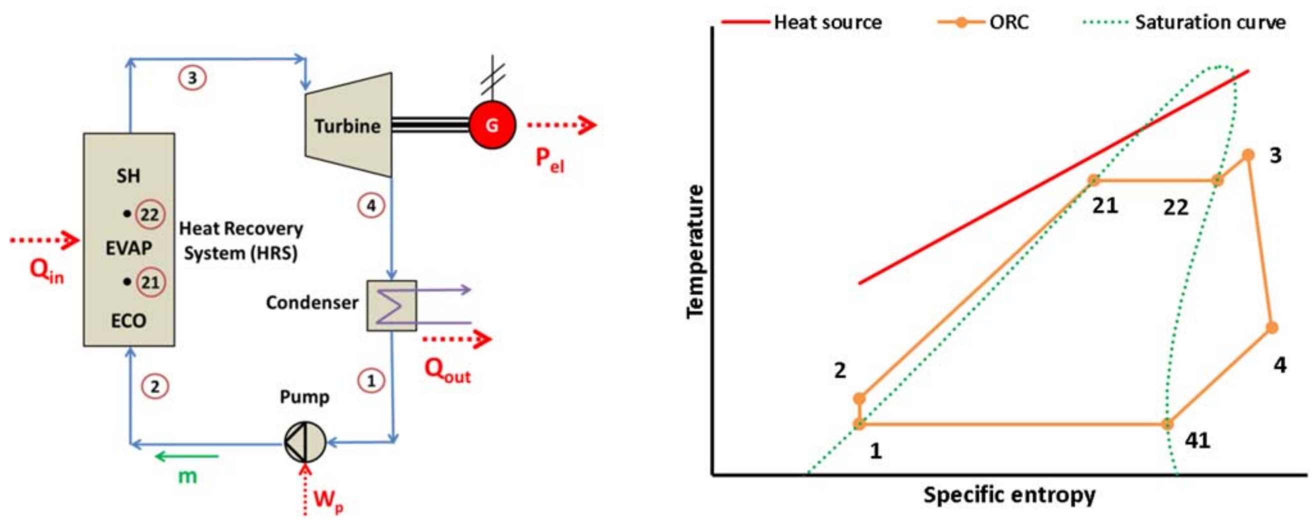


Figure 1. Basic RC power system layout with key components (T: turbine, P: pump).

1.1 Description of the basic ORC system

A basic ORC system is shown in Fig. 2a. The cycle includes a heat recovery system (HRS), a turbine, a condenser and a pump. The HRS is fed with heat input from an energy source to increase the enthalpy of the working fluid. The working fluid is a subcooled liquid at the HRS inlet (State 2) and it becomes a superheated vapour at the outlet of the HRS (State 3). Inside the HRS, there are three sections; the economiser, evaporator and superheater. In the economiser, the subcooled liquid changes into a saturated liquid (State 21). The evaporator is responsible for the latent heat exchange so that a saturated vapour can be produced (State 22), while the superheater produces a superheated vapour (State 3). In the ORC system, the superheating component is generally small and, in some cases, no superheating is performed. For dry refrigerants, superheating is not beneficial or only beneficial in small amounts (5 to 10 K), because of the positive slope of its *T*-*s* curve [5]. The superheated vapour (State 3) enters the turbine where it is expanded to low pressure (State 4). The condenser is responsible for heat rejection to the ambient so that a saturated liquid of low pressure (at State 1) can be produced. The saturated liquid enters the liquid pump where the pressure is increased with a small amount of work consumption (but not negligible), to complete the cycle. The complete thermodynamic process is illustrated in Fig. 2b.

The heat transfer in the HRS is described in Fig. 3. A critical parameter of the HRS design is the pinch point. This parameter refers to the minimum temperature difference between the heat source stream and the organic fluid in the HRS (usually between 5 K and 20 K [6, 7]). The possible pinch point locations in the HRS are given in Fig. 3, which shows the temperature-heat transfer rate (*T*-*Q*) diagram of the process. The three possible pinch point locations are the economiser inlet, the superheater outlet and in-between the economiser and the evaporator. For cases with a high heat source temperature, the pinch point is usually found at the economiser inlet, while for a very low heat source temperature, the pinch point is at the superheater outlet. It is most common for the pinch point to be between the economiser and the evaporator.



(a) **(b)**

Figure 2. a) Basic ORC system layout with key components. b) Temperature-specific entropy (*T*-*s*) diagram of an ORC system.

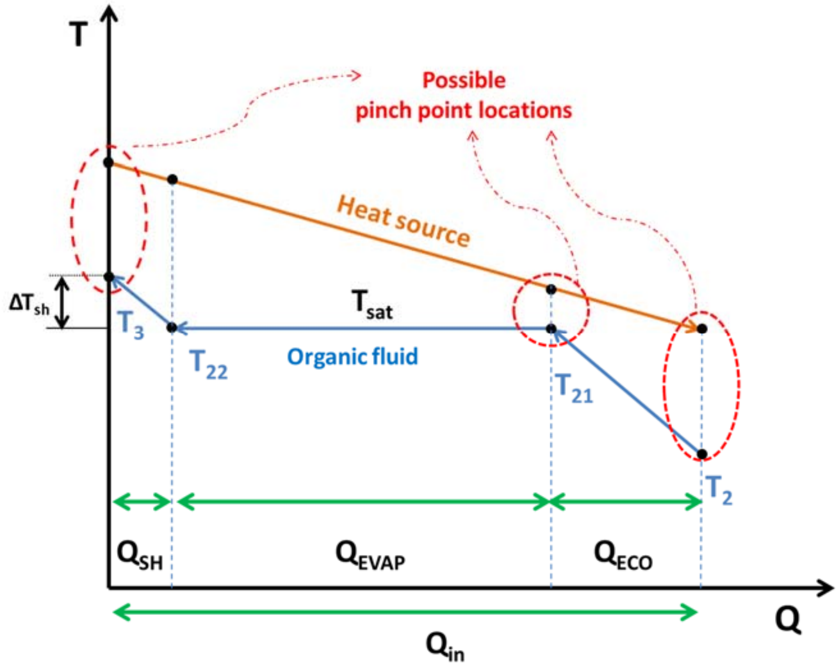


Figure 3. Temperature-heat transfer rate (*T*-*Q*) diagram of an HRS.

1.2 Working fluid selection

Various environmentally friendly, non-flammable and non-toxic organic fluids have been investigated to find high thermodynamic performance. Tchanche et al. [8] investigated the performance of a solar-ORC using low-temperature solar collectors together with the following environmentally friendly working fluids: RC318, R600a, R114, R600, R601, R113, Cyclohexane, R290, R407C, R32, R500, R152a, R717, Ethanol, Methanol, R718, R134a, R12, R123 and R141b. The results indicated that R134a is the most appropriate. Rayegan and Tao [9] developed a methodology for working fluid selection in solar-ORC systems with similar working conditions. They suggested a method to select ORC working fluids based on different parameters such as their molecular components, temperature-entropy diagram and effects on the thermal efficiency, net power generated, vapour expansion ratio, and exergy efficiency of the ORC systems. Their results suggested eleven working fluids for application in low to medium temperature solar-ORC systems. Prasad et al. [10] investigated a solar-ORC system with different multicomponent zeotropic mixtures in an effort to reduce cost while maintaining high thermal efficiency. They presented a method to select appropriate working fluid mixtures that can reduce the volume of the expander while maintaining the highest performance. Desai et al. [11] presented a thermo-economic analysis of a solar-ORC system for power generation. Linear solar concentrators were used to deliver heat to the ORC system which was investigated using different working fluids. Li et al. [12] also investigated different working fluids. Direct vapour generation was used in the proposed system for power generation. Freeman et al. [13] investigated a hybrid system for heating and power generation using solar-ORC. As a case study, the performance of the system was optimised for the UK using different ORC working fluids. They reported an efficiency improvement of over 50% with an optimised system using a suitable ORC working fluid. Zheng et al. [14] considered a solar-ORC system as an energy source in refrigeration. The performance of the solar-ORC system was investigated using eight pure fluids and five zeotropic mixtures with various compositions as the ORC working fluid. Using a mixture of R161/R600a, the performance of the system was improved by 39.6% and 54.7%, when compared to using pure R600a and R161, respectively. Furthermore, Györke et al. [15] presented a new classification based on characteristic points of organic fluids used as ORC working fluids.

To conclude, there is a great deal of literature on ORC working fluid selection. Apart from thermodynamic characteristics and fluid thermal properties, which have an important effect on efficiency, there are also additional factors that affect fluid selection. Environmental criteria such as global warming potential, ozone depletion potential, as well as toxicity and flammability have to be considered. Moreover, chemical stability of the working fluid should be considered, since it limits the maximum heat source temperature [16]. In the literature, there are several studies on stability. For example, Ginosar et al. [17] found that cyclopentane is a safe working fluid without stability issues. Other researchers have emphasised the need for studying the stability of siloxanes. Preißinger and Brüggemann [18] concluded that the working fluid, MM, which belongs to the siloxanes, is stable at temperatures of up to 300°C. ORC working fluid selection should therefore be a trade-off between energy efficiency, environmental criteria and safety aspects.

1.3 Heat sources

ORC systems are usually driven by heat sources at low or medium temperatures. Different types of energy sources can be used to deliver heat to an ORC system including waste heat, geothermal, solar, biomass, biodiesel, and biogas. Solar energy is converted to thermal energy using solar collectors. A solar collector can be considered as a heat exchanger for converting solar energy to thermal energy of the working fluid. Generally, there are two kinds of solar-ORC systems: direct and indirect. With the indirect solar-ORC system, solar energy is absorbed by a solar working fluid that circulates in the solar collector. The absorbed heat is then transferred to the organic fluid in a heat exchanger. With the direct solar-ORC system, the organic fluid circulates in the solar collector to absorb solar energy directly.

1.4 Modelling

The heat transfer rate in the HRS (Q_{in}) can be calculated from an energy balance on the working fluid control volume, where m refers to the mass flow rate and (h) refers to enthalpy:

$$Q_{\text{in}} = m \cdot (h_3 - h_2) \tag{1}$$

The power generation in the turbine (W_{T}) is calculated as:

$$W_{\text{T}} = m \cdot (h_3 - h_4) \tag{2}$$

The electricity production by the shaft (P_{el}) is calculated as:

$$P_{\text{el}} = \eta_{\text{mg}} \cdot W_{\text{T}} \tag{3}$$

Usually, the turbine process is modelled using an isentropic efficiency ($\eta_{\text{is,T}}$) as shown below:

$$\eta_{\text{is,T}} = \frac{h_3 - h_4}{h_3 - h_{4,\text{is}}} \tag{4}$$

The heat rejection rate from the condenser to the ambient (Q_{out}) is calculated as:

$$Q_{\text{out}} = m \cdot (h_4 - h_1) \tag{5}$$

The power consumption in the pump (W_p) is calculated as:

$$W_p = \frac{m \cdot (h_2 - h_1)}{\eta_{motor}} \quad (6)$$

The net electricity production of the ORC ($P_{el,net}$) is calculated as:

$$P_{\text{el,net}} = P_{\text{el}} - W_{\text{p}} \quad (7)$$

The thermal efficiency of the ORC (η_{orc}) is calculated as:

$$\eta_{\text{orc}} = \frac{P_{\text{el,net}}}{Q_{\text{in}}} \quad (8)$$

It should be noted that the heat input in the ORC (Q_{in}) is not equal to the total heat source input in the system (Q_{hs}). The heat source input is higher than the heat input in the ORC unit because of the inevitable thermal losses in the intermediate devices ($Q_{hs} > Q_{in}$). The conversion efficiency of the heat source (η_{th}) can be written as shown below:

$$\eta_{\text{th}} = \frac{Q_{\text{in}}}{Q_{\text{hs}}} \quad (9)$$

The total system efficiency (η_{sys}) is therefore given as:

$$\eta_{\text{sys}} = \frac{P_{\text{el,net}}}{Q_{\text{hs}}} = \eta_{\text{th}} \cdot \eta_{\text{orc}} \quad (10)$$

The conversion efficiency of the heat source is variable and dependent on the type of heat source. For a boiler system with biomass, for example, the conversion efficiency can be up to 94% [19]. In the case of a solar system, the conversion efficiency depends on operating parameters (fluid temperature, solar irradiation level, solar angle, etc.) and can be up to 75% [20]. In the case of waste heat recovery (WHR), the conversion efficiency can be written in terms of the ambient temperature (T_{am}) as:

$$\eta_{\text{th}}(WHR) = \frac{T_{\text{hs,out}} - T_{\text{hs,in}}}{T_{\text{hs,out}} - T_{\text{am}}} \quad (11)$$

Another critical parameter for the proper characterisation of the ORC unit is exergy efficiency. The exergy efficiency practically evaluates the quality of the heat source. The exergy efficiency of the system can be generally written as shown below:

$$\eta_{\text{ex,sys}} = \frac{P_{\text{el,net}}}{Q_{\text{hs}} \cdot \psi_{\text{hs}}} \quad (12)$$

The exergy factor of the heat source (ψ_{hs}) depends on the type of energy source. The exergy factor of fossil fuels depends on its composition and generally, it has values of close to 1. For a gas flow stream, it has the following expression:

$$\psi_{\text{hs}} = 1 - \frac{T_{\text{am}}}{T_{\text{hs}}} \quad (13)$$

For solar irradiation, there are various correlations that can be used in order to take into consideration that the sun is a radiation reservoir and not a heat reservoir. The equation that has been suggested by Petela is commonly used in the literature [21]:

$$\psi_{\mathrm{hs}} = 1 - \frac{4}{3} \cdot \frac{T_{\mathrm{am}}}{T_{\mathrm{sun}}} + \frac{1}{3} \cdot \left(\frac{T_{\mathrm{am}}}{T_{\mathrm{sun}}}\right)^4 \tag{14}$$

The sun's temperature (T_{sun}) is usually chosen to be close to 5800 K. Note that for all exergy factors the temperature unit is Kelvin.

1.5 Objectives and motivation of this work

Solar energy is a sustainable energy source and ORC is a proper candidate to be combined with solar energy systems. The reason for this compatibility between solar systems and ORC is based on the operating temperatures of up to 400ºC or 500ºC, at which ORC operates optimally. Thus, solar-energy-driven ORC is an attractive technology for developing sustainable future energy systems. The objective of this review paper is to summarise and discuss research that has been done on solar-ORCs. The review paper considers various solar collectors, but with more emphasis on indirect systems. Moreover, hybrid systems with solar and geothermal energy are included in this work because they often appear in literature and have promising performance results.

2 Solar collector options

An ORC engine can be coupled with various solar collectors because the power cycle can operate in a large range of heat source temperatures from 80°C to 500°C. The cycle can, therefore, be coupled with flat solar technologies or concentrating solar technologies. In the following sections, the most common solar technologies that can be used in ORC systems are briefly presented. Barber [22] technically and economically investigated the solar-ORC system as an efficient technology for power generation using three categories: flat-plate collectors, solar concentrators, and tracking solar concentrators. Fig. 4 illustrates the possible solar technologies for utilisation in ORC systems. Furthermore, Table 1 includes the main characteristics of solar collectors [23-25].

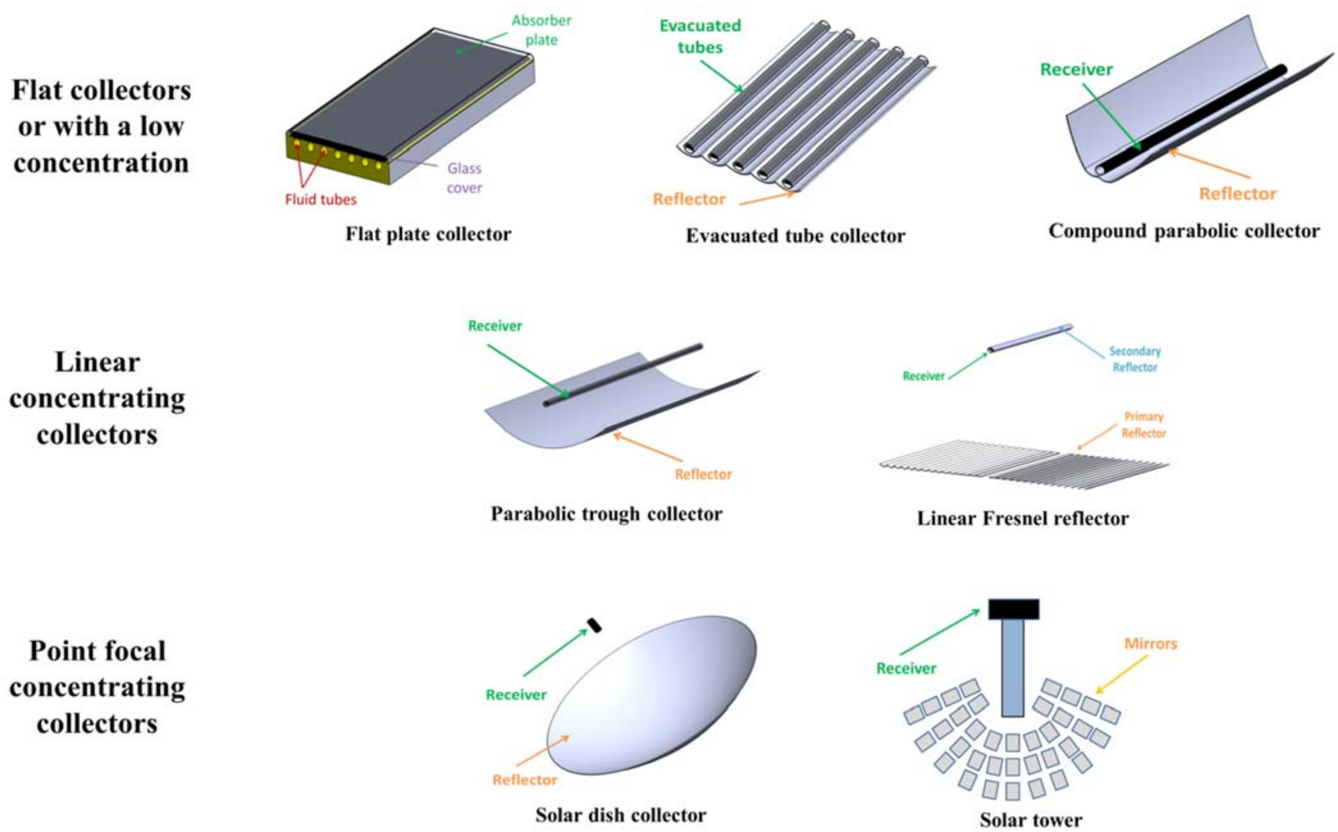


Figure 4. Solar thermal collector type separated into flat technologies, linear concentrating technologies and point focal concentrating technologies.

Table 1. Overview of solar collector options and their basic characteristics [23-25].

Collector type	Concentration ratio	Tracking	Temperature range	Solar irradiation utilisation	
				Beam	Diffuse
FPC	1	NO	<100°C	YES	YES
ETC	1-1.2	NO	<200°C	YES	YES
CPC	1.1-5	YES/NO	<200°C	YES	Partially
LFR	10-40	YES	<400°C	YES	NO
PTC	10-50	YES	<500°C	YES	NO
SDC	50-500	YES	<600°C	YES	NO
ST	500-1200	YES	<1000°C	YES	NO

Each collector type has a specific operating temperature range which dictates the organic fluid temperature range in the ORC. Consequently, there is a need for selecting the appropriate organic fluid with each solar technology in order to have optimum temperature compatibility.

a) Flat-plate collector (FPC): The FPC is a non-concentrating technology that operates at temperatures of up to 100°C. The FPC is the most common solar system for low-temperature applications. For operation at temperatures of close to 100°C, an optimal design is required using selective absorbers and proper insulation at the back and side surfaces. An FPC consists of an absorber plate with water tubes (risers) located in an insulated box with a glass cover as the top surface. The FPC does not require tracking and usually, its inclination is chosen for optimal seasonal or annual operation [26]. Lastly, an FPC utilises both diffuse and beam solar irradiation.

b) Evacuated tube collector (ETC): ETC consists of many evacuated tubes connected to a manifold. Usually, up to 10-12 evacuated tubes are used in the collector module. The collector can be used in low and medium-temperature applications of up to 200ºC. A booster reflector can be positioned behind the evacuated tubes in order to reduce the optical losses due to the space between the tubes. The design can therefore usually have a low concentration ratio of up to 1.2. An ETC is typically also a non-tracking collector with an inclination chosen for optimum seasonal exploitation of the solar resource. Both the beam and the diffuse solar irradiation resources are utilised.

c) Compound parabolic collector (CPC): CPC is a non-imaging solar concentrating technology [27] for low and medium temperature applications of up to 200°C. It consists of an evacuated tube and a parabolic-shaped reflector. The reflector can consist of three parts: two parabolic shapes and a connection between them. The CPC primarily exploits solar beam irradiation but it also captures partial diffuse solar irradiation. The concentration ratio of this collector can be up to 5 with typical values of around 3 [28].

d) Parabolic trough collector (PTC): PTC is the most mature solar concentrating technology and is used in the majority of operating power plants [29]. It consists of an evacuated tube and a parabolic-shaped linear trough reflector. It has a concentration ratio in the range of 10 to 50 and can, therefore, be classified as an imaging solar concentrating technology that only utilises the direct beam solar irradiation. It can operate at temperatures of up to 500ºC and usually, the working fluids are thermal oils, molten salts, or water/steam at high pressure. This collector relies on a one-axis tracking system in order to follow the sun's path during operation.

e) Linear Fresnel reflector (LFR): LFR is a linear concentrating technology similar to the PTC but it has segmented primary mirrors. The primary mirrors are located close to the ground in order to reduce mechanical difficulties and wind loads [30, 31]. This collector utilises solar beam irradiation and requires a single-axis tracking system. Generally, the receiver can be an evacuated tube with a secondary reflector; however, trapezoidal cavity designs also exist. The receiver is located about 3-4 m above the ground and does not move [32]. The LFR has a lower cost than the PTC but it also has lower efficiency due to higher optical losses. The concentration ratio of this technology is usually in the range of 10 to 40, while it can operate at temperatures of up to 400ºC.

f) Solar dish collector (SDC): SDC consists of a solar dish concentrator with a thermal receiver that produces heat at medium and high temperatures. Usually, cavity receivers are used and the concentration ratio is over 100 [33]. The cavity can be cylindrical, conical, spherical, or rectangular [34]. The SDC only utilises solar beam irradiation and requires a two-axis tracking system to create a focal point. Applications with Stirling engines are common.

g) Solar tower (ST): STs (or central receivers) are usually large solar systems consisting of numerous heliostats and a tower with a receiver mounted at its top. These systems are only used for high-temperature applications and generally for power generation. The technology can be regarded as cost-effective since new solar power plants are usually based on it. The ST only utilises solar beam irradiation, using a two-axis tracking system on every heliostat mirror, and can operate at temperatures of up to 1000ºC.

3 Solar-ORC systems

Solar energy is a flexible energy source that can be converted into heat at various temperatures, depending on the technology [35]. In the literature, there are many studies about solar-ORCs with non-concentrating technologies [36, 37], while there is also a great deal of work on concentrating technologies [38-40]. The use of concentrating collectors corresponds to higher temperature ranges and higher thermodynamic efficiencies in the ORC; however, this also presents difficulties such as tracking the sun and storing the heat efficiently. In this section, all the studies found in the literature are presented and discussed in detail.

3.1 Flat-plate collectors (FPCs)

A review of literature available on FPC-ORC technology is presented in this section. These studies consider low-temperature systems that present relatively low efficiencies but with the advantage of mature technology, low investment cost and low complexity. In 1983, Eldighidy and Taha [41] performed a study on the optimisation of the FPC by testing different tube diameters and working fluids such as R11, R21 and R113. They found that higher flow rates enhanced the system's performance and that the overall system efficiency was 6%. Marion et al. [42] investigated single and double glazing FPC as well as different organic fluids (R134a, R227ea, and R365mfc) in the ORC. By optimising their system they found a maximum efficiency of 11%. The use of a solar-ORC in a regenerative cycle was examined by Wang et al. [43]. The configuration included a storage system (see Fig. 5). It was concluded that R123 was the best fluid with a system efficiency of 7.8%. The impact of wind speed on an FPC-ORC was investigated by Marion et al. [44]. They found that a wind speed increase from 0 m/s to 10 m/s reduced the collector's thermal efficiency from 48% to 34% and consequently reduced the system efficiency from 6.9% to 3.1%. In a financial analysis, Hajabdollahi et al. [45] found that isobutene was the best choice for the regenerative solar-ORC system. In another work, Kutlu et al. [46] performed an off-design investigation of a solar-ORC with evacuated FPC. The evacuated FPC can achieve operation at higher temperatures compared to conventional FPCs. It was concluded that the system could be controlled with the mass flow rate to produce up to 5.7 kW of electricity. The combination of a solar-ORC system and a heat pump for power generation was investigated by Schimpf and Span [47, 48]. It was found that the system had economic benefit and isobutene was suggested as a more efficient choice than R134a.

An interesting idea in the literature is the use of mixtures as ORC working fluids in order to optimise heat transfer and to reduce exergy destruction. Mavrou et al. [49] found that a mixture of neopentane and 2-fluoromethoxy-2-methylpropane at 70% neopentane was the most appropriate choice for an ORC with a system efficiency of 4.9%. Habka and Ajib [50] conducted a comparative study between pure fluids and mixtures. They concluded that the R409A mixture was a better candidate than the pure fluids, R134a and R245fa. In another working fluid investigation by Helvaci and Khan [51], 1-butene was found to be the best organic working fluid for the solar-ORC.

The use of a phase-change material (PCM) for storage purposes in a solar-ORC was investigated by Freeman et al. [52]. They found a 20% daily efficiency enhancement by using the PCM thermal energy storage (TES). Alvi et al. [53] compared the direct and indirect solar-ORC systems for power generation. PCM was used as the TES and R245fa as the ORC working fluid. It was found that the direct solar-ORC system showed better performance.

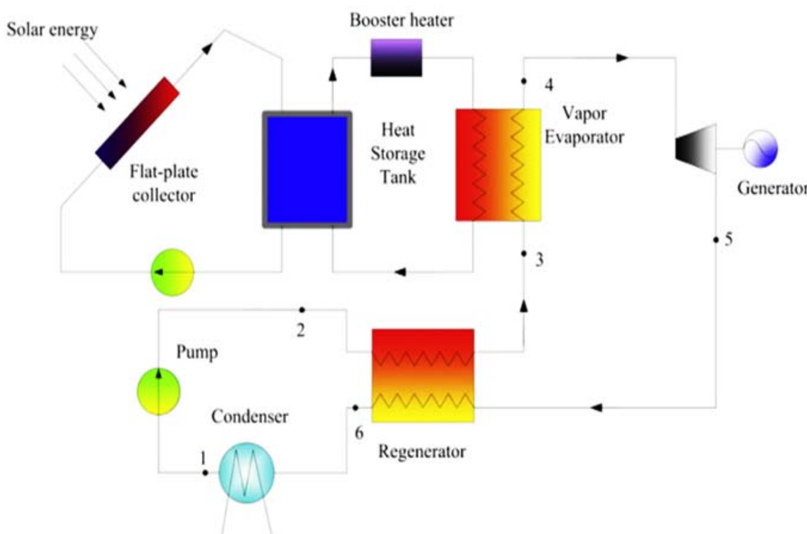


Figure 5. FPC-ORC regenerative system with storage tank and booster heater [43].

Another idea in the literature is the investigation of cogeneration, trigeneration and polygeneration. Extra devices are included in these configurations such as absorption chillers, mechanical compression cycles, heat exchangers and electrolysers. Boyaghchi et al. [54] investigated a combined cooling, heating and power (CCHP) system (see Fig. 6) with CuO/water nanofluid as the working fluid in the solar collector. They concluded that the R134a can be recommended as the best ORC working fluid with energy and exergy efficiencies of 39.8% and 3.1% respectively. Calise et al. [55] found that an evacuated FPC in a cogeneration system (electricity and heat) leads to a payback period of 5 years. In another work, Wang et al. [56] optimised a trigeneration system for heating, cooling and electricity. They found daily energy and exergy efficiencies of 13.6% and 9.2% respectively. Erden et al. [57] investigated a solar-ORC system for hydrogen production and power generation. FPCs and solar ponds were used as the heat source (see Fig. 7). It was found that hydrogen production increased when the thermal performance of the solar system increased. Khanmohammadi et al. [58] performed an optimisation study of a cogeneration system for power and hydrogen production. An exergy efficiency enhancement of up to 3.2% was found. Ramos et al. [59] optimised different subsystems of a solar-ORC system for combined heat and power generation (CHP). Different solar collectors were investigated including FPC and ETC. The simulations were performed with the TRNSYS software. It was found that the ORC system with ETC showed the highest performance but it also presents higher investment cost. Moreover, R245fa and R1233zd organic fluids were found to be the best choices. Vittorini et al. [60] studied a CHP micro-cogeneration system. They used water/glycol mixture with temperatures of up to 110ºC. Wang and Chen [61] examined a system with a solar-driven modified ORC, which includes an ejector, and that can also produce refrigeration. They found system performance enhancement (efficiency of 21%). A trigeneration system driven by FPC was optimised by Boyaghchi and Chavoshi [62]. Nanofluid-based FPC and R1234yf-R245fa in the ORC were investigated. According to their results, the energy efficiency enhancement was 17% and the exergy efficiency enhancement 24%. Lastly, Rashidi and Khorshidi [63] optimised a polygeneration system that included an ORC, absorption chiller and reverse osmosis (RO) device. The best-compromised solution was found at an exergy efficiency of 53%.

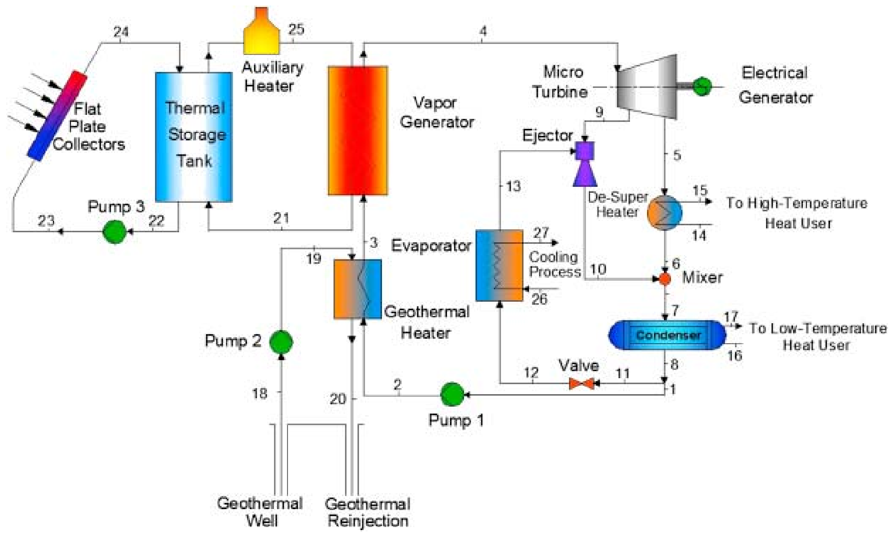


Figure 6. Solar-geothermal ORC for trigeneration [54].

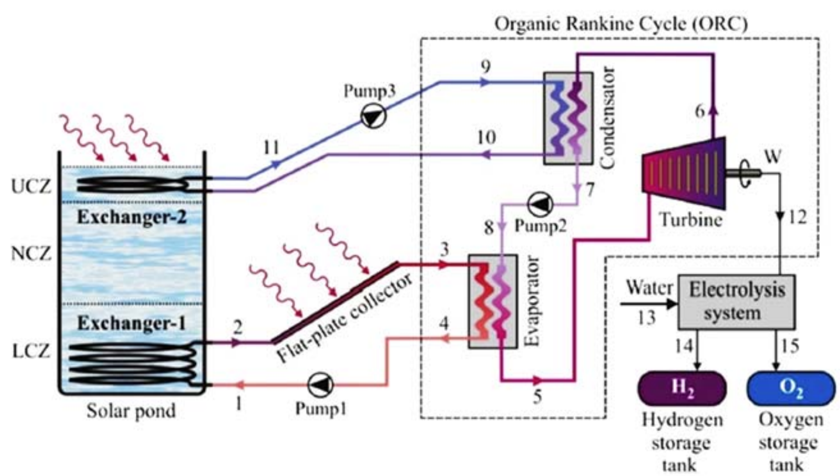


Figure 7. Solar-ORC driven by FPC and a solar pond [57].

A summary of solar-ORC systems using FPCs is presented in Table 2. To conclude, a number of articles investigating FPCs as the heat source of an ORC were considered. Some of the articles studied a simple system and investigated its productivity as a function of certain parameters. The energy efficiency of a simple system appears to be 8% to 10% at most. Other studies made an effort to increase the productivity of systems by adding storage tanks; in this case, the capital cost increased by up to 30%. Moreover, polygeneration coupled with FPCs that can generate electricity, heating and cooling increased the overall efficiency by up to 40% or more. A large proportion of studies employed multi-objective optimisation tools to find the optimum points at which the system would yield maximum exergy efficiency and minimum cost. Regarding the working fluid, there are several papers focusing on working fluids and their mixtures to obtain the best performance and minimum detrimental effects on the environment. Throughout the reviewed studies, only a few authors focused their attention on the collector and illustrated the impacts of its characteristics on the overall performance. More importantly, the effect of using FPC-ORCs on the reduction of carbon emissions has been completely ignored; regarding some global warming policies, this could have had a considerable effect on the final cost of each system.

Table 2. Summary of ORC systems employing FPCs.

Authors	Brief title	Highlights	Ref.
Eldighidy and Taha (1983)	FPC coupled with a storage tank and ORC.	Optimisation of the flow rate and the diameter in the collector. Maximum system efficiency of 6%.	[41]
Marion et al. (2012)	Optimisation of an ORC system.	Maximum system efficiency of 11%.	[42]
Wang et al. (2013)	Thermodynamic analysis of a solar-ORC.	R123 at the higher turbine inlet temperature with saturated vapour state yielded the highest daily efficiency of 7.8%.	[43]
Marion et al. (2014)	Wind effect on the performance of a solar-ORC.	System efficiency reduced from 6.9% to 3.1% with an increase in wind speed from 0 m/s to 10 m/s.	[44]
Hajabdollahi et al. (2015)	Thermo-economic optimisation of regenerative solar-ORC.	Isobutane was found to be the best working fluid.	[45]
Kutlu et al. (2018)	Off-design performance modelling of a solar-ORC.	The power output ranged from 4.3 to 5.7 kW in the daytime and could be controlled by changing the mass flow rate.	[46]
Schimpf and Span (2015)	Evaluation of a combined heat pump-ORC system.	Savings of up to 500 € for a single-family house.	[48]
Mavrou et al. (2015)	Working fluid mixtures for the solar-ORC.	The neopentane and 2-fluoromethoxy-2-methylpropane mixture (70% neopentane) delivered maximum power and efficiency of 1.07 kW and 4.9% respectively.	[49]
Habka and Ajib (2016)	Performance estimation of mixtures in a solar-ORC.	The mixtures R401A, R401B and R409A performed better than the pure fluids.	[50]
Helvaci and Khan (2017)	Analysis of a solar-ORC employing thermofluids.	Working fluids were analysed from an environmental and thermo-fluidic point of view: 1-butene was the best choice.	[51]
Freeman et al. (2017)	Solar-ORC combined with TES.	20% higher total daily electrical output could be achieved with a PCM while the capital cost increased by 30%.	[52]
Alvi et al. (2017)	Dynamic simulation of direct and indirect solar-ORC.	The efficiency of direct solar-ORC was higher.	[53]
Boyaghchi et al. (2015)	CCHP driven by geothermal and solar energy.	The maximum daily thermal and exergy efficiencies were 39.9% and 3.1% respectively.	[54]
Calise et al. (2015)	Simulation of solar CHP based on evacuated flat-plate.	The simple payback period can be about 5 years.	[55]
Wang et al. (2015)	Multi-objective optimisation of a trigeneration system.	Daily energy and exergy efficiencies of 13.6% and 9.2% respectively.	[56]
Erden et al. (2016)	Hydrogen production using FPC.	Using a solar pond for preheating led to higher hydrogen production rates.	[57]
Khanmohammadi et al. (2017)	Optimisation of a solar-ORC for hydrogen production.	Exergy efficiency enhancement of up to 3.2%.	[58]
Ramos et al. (2018)	Solar-ORC in the built environment.	Although the ETC generated more power than the FPC array, its total investment cost was 1.73 times higher.	[59]
Vittorini et al. (2018)	Analysis of a micro-cogeneration system.	Operation with water/glycol mixture at up to 110^{o}C.	[60]
Wang and Chen (2018)	ORC combined power system and ejector refrigeration.	System performance increased to efficiency of 21%.	[61]
Boyaghchi and Chavoshi (2018)	Monthly optimisation and assessment of a micro-CCHP.	Maximum energy and exergy efficiency enhancements were 17% and 24% respectively.	[62]
Rashidi and Khorshidi (2018)	Optimisation analysis of a polygeneration system.	The best compromised solution was found at an exergy efficiency of 53%.	[63]

3.2 Evacuated-tube solar collectors (ETCs)

The ETC is usually a stationary collector used in low and medium-temperature applications. The advantage of this technology compared to FPC is the possibility of operating above 100ºC; however, ETC has increased investment cost. In the literature, the combination of ETC with ORC has been investigated for power generation as well as for other useful outputs.

Firstly, the works on ETC-ORC for power generation are discussed. Scardigno et al. [64] optimised a hybrid ORC system driven by solar and low-grade energy sources. The system was optimised based on achieving the highest energy and exergy performance with the lowest levelised energy cost. The lowest levelised energy cost was found at 0.114 \$/kWh with the highest energy efficiency of 9.7% using cyclopropane as the ORC working fluid. Lv et al. [65] numerically and experimentally investigated a hybrid system for heating and power generation using an ETC. In another experimental work, He et al. [66] tested an ETC-ORC (see Fig. 8) which presented a maximum exergy efficiency of 36.3%.

Figure 8. Experimental setup of an ETC-ORC [66].

The following literature involves power and fresh water production using ETC-ORC. Manolakos et al. [67] developed a solar-ORC system coupled with a desalination system. An RO unit was used for producing fresh water using power generated from the ORC system. The ORC unit's condenser was used as a preheating system for the desalination process. The maximum system efficiency was 7% and the operating temperatures were in the range of 70-80ºC. Manolakos et al. [68-70] experimentally studied a solar desalination system with ETC-ORC technology for power generation. The efficiency of the expander was calculated as 14.7% and 28.5% for cloudy and sunny weather conditions respectively. Manolakos et al. [71] compared two suggested RO systems based on PV panels and solar-ORC systems under technical and economic aspects. The cost of desalination was calculated as 7.77 €/m^3 with PV and 12.5 €/m^3 with ETC-ORCs. The overall ETC-ORC system efficiency was calculated at 5%. Kosmadakis et al. [72-74] developed a solar desalination system that was coupled with an ORC system for power generation. The cost of the generated power was found to be 2.74 €/kWh using ETCs. Karellas et al. [75] investigated a hybrid solar desalination system including ORC and PV systems for producing fresh water and power. More specifically, it was found that the hybrid system could produce potable water at a cost of 6.52 €/m^3 when subsidised with 40% of the investment capital. In another dynamic analysis, Twomey et al. [76] studied the behaviour of an ETC-ORC with a scroll expander (with maximum isentropic efficiency of 59%). System efficiency of 3.5% was calculated.

Studies about ETC-ORC for cooling are also found in the literature. Wu et al. [77] economically considered an ETC-ORC for cooling purposes. They estimated the cost of an optimised cooling unit at 0.24 € per kW of cooling power. Moreover, Ahmadzadeh et al. [78] economically and exergetically investigated a system that included power generation and an ejector refrigeration system. The optimised system obtained 19% energy efficiency while the initial system was at 15%.

The last part of this section considers the literature on ETC-ORCs for the production of various useful outputs by the utilisation of extra energy devices. A polygeneration system for heating, cooling and electricity was studied by Boyaghchi and Heidarnejad [79]. The energy and exergy efficiencies were found to be 23.66% and 9.51% in summer and 48.45% and 13.76% in winter. Atiz et al. [80] investigated an ORC-hydrogen production system and reported energy and exergy efficiencies of 5.9% and 18.2% respectively for the overall system. In another investigation, Wu et al. [81] studied three different power generation systems economically and environmentally. The investigated systems were CCHP-ORC, solar-ORC, and biomass-ORC. The solar-ORC system showed the best economic performance.

A summary of ETC-ORC systems is reported in Table 3. To conclude, ETC is a low and medium temperature heat source for the ORC, with an exergy efficiency of around 20% for a conventional system. Numerous studies have been conducted in order to enhance the system performance by changing the pressure and the temperature of the ORC's components. For instance, by increasing the generator pressure of a novel solar-driven combined power and ejector refrigeration system to 1540 kPa, the exergy efficiency increased to 58.9%. Furthermore, some solar-ORC systems can also contribute to generating either fresh water, with an efficiency of approximately 7%, or hydrogen. From the review above, it was found that the effect of different ORC working fluids has not been comprehensively investigated, even though it plays an indisputable role in the exergy and energy efficiency of the system. The possibility of using nanofluids in ETCs has also not been considered. For future study, it is recommended that the collector structure can be used to determine the best operating point of the solar-ORC system. From an economic point of view, far deeper hands-on research is needed to show the exact financial profits of the system in order to draw the attention of investors and governments, and in turn, future studies should focus on systems with higher capacity.

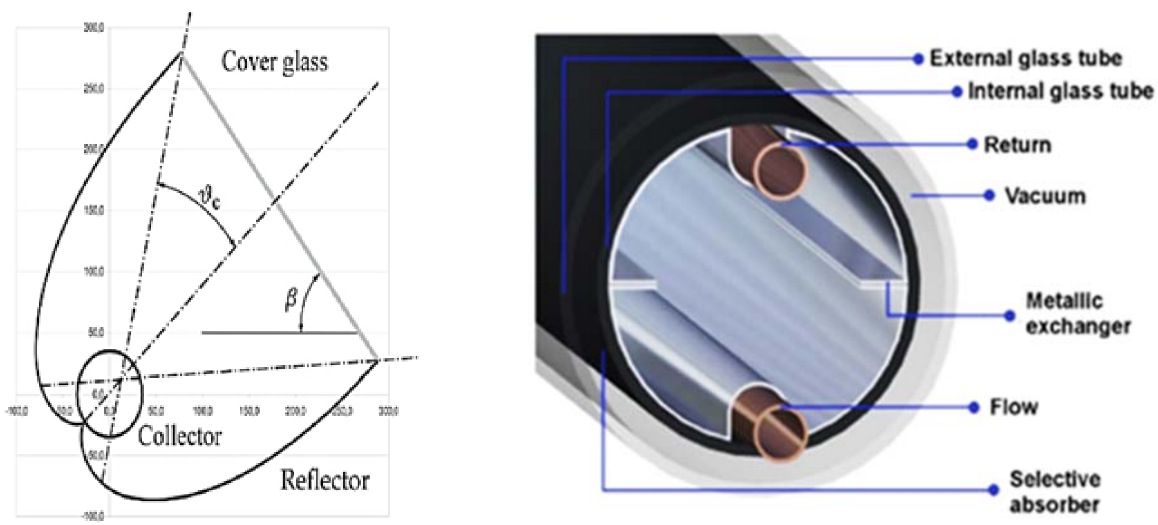
Table 3. Summary of ORC systems employing ETCs.

Authors	Brief title	Highlights	Ref.
Scardigno et al. (2015)	Genetic optimisation of a hybrid solar-ORC.	The design parameters such as the working fluid were optimised to reach the highest first and second law efficiencies and the lowest levelised energy cost.	[64]
Lv et al. (2017)	High-performance solar thermoelectric system.	Enhancement of thermal and electrical efficiency by double-layer glass vacuum tube and flat-plate structure of the heat pipe.	[65]
He et al. (2017)	Low-temperature ORC operating at off-design conditions.	The maximum exergy efficiency was 36.3%.	[66]
Manolakos et al. (2005)	Solar-ORC for RO desalination.	ORC coupled with an RO unit at temperatures in the range of 70-80°C was investigated; the overall efficiency was 7%.	[67]
Manolakos et al. (2009)	Performance of small-scale RO-ORC.	A low-temperature ORC engine integrated with an RO unit was studied experimentally; the overall efficiency was 5%.	[71]
Manolakos et al. (2008)	Economic comparison between PV-RO system and solar-ORC-RO.	The cost of desalination using the solar-ORC-RO system is 1.67 times higher than for the PV-RO system.	[72]
Kosmadakis et al. (2010)	Theoretical study of a two-stage solar-ORC.	The effect of the collectors' slope and the total number of evacuated tube collectors were evaluated economically.	[74]
Karellas et al. (2011)	Hybrid solar-ORC-PV-RO desalination.	The hybrid system could produce potable water with a cost of 6.52 €/m^3 when subsidised with 40% of the investment capital.	[75]
Twomey et al. (2013)	Small-scale solar-ORC using a scroll expander.	The system efficiency was 3.5% and the maximum isentropic efficiency of the scroll expander was 59%.	[76]
Wu et al. (2017)	Optimisation of an ORC cooling system.	The cost of cooling was 0.24 € per kWh of cooling.	[77]
Ahmadzadeh et al. (2017)	Solar-driven combined power and ejector refrigeration.	Optimised system's energy efficiency was close to 19%.	[78]
Boyaghchi and Heidarnejad (2015)	Solar-driven trigeneration system.	The energy and exergy efficiencies were 23.66% and 9.51% respectively in summer; 48.45% and 13.76% in winter.	[79]
Atiz et al. (2018)	Assessment of ETCs.	The energy and exergy efficiencies were reported as 5.9% and 18.2% respectively, while the H_2 production was at 3.2 kg/day.	[80]
Wu et al. (2018)	Design of an ORC-coupled trigeneration system.	The solar-ORC and biomass-ORC performed better both financially and environmentally compared to separate systems.	[81]

3.3 Compound parabolic collectors (CPCs)

The use of CPC-ORC is another alternative that has been studied extensively in the literature. The concentrator increases the solar irradiation on the receiver resulting in better performance. The CPC can operate with or without tracking. It mainly utilises solar beam irradiation but also captures part of the diffuse solar irradiation. Generally, CPCs are more efficient than ETCs but they are more complex. Jing et al. [82] numerically optimised a CPC-ORC. The CPC had a concentration ratio of around 3, the operating temperature levels were around 120°C and the system performance was around 7.5%. They investigated the use of an alternative design with a two-stage heat exchanger that could enhance the system performance by up to 20%. Pei et al. [83] presented a new design of a regenerative ORC system using a CPC. The system included two solar loops and PCM storage. It was concluded that the system efficiency was 8.6% with regeneration and 4.9% without regeneration. Wang et al. [84] presented an off-design model of a CPC-ORC which was evaluated on a yearly basis and its efficiency was ranged between 4% and 7%. In another study, Antonelli et al. [85] designed a CPC-ORC for power generation. In Fig. 9a, the cross-section of the collector is shown with the orientation and the collector slope depicted, while in Fig. 9b the internal design of the U-tube receiver is shown. It was concluded that a design with a concentration ratio in the range of 1.1 to 1.4 would lead to a yearly operation of up to 3500 h in Italy. Moreover, Antonelli et al. [86] simulated a CPC-ORC dynamically. They found that a concentration ratio of 1.25 led to an ORC efficiency of 8.2% and a system efficiency of 3.4%, while a concentration of 2 led to an ORC efficiency of 10.9% and system efficiency of 5.6%. Tiwari et al. [87] suggested a novel solar-ORC system for power generation which incorporated an asymmetrical CPC. The CPC design had a complex reflector and a glazed reverse absorber (see Fig. 10) which led to a system efficiency of close to 8%.

In a comparative work, Sonsaree et al. [88] compared the use of CPC in an ORC with the use of FPC and ETC. They concluded that CPC led to the lowest LCOE of around 0.21 $/kWh, while FPC led to the highest LCOE. Li and Li [89] thermally and economically optimised a solar-ORC system based on a typical solar radiation year. They used a multi-objective genetic algorithm for optimisation. They found that the profit growth rate would increase with an increasing system scale. Lastly, Garg and Orosz [90] thermo-economically studied an ORC system with different heat sources such as solar and waste heat. The scroll expander design was emphasised and maximum isentropic efficiency of around 65% was found.



(a) **(b)**

Figure 9. (a) Schematic of a CPC section with *C* = 1.5 (b) representation of an evacuated-tube collector with U-pipe [85].

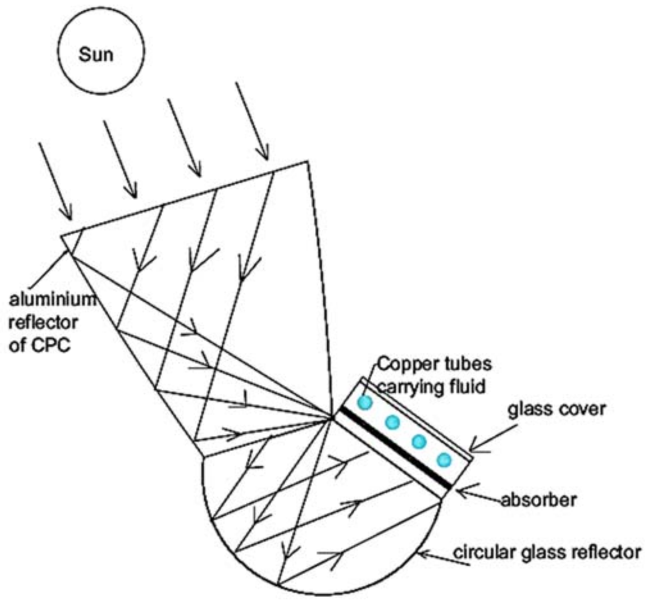


Figure 10. Schematic of the solar system in Ref. [87].

The last part of this section considers studies on CPC-ORC for trigeneration or polygeneration. Bocci et al. [91] investigated a polygeneration system with the CPC area of 50 m^2, the storage tank volume of 3 m^3, the nominal power of 3 kW, the cooling nominal power of 8 kW and the fresh water supply of 200 L/h. They stated that the system was a promising idea but that it would need financial support from the government to be sustainable. Cioccolanti et al. [92] numerically and experimentally examined a solar-driven trigeneration system. They proved that the system efficiency could be improved by 6.5% if the proper temperature levels were selected in the storage tank. In another study, Cioccolanti et al. [93] also investigated a solar-driven trigeneration system for residential applications using TRNSYS simulation software. A relatively low electrical efficiency was found in summer due to the operation of the absorption chiller.

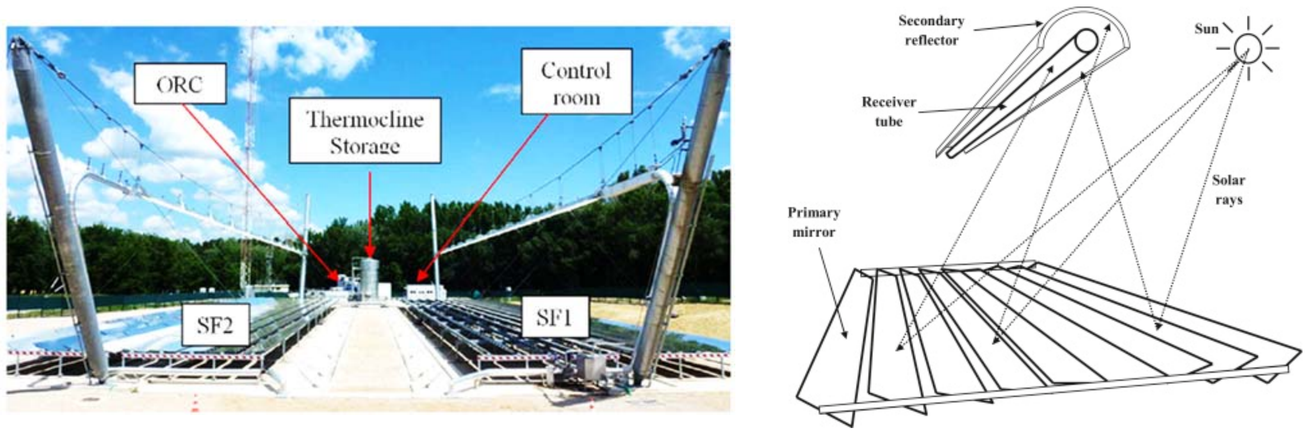
A summary of ORC systems with CPCs is presented in Table 4. To conclude, conventional CPC-ORCs have an energy efficiency of about 5%. Throughout the reviewed articles, one can observe that a large proportion of the papers are related to improving the performance of the systems by means of employing volumetric expanders, two-stage heat exchangers, or the glazed reverse absorber CPC. However, there is a lack of detailed experimental, environmental and economic assessments that leaves researchers with a vast untouched field of study.

Table 4. Summary of ORC systems employing CPCs.

Authors	Brief title	Highlights	Ref.
Jing et al. (2010)	CPC with C=3 is coupled to ORC with heat exchangers.	The system efficiency of around 7.5% can be improved with the use of heat exchangers.	[82]
Pei et al. (2010)	Regeneration system with PCM.	The system efficiency was 8.6% with regeneration and 4.9% without regeneration.	[83]
Wang et al. (2014)	Off-design performance analysis of a solar-ORC.	The yearly system efficiency ranged from 4% to 7%.	[84]
Antonelli et al. (2015)	Detail design of a CPC-ORC.	A concentration ratio between 1.1 and 1.4 can lead to yearly operation of up to 3500 hours in Italy.	[85]
Antonelli et al. (2016)	Dynamic modelling of a low-concentration solar-ORC.	C=1.25 led to η_{ORC}=8.2% and η_{sys}=3.4%. C=2 led to η_{ORC}=10.9% and η_{sys}=5.6%.	[86]
Tiwari et al. (2017)	Complex reflector with a glazed reverse absorber.	System efficiency of close to 8%.	[87]
Sonsaree et al. (2018)	Comparison of a CPC, ETC and FPC coupled to an ORC.	The CPC led to the minimum LCOE of around 0.21 $/kWh.	[88]
Li and Li (2018)	Optimisation of a solar-ORC based on a typical solar radiation year.	The profit growth rate increased as the system scale increased.	[89]
Garg and Orosz (2018)	Design of ORC with different heat sources.	The maximum isentropic efficiency of the scroll expander was around 65%.	[90]
Bocci et al. (2015)	Solar-driven polygeneration system.	The proposed system produced heating/cooling, electricity and fresh water.	[91]
Cioccolanti et al. (2018)	Solar-driven trigeneration system.	Performance improvement of 6.5% by optimising the operating temperature levels.	[92]

3.4 Linear Fresnel reflectors (LFRs)

LFR is a cost-effective solar concentrating technology that has gained more and more attention in recent years. Rodat et al. [94] examined an LFR-ORC with thermocline storage which operated with synthetic oil as the working fluid (see Fig. 11a). The system was designed to operate with a collector inlet temperature of 150ºC and a collector outlet temperature of 300ºC. Cocco and Serra [95] investigated an LFR-ORC with a solar multiple of between 1.5 and 2. The LFR had a secondary reflector (see Fig. 11b). The storage capacity was optimised and a minimum LCOE of close to 420 €/MWh was found for 8 hours of storage capacity. In another work, Xu et al. [96] investigated an ORC based on direct vapour generation, using an LFR (see Fig. 12). The overall efficiency of the system was estimated at 19.7% using cyclohexane as the ORC working fluid. Petrollese and Cocco [97] optimised a solar power generation system with PV and LFR-ORC. It was found that the combination of the two solar technologies reduced the LCOE by about 30%-40% compared to the CSP-only solution. Cioccolanti et al. [98] dynamically evaluated a residential LFR-ORC with TRNSYS for the climate conditions of Cagliari in Italy. The unit had a 2 kW electricity capacity and PCM as TES. The authors found that the mean annual ORC efficiency was 7.46% while the mean annual system efficiency was 4.5%.



(a) **(b)**

Figure 11. a) View of test facility with LFR, ORC and storage tank [94] b) LFR operation schematic [95].

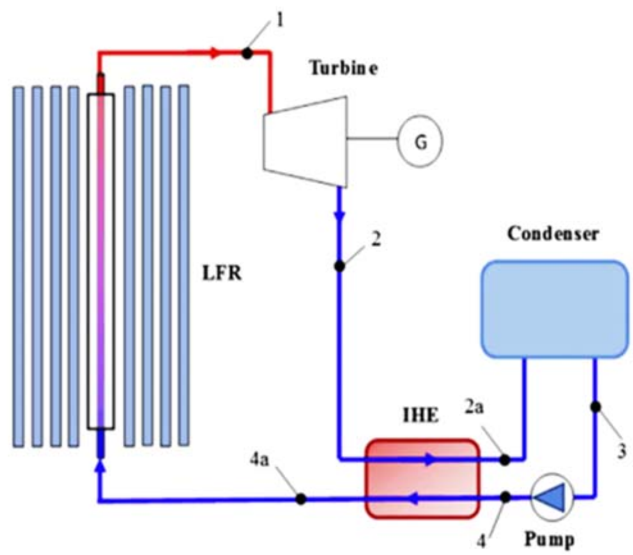


Figure 12. LFR-ORC and direct steam generation [96].

The last part of this section considers LFR-ORC systems with cogeneration. Cocco et al. [99] investigated a cogeneration system for electricity and heating (see Fig. 13). The system included TES with molten salt and two storage tanks. The heat output was higher than the power output and the system exergy efficiency generally ranged between 7% and 11%. Boyaghchi and Sohbatloo [100] investigated a complex system with LFR-ORC for power and liquefied natural gas (LNG). The system was optimised with a multi-objective optimisation method and the final results showed that the energy and exergy efficiencies were 7.3% and 12.6% respectively. An analysis of a cogeneration unit by Cioccolanti et al. [101] with TRNSYS proved that the ORC was able to operate 5351 hours per year for the climate conditions of Italy. The yearly system efficiency was 4.5% and the ORC efficiency of 7.46%.

A summary of ORC systems with LFRs is presented in Table 5. To conclude, LFR has been gaining popularity to provide energy for ORC units. The typical energy efficiency of an ORC driven by LFR is not so high. Hence, several studies focused on improving the performance by integrating heat storage, direct vapour generation, natural gas liquefaction, or PV panels into the solar-ORC system; the thermal efficiency could increase by around 30% with hybridisation. More research needs to be done, but it is possible to speculate that LFR will become one of the most practical collectors. There is a vast untouched research field for further modification and optimisation using economic, environmental and thermodynamic aspects. An interesting idea is to investigate different receivers in an LFR coupled to an ORC, as was done by Rodat et al. [102] who studied the use of a trapezoidal cavity receiver.

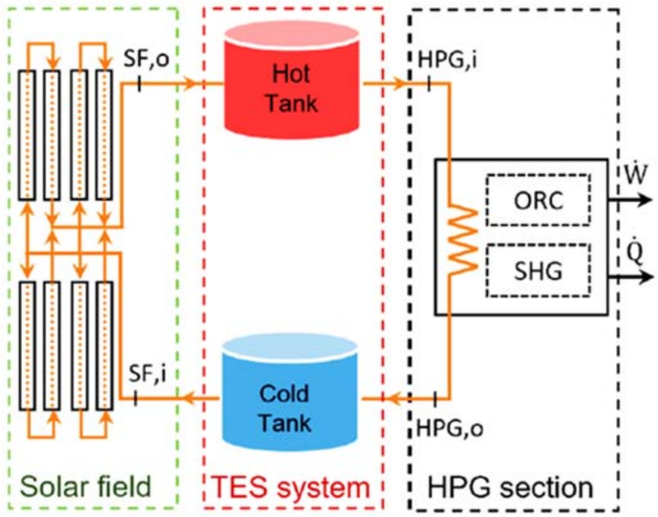


Figure 13. LFR-based plant with two molten salt storage tanks [99].

Table 5. Summary of ORC systems employing LFRs.

Authors	Brief title	Highlights	Ref.
Rodat et al. (2015)	ORC and thermocline-direct TES.	The LFR operated between 150ºC and 300ºC.	[94]
Cocco and Serra (2015)	Financial optimisation of an LFR-ORC.	Optimum storage capacity of close to 8 hours with an LCOE of close to 420 €/MWh.	[95]
Xu et al. (2015)	A direct vapour generation supercritical ORC.	System efficiency of 19.7%.	[96]
Petrollese and Cocco (2016)	CSP with LFR-ORC and PV.	The hybrid CSP-PV system led to a 30-40% lower LCOE compared to the CSP-only, depending on the location.	[97]
Cioccolanti et al. (2018)	Cogeneration for heating and power generation.	Maximum system efficiency of 5.8% was found in May.	[98]
Cocco et al. (2017)	Cogeneration for heating and power generation.	The heat output was more than the electricity output; the system exergy efficiency ranged between 7% and 11%.	[99]
Boyaghchi and Sohbatloo (2018)	Novel solar-driven natural gas liquefaction.	The optimisation results showed that energy and exergy efficiencies were 7.3% and 12.6% respectively.	[100]
Cioccolanti et al. (2017)	Simulation of micro-solar 2 kWe ORC with PCM.	Annual ORC efficiency of 7.46% and system efficiency of 4.5%.	[101]
Rodat et al. (2018)	Fresnel solar power plant prototype with storage.	Good consistency was observed between the numerical results and measured experimental results.	[102]

3.5 Parabolic trough concentrators (PTCs)

A PTC is a linear concentrating collector which can easily operate at temperatures of up to 400ºC with thermal oil and up to 600ºC with molten salt. Moreover, ORC technology can be coupled with a great variety of organic working fluids and can also be used in artificial polygeneration systems. Researchers usually select this collector because of its maturity, its reasonable cost and its relatively high efficiency.

At this stage, it has to be stated that the combination of PTC with ORC can be conducted in various ways. A typical configuration is to use a separate working fluid in the solar field (thermal oil or molten salt) in order to transfer heat to the ORC through a heat recovery system. For example, Xi et al. [103] investigated the use of thermal oil to feed an ORC to produce electricity as well as provide heat to a bottoming polygeneration unit. The use of molten salt in a PTC-ORC system can be applied in order to operate at higher temperatures of up to 600ºC [104]. Another configuration example is the use of PTC as the heat source in a complex system for power generation or polygeneration including a bottoming power generation cycle. This was studied by Tukenmez et al. [105] where the ORC was the bottoming cycle of a Brayton cycle which operates with air as the working fluid. Recent studies suggest more complex designs where compressors, turbines, heat exchangers, distillation units and other devices are coupled to a PTC for polygeneration. Ghorbani et al. [106] studied such a configuration for power and fresh water production involving solar energy (PTC) and LNG.

3.5.1 Power generation

Firstly, a discussion on PTC-ORCs for power generation is presented in this subsection and Table 6a summarises the main points of these studies. In 2011, Tchanche et al. [5] presented a detailed review of the various applications of solar-ORC systems. Schuster et al. [107] energetically and economically investigated various ORC systems with different heat sources such as biomass, geothermal, and solar energy. The application of the solar-ORC system in desalination systems was proposed as an efficient way of providing drinking water in water-stressed areas. Working fluids were investigated by Roy et al. [108] who numerically optimised a non-regenerative ORC with superheating. The fluids R-12, R-123, R-134a and R-717 were tested and R-123 was found to be the best. In experimental work with a PTC-ORC (see Fig. 14), Taccani et al. [109] found that R245fa was the best working fluid which led to a system efficiency of 8%. Muñoz et al. [110] suggested a novel system for power generation using a solar Rankine-Brayton cycle. Different fluids were evaluated and the results showed that propane and R125 were the most appropriate for achieving the highest performance in the range of 30% to 40%.

Quoilin et al. [111] optimised a solar-ORC by sizing different ORC components, selecting different fluids and investigating single or double stage expansion machine configurations. The overall electrical efficiency reached 8%. Tzivanidis et al. [112] optimised a PTC-ORC based on exergy and financial aspects. They reported the optimum dimensions of the solar system with cyclohexane as the most suitable working fluid, as well as a payback period of about 9 years and a system efficiency of 15%. Ashouri et al. [113] optimised a double pressure PTC-ORC with a storage tank. The system was exergo-economically investigated and maximum exergy efficiency of 22.7% was found. The use of nanofluids in the PTC field was investigated by Bellos and Tzivanidis [114]. Various nanofluids and organic fluids in the ORC were investigated in order to maximise the system's power output. The best choice was found to be toluene in the ORC and thermal oil/CuO nanofluid (with a 4% nanoparticle concentration) in the PTC. This resulted in a system efficiency of 20.11%, which was a 1.75% improvement compared to the case with pure thermal oil in the PTC field.

In the literature, dynamic approaches to solar PTC-ORCs are common. He et al. [115] simulated a PTC-ORC using TRNSYS software. They found that the system efficiency was about 15% while the ORC efficiency was as high as 26%. Majumdar et al. [116] investigated a novel solar-ORC system using a dynamic moving boundary model that was developed for medium-temperature collectors. A time-dependent model was developed for the variation of heat transfer fluid temperature. The overall system efficiency was estimated to be 21%. Ni et al. [117] investigated a solar-ORC system under cloudy weather conditions using a dynamic model. A PID control strategy was suggested for the system. The performance of the system was improved by 24% when using the suggested PID control strategy.

An important part of the literature is comparative studies between different configurations. Desai and Bandyopadhyay [118] compared the water/steam RC with the ORC financially and energetically using PTC and LFR. They concluded that the LCOE for the water/steam RC was 0.353$/kWh with PTC and 0.422 $/kWh with LFR, while the LCOE for PTC-ORC was 0.344 $/kWh. However, in another work, Desai and Bandyopadhyay [119] found the LCOE of a PTC water/steam RC to be 0.189 $/kWh. Li et al. [120] suggested a new solar-driven power generation system including RC and ORCs. The system efficiency was found to be 15.6% with the hot-side temperature at 523 K and the cold-side temperature at 293 K. Moreover, they stated that the main exergy destruction occurred in the solar collectors (about 80%). Li et al. [121] studied a solar-driven water/steam RC which was coupled to a bottoming ORC and found that the system efficiency ranged between 13.7% and 15.5%. In another work, Li et al. [122] proposed a novel power system using direct steam generation from PTC, as well as a bottoming ORC. Two-stage accumulators were applied to achieve smooth power conversion. The payback period was calculated at 5 years. Li et al. [123] investigated a power generation system with a water/steam RC (direct or indirect) and a bottoming ORC (see Fig. 15). They found that the direct system had a 1.1% higher system efficiency than the indirect system. Singh and Mishra [124] numerically considered a PTC as the heat source for power generation using a supercritical CO_2 cycle with a bottoming ORC (see Fig. 16). The system had a maximum efficiency of 43.5%. Patil et al. [125] compared PTC-ORC and PV technologies for power generation. They found that, for the same capacity factor of 56%, the PTC-ORC led to an LCOE of 0.19 $/kWh while the PV led to an LCOE of 0.26 $/kWh. However, if the PV system was designed with a capacity factor of 27% it could lead to an LCOE of 0.12 $/kWh. Al-Nimr et al. [126] investigated a power generation system using a solar-ORC and concentrated photovoltaic/thermal (CPVT) technology with PTC. Different parameters including solar radiation, ambient temperature and turbine inlet temperature were investigated. It was found that the CPVT-ORC was about 16%-18% more efficient than the CPVT-only system.

The expander is the most important device in the ORC and therefore expander studies on PTC-ORCs have been considered in the literature. In experimental work, Kosmadakis et al. [127, 128] investigated the performance of an ORC system with PTC at 95ºC. The laboratory ORC components are depicted in Fig. 17a, while the ORC housing and the PTC field are shown in Fig. 17b. They emphasised the investigation of the expander performance and found the system efficiency to range between 4.4% and 6%. Deligant et al. [129] investigated the performance of a PTC-ORC with emphasis on the design of a radial expander using CFD analysis. Isentropic expander efficiencies of up to 78% were found. Al Jubori et al. [130] optimised the structure of a turbine as the expander of a solar-ORC system. A three-dimensional simulation was developed in the ANSYS-CFX software. Different organic fluids were evaluated as the ORC working fluid. It was found that the performance of the system was enhanced with the optimised turbine using R123 as the ORC working fluid. The system efficiency was 10.5%.

A great deal of literature focuses on TES in PTC-ORCs. Casati et al. [131] investigated the influence of TES in solar-ORC systems for power generation. They found that the system efficiency could be 18% with direct TES and a flashing cycle configuration. Chacartegui et al. [132] studied a solar-ORC system with TES based on direct and indirect methods. The performance of the systems with different ORC working fluids was investigated. Toluene presented the best performance at 31.5% with a power block cost of 825 €/kW. The indirect storage layout was recommended with higher power output and lower electricity costs. Rodríguez et al. [133] concluded that 1 hour of storage led to a 35% higher yield and that the use of a thermocline reduced the cost of the system by about 30% compared to a design with two storage tanks using molten salt. Caldiño-Herrera et al. [134] evaluated a PTC-ORC with two storage tanks (hot and cold) that had an auxiliary heater. The ORC operated with R245fa working fluid and the system efficiency was about 8%.

Lastly, there are some studies about solar-geothermal ORCs for power generation. Erdogan et al. [135] examined a solar-geothermal ORC system and emphasised the proper design of the shell and tube heat exchanger. They optimised the system and found efficiencies of up to 6.5%. In another work, Cakici et al. [136] thermodynamically investigated a solar-geothermal ORC system with R134a as the organic fluid. They performed a parametric analysis and found the system efficiency to be close to 12%. Heberle et al. [137] modified a geothermal ORC system with a PTC. It was found that the performance of the geothermal ORC system improved by about 4.5%.

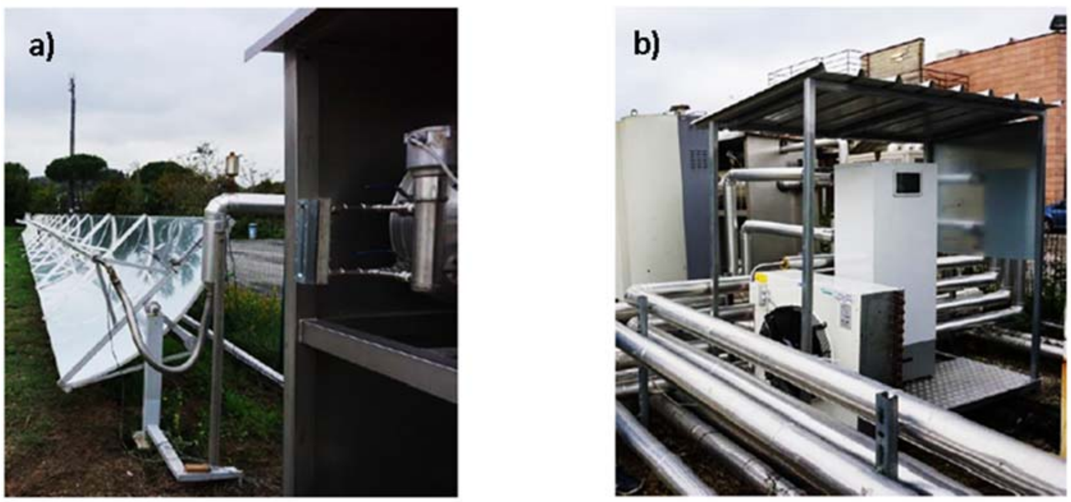
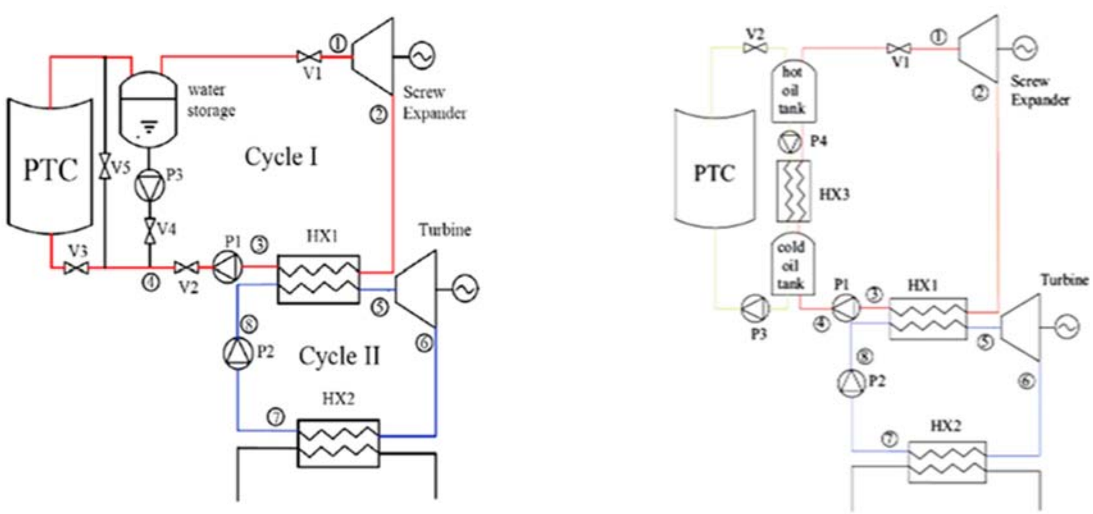


Figure 14. Solar-ORC prototype: (a) PTC b) ORC prototype and dry cooler [109].



(a) **(b)**

Figure 15. Schematic diagrams of (a) direct and (b) indirect solar-RC systems [123].

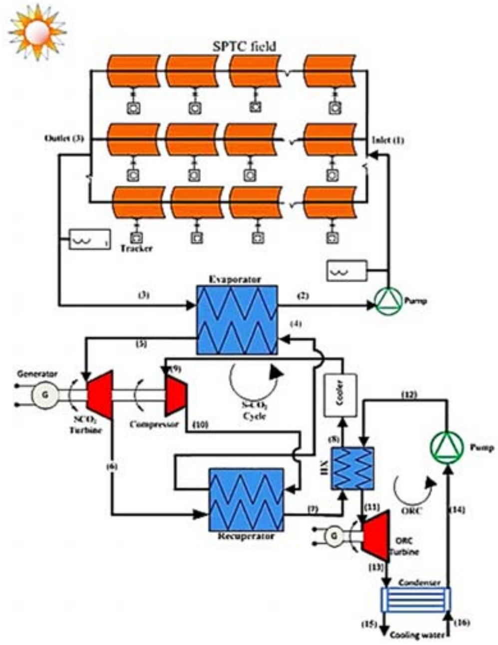
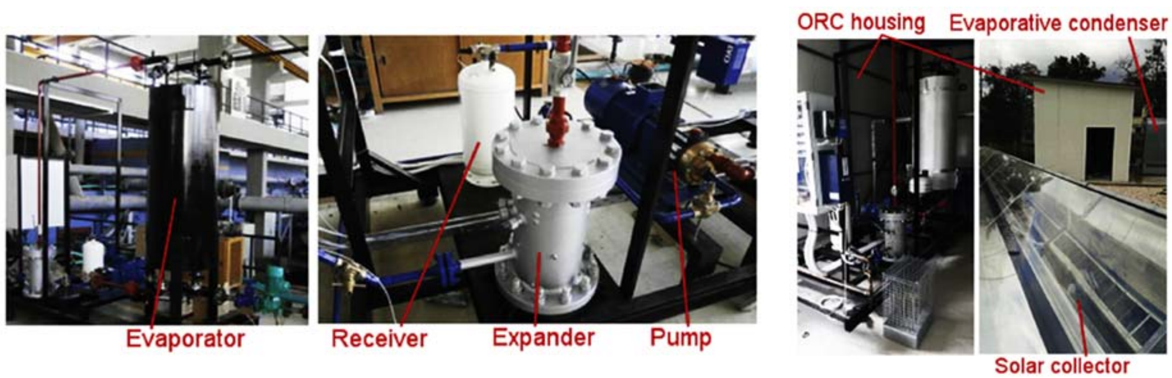


Figure 16. Solar-ORC together with a supercritical CO_2 cycle [124].



(a) **(b)**

Figure 17. a) Details of the ORC experimental setup b) PTC and ORC housing [127].

3.5.2 Desalination

In this section, PTC-ORCs for desalination are presented and Table 6b summarises the main points of these studies. Delgado-Torres and García-Rodríguez [138, 139] investigated such a system by applying different ORC working fluids. The total efficiency of the system was calculated as 22.3%, 19.3%, and 18.3% using toluene, D4 and MM as the ORC working fluids respectively. In another study, Delgado-Torres et al. [140] compared the use of two PTCs as the heat source of the desalination system. The mechanical power was generated using an ORC system with three different organic fluids. The authors reported a fresh water production rate of 0.11 m^3/h using toluene as the ORC working fluid. Bruno et al. [141] numerically optimised a solar desalination system with an ORC system for power generation. Three solar collector technologies were investigated to deliver heat to the ORC system, including PTC, FPC and ETC-CPC. For each solar collector, the influence of different ORC working fluids on the total efficiency was investigated, after which the solar-ORC systems were coupled with a desalination system for freshwater production. The best performance was calculated for the PTC-ORC with isopentane as the ORC working fluid. For the optimised case, the ORC system efficiency was 32% and the total efficiency was estimated at 21%. In another investigation, Delgado-Torres and García-Rodríguez [142] optimised the aperture area of different solar collectors together with different ORC working fluids. The results revealed that dry working fluids showed a lower optimised aperture area compared to wet working fluids, except for ammonia. Nafey and Sharaf [143] energetically, exergetically and economically evaluated a solar desalination system based on RO technology driven by an ORC system. They considered different solar collectors and organic fluids and concluded that PTC was the best collector, while toluene and water were the best working fluids. More specifically, the overall efficiency, the exergy efficiency and specific capital cost of the ORC-RO with PTC and water as working fluid were 30.47%, 22.52% and 0.904 $\$/m^3$ respectively. Moreover, Peñate and García-Rodríguez [144], Ibarra et al. [145] and Li et al. [146] suggested solar desalination based on ORC systems for power generation using PTC and RO technology. Ibarra et al. [145] reported a water production rate of 1.2 m^3/h, solar field efficiency of 60% and a system efficiency of 7%. Li et al. [146] evaluated an ORC system with superheated conditions at the turbine inlet. After an optimisation procedure, a power output of 200 kW and water production rate of 40 m^3/h were reported.

3.5.3 Cogeneration

The use of ORC-PTC systems for cogeneration is also usual in the literature and Table 6b includes these studies. Firstly, Freeman et al. [147] studied a solar-ORC system for combined power and heating. Concentrating PTC and non-concentrating ETC with the same area were compared. The yearly electric output of the investigated system was 776 kWh and the complete system capital cost was estimated in the range of £2700 to £3900. Also, they found the performance of the two investigated solar collectors to be very similar. Rady et al. [148] presented a cogeneration system consisting of a solar-ORC for power and cooling. PTC and LFR technologies were investigated and the results showed that the use of LFR resulted in a 50% reduction in annual operating hours. Borunda et al. [149] simulated a cogeneration solar-ORC for electricity and industrial heat which included auxiliary electrical heaters. The system had an electrical efficiency of around 7.5%, system efficiency of around 60% and the solar coverage was close to 35%.

3.5.4 Polygeneration

Polygeneration is an interesting idea which needs high-temperature heat sources and thus PTC is a common choice in these configurations. This section presents the PTC-ORC-based polygeneration systems and Table 6c summarises these studies. Al-Sulaiman et al. [150] studied a novel PTC-ORC for producing electricity, heating and cooling. Three scenarios were investigated: solar only, both solar and TES, and TES only. The total efficiency of the first, second and third scenarios was calculated as 94%, 47% and 42% respectively. In another study, Al-Sulaiman et al. [151] exergetically considered a trigeneration system for producing power, heating and cooling. The three scenarios from Ref. [150] were also investigated and the maximum electrical-exergy efficiencies were calculated as 7%, 3.5% and 3% respectively. Moreover, Al-Sulaiman et al. [152] energetically investigated ORC systems with solid oxide fuel cell (SOFC), biomass and solar energy as the heat source. The maximum total efficiency of the system using solar energy was calculated at 90%. Al-Sulaiman [153, 154] performed exergy analyses on the combined steam and organic Rankine cycle using a PTC as the heat source. Different working fluids were investigated. R134a was found to be the best choice for the ORC with 26% system exergy efficiency. Suleman et al. [155] developed a trigeneration system for electricity, cooling and drying using solar and geothermal heat sources. They concluded that the overall energy and exergy efficiencies of the system were calculated as 54.7% and 76.4% respectively. In another interesting study, Almahdi et al. [156]

developed a polygeneration system for electricity, heating, cooling, and hydrogen production using PTC-ORC technology. The energy and exergy efficiency of the suggested system was estimated at 20.7% and 13.7% respectively. Hogerwaard et al. [157] considered a PTC-based system for power, refrigeration and desalination. This system combined an ORC and a Brayton cycle, with energy and exergy efficiencies of 28.4% and 27% respectively. Bellos and Tzivanidis [158] optimised a trigeneration system for heating, cooling and electricity (see Fig. 18). Different ORC working fluids were investigated. Toluene was found to be the best choice which led to a global maximum system exergy efficiency of 29.4%.

Astolfi et al. [159] investigated a polygeneration system using PTC and PV for desalination and power generation. It was concluded that the suggested system was economically acceptable compared to the traditional desalination system using fossil fuel. Renewable energy penetration was as high as 80%. Chang et al. [160] studied a polygeneration system including cooling, heating and power generation. A hybrid system consisting of a proton-exchange membrane fuel cell (PEMFC), PTC, ORC and vapour compression cycle was considered. The system presented an energy efficiency of 75% in summer and 85% in winter. Islam et al. [161] evaluated two complex solar-driven polygeneration systems with ORC and thermoelectric generator for electricity, heating, cooling, hydrogen and oxygen production. They found maximum energy and exergy efficiencies of 59.6% and 51.75% respectively. Eisavi et al. [162] thermodynamically investigated a cogeneration/trigeneration system driven by solar energy which included an ORC and an absorption heat pump. The authors found an energy efficiency of 96% and exergy efficiency of 12.8%. El-Emam and Dincer [163] investigated a solar-driven polygeneration system for heating, cooling, hydrogen, fresh water and electricity with maximum system exergy efficiency of 39%. Zhang et al. [164] numerically and experimentally considered a trigeneration system including cooling, heating and power generation. The system efficiency was reported as 10% using R123 as the ORC working fluid. Wang et al. [165] investigated a trigeneration system for cooling, heating and power generation using solar energy for a hotel in China. Compressed air energy storage was directly connected to the solar collectors for power generation. The system included ORC, a gas turbine and an absorption chiller. Its energy and exergy efficiencies were 98.3% and 68.9% respectively. Yüksel [166] investigated a trigeneration system including electricity, cooling, and hydrogen using solar energy. It was concluded that, when the solar irradiation increased from 400 W/m^2 to 1000 W/m^2, the exergy efficiency and the hydrogen production rate increased from 58% to 64% and from 0.102 kg/h to 0.103 kg/h, respectively. Bellos et al. [167] also investigated a trigeneration system for cooling, heating and power generation. A multi-objective optimisation was applied for calculating the optimum conditions of the investigated system. Different ORC parameters were optimised including the heat source temperature of the HRS, the turbine inlet pressure and the heat-rejection temperature at the condenser. It was found that toluene was the most appropriate organic fluid for the ORC system. The optimum system was investigated for operation during a typical year. The exergy efficiency was observed to be 25.2% and the energy efficiency 150.8% at the optimum point. In another work on a solar-driven trigeneration, Zhao et al. [168] found a 46% exergy efficiency. The system included a PTC, ORC and absorption chiller and produced cooling, heating, and electricity. In another work, Khalid et al. [169] investigated a trigeneration system for electricity, heating and cooling with PTC-ORC which presented an LCOE of 0.181 $/kWh for the optimised case. In another investigation, Yüksel et al. [170] investigated a solar-driven polygeneration system for heating, cooling, electricity and hydrogen production (see Fig. 19). They performed a parametric investigation and the system efficiency was found to be around 55%. Sharifishourabi and Arab Chadegani [171] suggested a new polygeneration system for cooling, heating, hydrogen and electricity. The system included an ORC, triple-effect absorption chiller, electrolyser and heat exchangers. The energy and exergy efficiencies of the suggested system were reported as 14% and 26% respectively. The cooling, heating and electricity outputs were 428 kW, 2114 kW and 2380 kW respectively, while the hydrogen production rate was 1.664 g/s. Calise et al. [172] performed a dynamic study on a solar-geothermal polygeneration system for heating, cooling, electricity and fresh water. The payback period was found to be 8.5 years with an ORC efficiency of 15%.

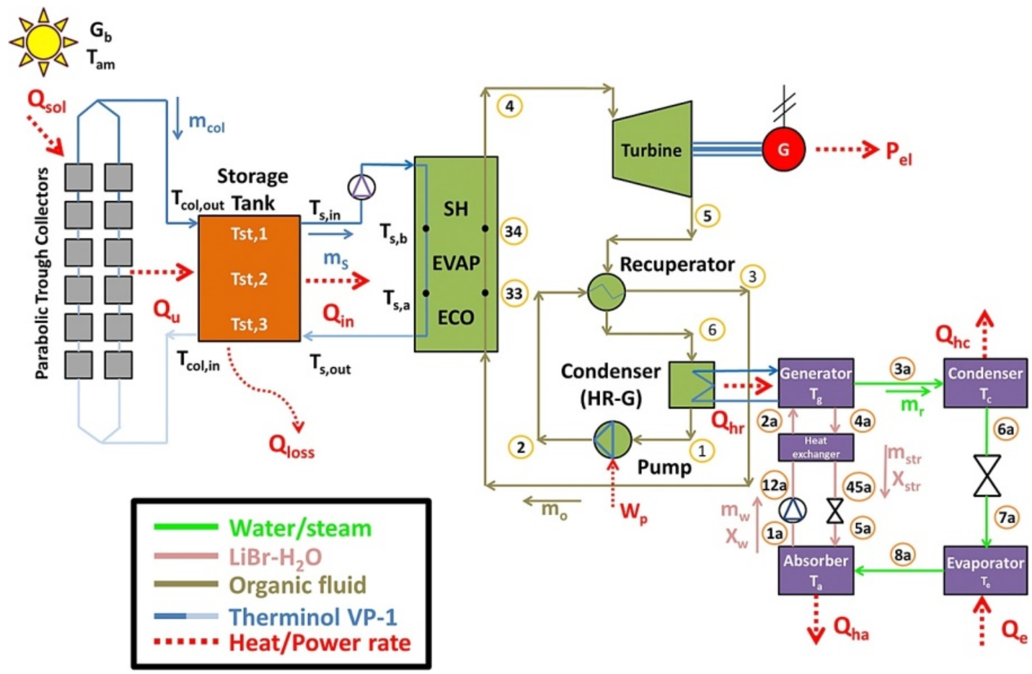


Figure 18. PTC-based trigeneration system with ORC and absorption heat pump (LiBr/H_2O) [158].

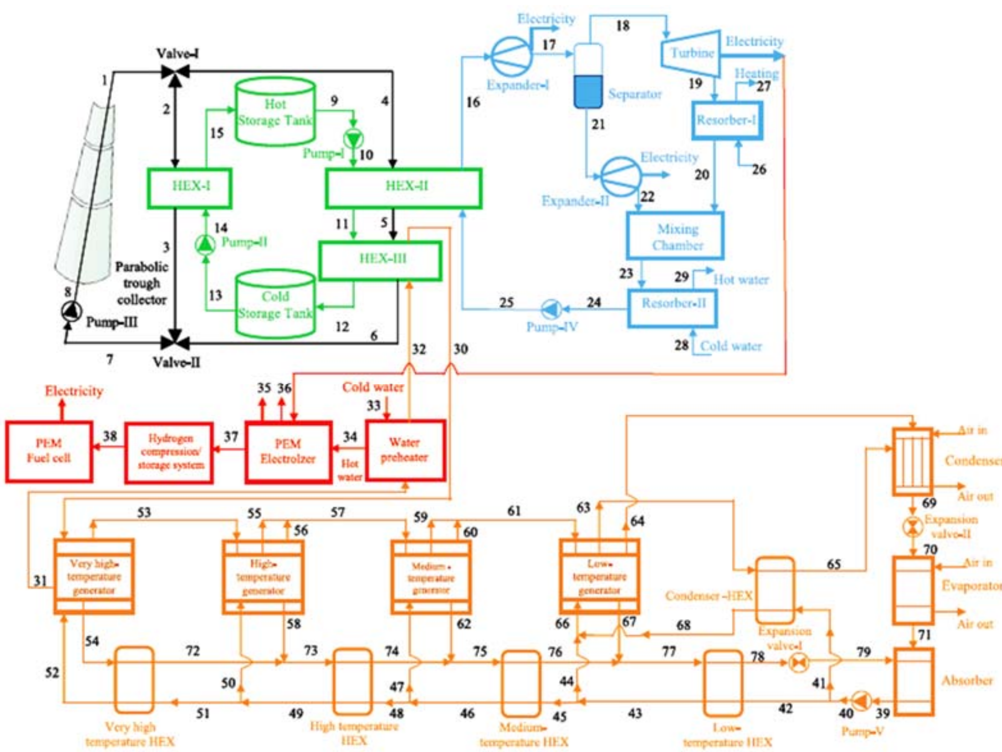


Figure 19. Solar polygeneration system with ORC included [170].

3.5.5 Summary

A summary of ORC systems with a PTC as the heat source is reported in Tables 6a, 6b and 6c. PTCs were found to be the most widely implemented collectors for driving ORC systems – more than 37% of the articles considered were related to this form of integration. In most cases, but with some notable exceptions especially in locations with a lower solar resource and/or more cloudy climates [13, 173], PTCs had better performance compared to other collector types; in other cases, ETCs have also proven quite promising. Beyond pure energy provision, there are numerous studies in the literature that focus on the integration of ORC systems with PTCs and RO desalination. Such systems have been suggested for producing fresh water across a range of scales, with delivered quantities ranging from 0.1 m^3/hr to 40 m^3/hr and with overall efficiencies that vary between 7% and 90%. Polygeneration systems producing power, heating/cooling, as well as hydrogen or clean water have been attracting significant attention in the literature in recent years. These systems have been shown as being capable of yielding up to 5.9 kg of H_2 per hour and more than 90% total energy efficiency, which suggests an excellent energy conversion potential if this can be done simply, affordably and reliably – this remains a challenge.

The selection of the best working fluids for yielding higher energetic and exergetic efficiencies and lower specific capital costs were also taken into consideration in many research works. Some authors observed the performance of the system on a monthly and hourly basis under different direct normal irradiance (DNI) and concluded that solar radiation was the most important parameter which determined the total output. Furthermore, the effect of parameters such as the temperature of the working fluid, heat storage capacity and plant size on economic indices, namely payback period, internal rate of return (IRR) and specific capital cost, was the main objective of many studies.

It appears that ORC systems powered by PTCs are gradually maturing technology. The most significant concern relates to the economic aspects and the reliability of these systems, so further experimental data can help researchers tackle these challenges rationally. Secondly, even though emission standards and policies have been introduced in many countries, just one article focused on the impacts of emission reductions on the environment and overall costs, and as a result, more studies in this area are needed.

Table 6a. Summary of ORC systems employing PTCs for power production

Authors	Brief title	Highlights	Ref.
Schuster et al. (2009)	Study of different ORC systems and various heat sources.	Solar desalination with ORC was found to be a promising idea.	[107]
Roy et al. (2011)	Performance analysis of an ORC.	R-123 as ORC working fluid yielded the maximum efficiency of around 19% at a turbine inlet temperature of 470 K.	[108]
Taccani et al. (2016)	Experimental characterisation of a small-scale solar-ORC.	With R245fa, the system efficiency was 8%.	[109]
Muñoz et al. (2017)	Hybrid Rankine-Brayton cycle.	Propane and R125 were the best fluids with efficiencies of between 30% and 40%.	[110]
Quoilin et al. (2011)	Low-cost solar-ORC for power generation.	The overall electrical efficiency of the PTC-ORC was close to 8%.	[111]
Tzivanidis et al. (2016)	Energetic and financial investigation of a solar-ORC.	System efficiency of 15% and a payback period of close to 9 years.	[112]
Ashouri et al. (2018)	Solar double pressure ORC system.	In the optimal conditions, the system would yield an exergy efficiency of 22.7%.	[113]
Bellos and Tzivanidis	Nanofluid-based PTC for	System efficiency of 20.11% using nanofluid (1.75%	[114]

(2017)	driving an ORC.	higher than when using pure thermal oil).	
He et al. (2012)	Simulation of a PTC-ORC using TRNSYS software.	System efficiency of around 15% and ORC efficiency of up to 26%.	[115]
Majumdar et al. (2018)	Evaluation of transient characteristics of solar systems.	Overall system efficiency of 21%.	[116]
Ni et al. (2018)	Dynamic performance investigation of a PTC-ORC.	A 24% enhancement was found by utilising a PID control strategy.	[117]
Desai and Bandyopadhyay (2016)	Comparison of PTC and LFR coupled to ORC.	For the water RC, the LCOE was 0.353 $/kWh with PTC and 0.422 $/kWh with LFR. The LCOE for the PTC-ORC was 0.344 $/kWh.	[118]
Li et al. (2016)	Solar electricity generation using cascade RC.	System efficiency of 15.6%. 80% of the exergy destruction was performed in the PTC.	[120]
Li et al. (2017)	Water/steam RC and bottoming ORC.	System efficiency of 13.7%-15.5%.	[121]
Li et al. (2017)	RC with direct steam production from PTC and bottoming ORC.	Payback period of 5 years.	[122]
Li et al. (2017)	RC with direct or indirect steam production from PTC and bottoming ORC.	The direct system had a 1.1% higher system efficiency than the indirect system.	[123]
Singh and Mishra (2018)	PTC driving a combined supercritical CO_2 and ORC.	The highest system efficiency was 43.5%.	[124]
Patil et al. (2017)	Comparison of PTC-ORC and PV systems.	For the same capacity factor of 56%, the PTC-ORC led to an LCOE of 0.19 $/kWh while the PV led to 0.26 $/kWh.	[125]
Al-Nimr et al. (2017)	Combined CPVT and ORC solar power system.	The CPVT-ORC is about 16%-18% more efficient than the CPVT-only system.	[126]
Kosmadakis et al. (2016).	Experimental analysis of a low-temperature PTC-ORC.	System efficiency of 4.4% to 6%.	[128]
Deligant et al. (2018)	Analysis of radial expander in a PTC-ORC.	Maximum isentropic expander efficiency of 78%.	[129]
Al Jubori et al. (2017)	Small-scale axial turbine for a low-temperature heat source.	System efficiency of 10.5% with R123.	[130]
Casati et al. (2013)	Different storage systems.	System efficiency of 18% with direct TES and a flashing cycle configuration.	[131]
Chacartegui et al. (2016)	Two heat storage integrations for a solar-ORC.	Toluene was found to be the best working fluid and the indirect storage system was the best.	[132]
Rodríguez et al. (2016)	TES solutions for CSP-ORC.	The thermocline design reduced 30% of the costs compared to the molten salt storage tank design.	[133]
Caldiño-Herrera et al. (2017)	ORC-PTC with two storage tanks and an auxiliary heater.	System efficiency of close to 8%.	[134]
Erdogan et al. (2017)	Solar-geothermal ORC.	System efficiency of up to 6.5%.	[135]
Cakici et al. (2017)	Solar-geothermal ORC.	System efficiency of close to 12%.	[136]
Heberle et al. (2017)	Geothermal ORC based on solar thermal systems.	Performance of the geothermal ORC system improved by about 4.5% when employing PTC.	[137]

Table 6b. Summary of ORC systems employing PTCs for desalination and cogenertaion

Authors	Brief title	Highlights	Ref.
Delgado-Torres and García-Rodríguez (2007)	Driving a desalination system by means of an ORC.	Energy efficiencies of 22.3%, 19.3% and 18.3% were found with toluene, D4 and MM respectively.	[139]
Delgado-Torres et al. (2007)	Preliminary design of a solar thermal-powered RO system.	0.11 m^3/h of fresh water was produced with toluene as the working fluid.	[140]
Bruno et al. (2008)	Modelling and optimisation of an ORC-RO.	Compared to FPC and EPC, the PTC Eurotrough with n-propilbenzene had the highest ORC and system efficiencies of 32% and 21% respectively.	[141]
Delgado-Torres and García-Rodríguez (2010)	Optimisation of a low-temperature solar-ORC.	Dry working fluids were preferred to wet fluids because of smaller aperture area.	[142]
Nafey and Sharaf (2010)	Solar-ORC-RO: energy, exergy, and cost evaluations.	The energy efficiency, the exergy efficiency and the specific capital cost of the ORC-RO with PTC were 30.47%, 22.52% and 0.904 $/$m^3$ respectively.	[143]
Peñate and García-Rodríguez (2012)	Seawater RO desalination driven by solar-ORC.	ORC-RO systems are economically superior for medium-range capacities in remote areas.	[144]
Ibarra et al. (2014)	Performance of a 5-kW solar-ORC-RO.	The water production rate, the collector efficiency and the system global efficiency were 1.2 m^3/h, 60% and 7% respectively.	[145]
Li et al. (2013)	Concentrating solar collectors coupled with an ORC-OR.	The system produces 200 kW of power and 40 m^3/h of water.	[146]
Freeman et al. (2015)	Solar-ORC for CHP.	The performance of PTC and ETC was found to be very similar by yielding 776 kWh per year.	[147]
Rady et al. (2015)	Cogeneration CSP plant.	Comparing PTC and LFR, the use of LFR led to a 50% reduction in operating hours per year.	[148]
Borunda et al. (2016)	Cogeneration for electricity and industrial heat.	The electrical efficiency was 7.5%, system efficiency was 60% and solar coverage was 35%.	[149]

Table 6c. Summary of ORC systems employing PTCs for polygeneration.

Authors	Brief title	Highlights	Ref.
Al-Sulaiman et al (2012)	Using PTC for cooling, heating and power.	The system efficiency was 94% in solar-only mode, 47% in solar-storage mode and 42% in storage-only mode.	[150]
Al-Sulaiman et al (2011)	Modelling of a solar-driven trigeneration system.	The system electrical-exergy efficiency with solar-only, solar-storage and storage-only was 7%, 3.5% and 3% respectively.	[151]
Al-Sulaiman et al (2011)	Three trigeneration systems using ORC.	The maximum electrical efficiency for the solar-trigeneration system was around 15% for the solar mode and 7% for the storage and solar mode.	[152]
Al-Sulaiman (2013)	PTC integrated with steam and binary vapour cycles.	The smallest solar field size was obtained with R134a as the ORC working fluid.	[154]
Suleman et al. (2014)	Solar-geothermal trigeneration system.	The overall energy and exergy efficiencies were estimated at 54.7% and 76.4% respectively.	[155]
Almahdi et al. (2016)	Polygeneration for electricity, heating, cooling and hydrogen.	The energy and exergy efficiencies were 20.7% and 13.7% respectively.	[156]
Hogerwaard et al.	Trigeneration system with ORC	The energy and exergy efficiencies were 28.4% and	[157]

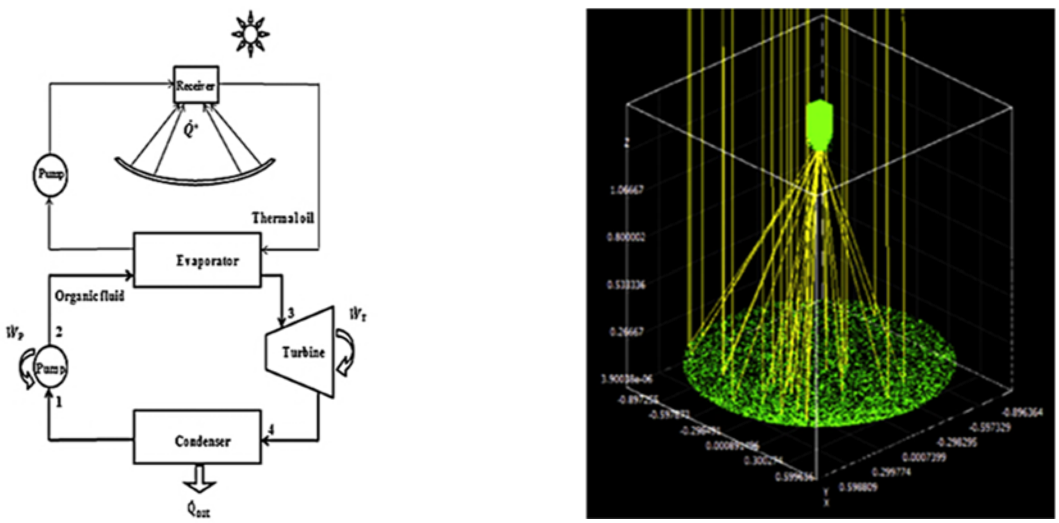
(2017)	and Brayton cycle.	27% respectively.	
Bellos and Tzivanidis (2017)	Solar-driven trigeneration system based on ORC.	Toluene was the best fluid and the system exergy efficiency was 29.7%.	[158]
Astolfi et al. (2017)	Polygeneration with PTC-ORC and PV.	A viable system with renewable energy penetration of up to 80%.	[159]
Chang et al. (2017)	Hybrid PEMFC-solar energy residential micro-CCHP system.	System efficiency of 75% in summer and 85% in winter.	[160]
Islam et al. (2018)	Polygeneration with ORC and thermoelectric generator for H_2, O_2, electricity, heating and cooling.	Energy and exergy efficiencies of 59.6% and 51.75% respectively.	[161]
Eisavi et al. (2018)	Trigeneration system for heating, cooling and electricity.	Energy efficiency of 96% and exergy efficiency of 12.8% for heating-power mode.	[162]
El-Emam, and Dincer (2018)	Polygeneration system for heating, cooling, hydrogen, fresh water and electricity.	Maximum system exergy efficiency of 39%.	[163]
Zhang, et al. (2018)	Trigeneration system for heating, cooling and electricity.	System efficiency of 10% with R123.	[164]
Wang et al. (2018)	Off-design trigeneration system with ORC, gas turbine and absorption chiller.	The energy and exergy efficiencies of the system were calculated as 98.3% and 68.9% respectively.	[165]
Yüksel (2018)	Modified PTC-ORC for hydrogen production.	Increasing G_b from 400 to 1000 W/m^2, the exergy efficiency increases from 58% to 64% and the H_2 production from 0.102 to 0.103 kg/h.	[166]
Bellos et al. (2018)	Trigeneration system for heating, cooling and electricity.	Energy efficiency of 150.8% and exergy efficiency of 25.2% was found.	[167]
Zhao et al. (2018)	Trigeneration system for heating, cooling and electricity.	System exergy efficiency of up to 46%.	[168]
Khalid et al. (2016)	Trigeneration system with PTC-ORC.	The LCOE of the optimised system was reported as 0.181 $/kWh.	[169]
Yüksel et al. (2016)	Polygeneration for electricity, heating, cooling and hydrogen.	System energy efficiency of around 55%.	[170]
Sharifishourabi and Arab Chadegani (2017)	Polygeneration system for cooling, heating, hydrogen and electricity.	The energy and exergy efficiencies were calculated as 14% and 26% respectively.	[171]
Calise et al. (2017)	Solar-geothermal polygeneration for heating, cooling, electricity and freshwater.	Payback period of 8.5 years and ORC efficiency of 15%.	[172]

3.6 Parabolic solar dish collectors (SDCs)

An SDC is a focal-point, medium-to-high temperature collector. Heat absorbed by the heat transfer fluid in the receiver of the SDC can be used to deliver heat to an ORC system (SDC-ORC) for power generation. In this section, investigations into SDC-ORCs are considered.

Moreover, a lot of attention has been given to the shape of the solar receiver. Loni et al. [174] optically and energetically investigated an SDC-ORC (see Fig. 20a) using a cubical cavity receiver with R141b as the working fluid. The depiction of the collector's optical analysis is shown in Fig. 20b. The authors concluded that the overall thermal efficiency increased by decreasing the inner tube diameter and the inlet temperature. Furthermore, Loni et al. [175] numerically investigated an SDC-ORC using a cylindrical cavity receiver as the absorber (see Fig. 21). The optimum dimensions of the investigated solar system were reported –

the optimum cavity depth was found to be the same as the aperture diameter. In Ref. [176], a cubical cavity receiver was thermally and thermodynamically investigated. Different organic fluids were used as the ORC working fluid. The influence of the ORC working fluid's turbine inlet temperature on the system performance was considered. It was found that the solar-ORC system using methanol as the working fluid had the highest system efficiency of 37.5% and consequently the lowest irreversibility. A rectangular cavity receiver was evaluated exergetically in Ref. [177]. The influence of the cavity structural parameters on the exergy performance of the system was investigated. It was found that the cavity receiver with a cavity height equal to the cavity aperture side length showed the highest performance. In another work, Loni et al. [178] numerically investigated a nanofluid-based SDC coupled to ORC. They studied the effect of the size and the concentration of the alumina nanoparticles in an alumina/oil nanofluid. It was found that the power generation of the system increased by decreasing the nanoparticle size and increasing the nanofluid concentration.



(a) (b)

Figure 20. (a) Schematic of the SDC-ORC (b) Optical analysis of an SDC [174].

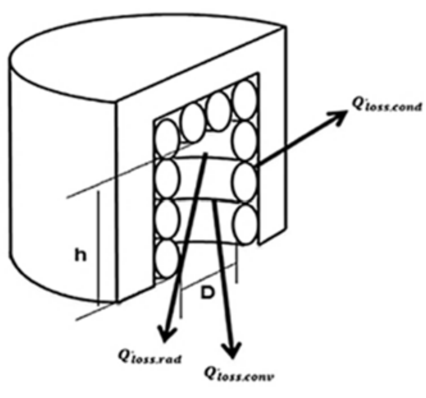


Figure 21. Illustration of the heat loss mechanisms in a cavity receiver of an SDC [175].

In other studies, SDC-ORCs were considered for polygeneration. Ozturk et al. [179] proposed a system to produce electricity, heating, cooling, hydrogen and oxygen. The overall energy and exergy efficiencies were calculated as 52.7% and 57.4% respectively. Moradi and Mehrpooya [180] optimised a polygeneration system for heating/cooling and power generation. They used a hybrid energy source including solid oxide fuel cell and solar energy. They found electrical and overall efficiencies of 48.7% and 79.5% respectively. In another work, Yilmaz et al. [181] developed a solar polygeneration system capable of producing electricity, hydrogen, heating, cooling, water and drying. They found that higher exergetic performance could be achieved by using a higher inlet pressure to the turbine. The energetic and exergetic performance of the plant was calculated as 48.19% and 43.8% respectively. Javidmehr et al. [182] considered a cogeneration system energetically and economically. An ORC system and a micro gas turbine were used for power generation. The performance of the system was optimised and it reached a maximum system efficiency of 70%.

A summary of research works where SDC-ORC was considered is reported in Table 7. In most of the studies, the collectors were employed to generate electricity, heating and cooling simultaneously. Moreover, a lot of research has been focused on the investigation of different cavity receivers for coupling with ORC. Generally, the efficiencies are high because the SDC can operate at relatively high temperatures. More specifically, the energy efficiency of an ORC-only system can be 37.5%, while in polygeneration systems the efficiency can be as high as 70%. However, there is a lack of experimental literature and therefore a need for developing small and large-scale setups for testing SDC-ORCs for electricity production or polygeneration.

Table 7. Summary of ORC systems employing SDCs.

Authors	Brief title	Highlights	Ref.
Loni et al. (2016)	SDC-ORC with rectangular-cavity tubular receiver.	The overall thermal efficiency increased by decreasing the inner tube diameter and the inlet temperature.	[174]
Loni et al. (2016)	Solar receiver with a tubular cylindrical cavity.	The optimum cavity depth was found to be equal to the cavity diameter.	[175]
Loni et al. (2016)	ORC using a tubular solar cavity receiver.	Among the tested working fluids, methanol provided the maximum thermal efficiency of 37.5%.	[176]
Loni et al. (2017)	Solar-ORC with square prismatic cavity receiver.	The depth had to be the same as the aperture dimension for optimum performance.	[177]
Loni et al. (2018)	Effects of volume fraction of alumina nanoparticles on the ORC.	Higher efficiency for smaller nanoparticle size and higher nanofluid concentration.	[178]
Ozturk, and Dincer (2013)	Solar-based polygeneration system.	The energy and exergy efficiency of the system was calculated as 52.7% and 57.4% respectively.	[179]
Moradi and Mehrpooya (2017)	Hybrid solid oxide fuel cell and SDC.	The electrical and overall efficiency was 48.7% and 79.5% respectively.	[180]
Yilmaz et al. (2018)	A solar-based system with hydrogen production.	The energetic and exergetic performance was calculated as 48.19% and 43.8% respectively.	[181]
Javidmehr et al. (2018)	Economic analysis of a polygeneration system.	Maximum system efficiency of 70% was reported.	[182]

3.7 Solar tower (ST)

The ST system is a configuration that can be used in high-temperature applications because of the high concentration ratios. Consequently, there is a potential for achieving high exergy efficiency and to develop highly efficient power or polygeneration units. This section considers ST coupled to a system that includes ORCs. Fig. 22 shows a hybrid solar power generation system including CPV and solar-ORC which was investigated by Han et al. [183]. They found that, with 500 suns, the total efficiency could increase from 28.4% to 44% by using the hybrid system instead of the conventional CPV system.

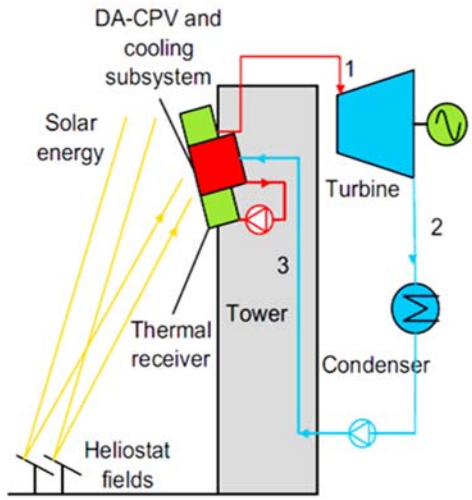


Figure 22. Schematic of the ST power system [183].

Balta et al. [184] performed an energy and exergy analysis on a system that incorporated ORC, Brayton cycle, ST and electrolyser for power and hydrogen production. For power-only, the energy and the exergy efficiencies were 24.8% and 22.45 respectively, while with hydrogen production these efficiencies became 87% and 88% respectively. Zare and Hasanzadeh [185] considered a power generation system using an ST and a combined system that including a Brayton cycle and two bottoming ORCs (see Fig. 23). The overall system exergy efficiency was found to be over 30%.

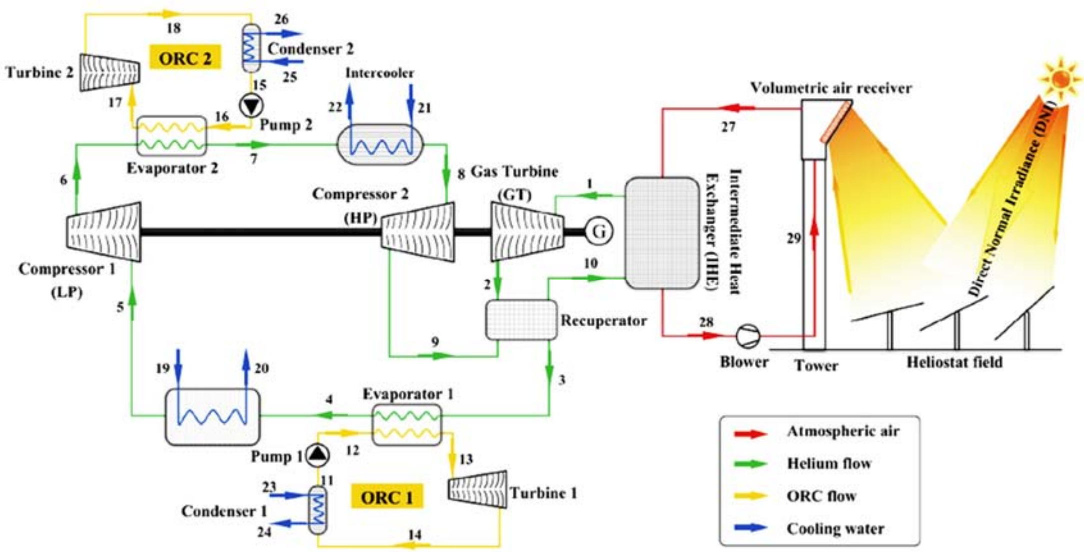


Figure 23. ST coupled to a Brayton cycle which drives two bottoming ORCs [185].

Khaliq [186] studied a modified ORC with an ejector for cooling and electricity. They used ST to feed the system and the energy efficiency reached 30%. In another work, Han et al. [187] investigated a power generation system including CPV and ST under energy and exergy aspects. The maximum system efficiency was found to be 37.2%.

Yilmaz [188] evaluated the performance of a polygeneration system using solar energy. The suggested system could generate different useful products including power, heating, cooling, freshwater, and hydrogen. The power generation system included a Brayton cycle, an RC, and an ORC. The overall energy and exergy efficiencies of the system were 78.9% and 47.6% respectively. Javanshir et al. [189] thermodynamically investigated a power generation system with CSP as the heat source. The ORC, steam RC, Brayton cycle, and combinations of power cycles were evaluated. Results showed that the CSP system with a combined ORC and Brayton cycle had the highest performance. More specifically, for a maximum cycle temperature of above 650°C, the highest thermal efficiency of around 45% was attributed to the combined CO_2 Brayton and ORC unit. In another work, Li et al. [190] suggested a new two-step power generation system for increased storage capacity using direct steam generation. In the first step, the solar working fluid (water) was vaporised in the solar system and power was generated by flowing the steam through a turbine. In the second step, heat rejected by the condenser was transfer to an ORC system for power generation. It was concluded that the storage capacity could be improved by 460% using the suggested system.

A summary of ORC systems using STs as the heat source is presented in Table 8. ST systems are able to accommodate a wide range of cycles including ORCs with high-temperature working fluids. Many articles focused on the assessment of hybrid systems, such as ST coupled with CPV technology, hydrogen production systems, or Brayton cycles. Generally, high efficiencies can be found especially in cases with hydrogen production or with the incorporation of Brayton cycles with ORC. In the future, there is a need for more optimisation studies and experimental works.

Table 8. Summary of ORC systems employing STs.

Authors	Brief title	Highlights	Ref.
Han et al. (2015)	Hybrid CPV and solar-ORC.	The application of a hybrid system instead of the conventional CPV increased efficiency from 28.4% to 44.0%.	[183]
Balta et al. (2016)	Analysis of a hydrogen production system.	The H_2 production increased the energy and exergy efficiencies from 24.8% to 87% and from 22.4% to 88% respectively.	[184]
Zare and Hasanzadeh (2016)	Closed Brayton cycle-based combined solar-ORCs.	System exergy efficiency of over 30% was found.	[185]
Khaliq (2017)	Solar system for cogeneration of power and cooling.	System efficiency of up to 30%.	[186]
Han et al. (2017)	CPV and ST-ORC.	Maximum system efficiency of 37.2%.	[187]
Yilmaz (2018)	Solar energy-based polygeneration system.	The overall energy and exergy efficiencies of the system were 78.9% and 47.6% respectively.	[188]
Javanshir et al. (2018)	Analysis of single and combined power cycles.	For a maximum temperature above 650°C, the highest thermal efficiency was 45% with the combined CO_2 Brayton and ORC unit.	[189]
Li et al. (2019)	Direct steam generation solar power systems.	A 460% storage capacity increase was possible by using a direct solar collector.	[190]

3.8 Other solar-powered systems

In the literature, there are power systems that are driven by alternative solar technologies [191]. Ziapour et al. [192, 193] developed a solar-ORC system using a solar pond (see Fig. 24). A thermoelectric generator was used as the condenser of the ORC system. Results showed that the performance of the system increased with the application of a thermoelectric generator. Lee et al. [194] suggested a novel idea for power generation using a solar chimney to deliver heat to an ORC. Different dimensions of the system were optimised for achieving the best performance. Some experimental tests were conducted on the solar chimney and ORC system (see Fig. 25). The highest outlet temperature and efficiency of the solar system were calculated as 125°C and 65% respectively, based on experimental tests. The daily electric output of the system was reported as 12 kWh per 41 m^2 of solar chimney area. A summary of the ORC systems mentioned in this section is presented in Table 9.

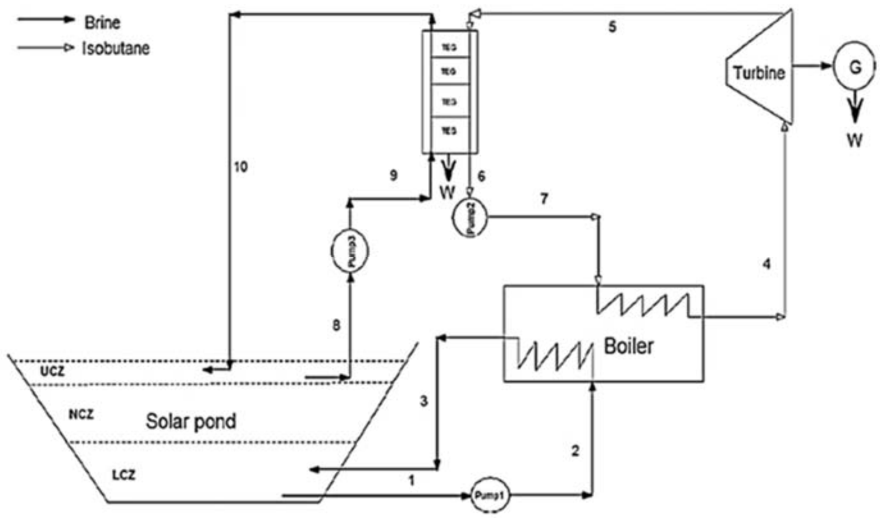
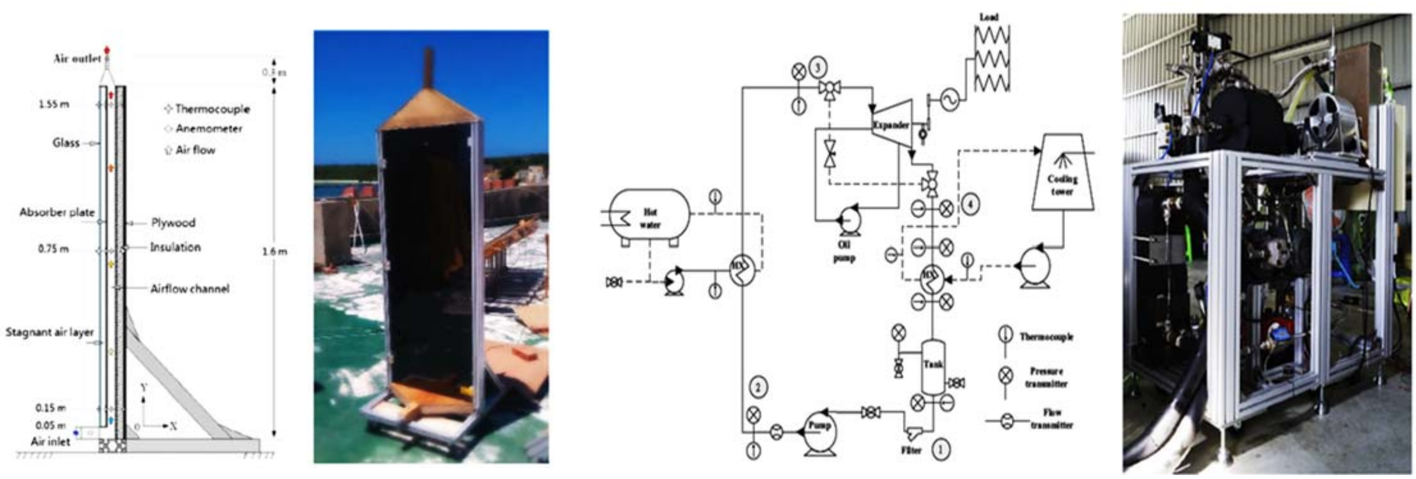


Figure 24. Schematic of an ORC driven by a solar pond [192].



(a) **(b)**

Figure 25. Schematics and photographs of (a) the solar chimney (b) the ORC [194].

Table 9. Summary of ORC systems employing alternative solar systems.

Authors	Brief title	Highlights	Ref.
Ziapour et al. (2016)	Energy extraction in a solar pond power plant.	The overall thermal efficiency of the solar pond power plant reached a maximum when employing both thermosyphons and heat exchangers.	[193]
Lee et al. (2015)	Investigation of solar chimney integrated with ORC system.	The proposed solar system yielded a maximum outlet temperature, efficiency and electricity output of 125°C, 65% and 12 kWh/day respectively.	[194]

3.9 Hybrid systems

Hybrid systems featuring ORCs have seen an increased interest in recent years due to their higher efficiency and reliability. Hybrid systems utilise solar energy together with other energy sources, such as waste heat from a heat engine, geothermal energy, biomass, biogas or LNG, to feed the ORC. This section is devoted to the literature available on these systems.

3.9.1 Solar-geothermal

The majority of the literature focuses on the combination of solar and geothermal energy sources. Table 10a includes the studies about solar-geothermal systems with ORC and the main details of these studies are given inside this table. Astolfi et al. [195] investigated such a hybrid system using PTC. The yearly performance of the system was estimated using hourly data. The LCOE was calculated to be 145-280 €/MWh. In another work, Tempesti and Fiaschi [196] investigated a 50 kW power generation system using ORC systems driven by ETC-geothermal. The system could provide heating when needed and could therefore be converted into a cogeneration system. Different organic fluids were considered as the ORC working fluid, including R134a, R236fa, and R245fa. The best performance was found with R245fa. Ghasemi et al. [197] considered a hybrid ORC system (PTC-geothermal) and a maximum system efficiency of 17.9% was found. In another work, Ayub et al. [198] found that the hybrid configuration (PTC-geothermal) had a maximum efficiency of 8% while the solar-only case presented a maximum efficiency of 6.3%. It was found that the levelised electricity cost parameter reduced by about 2% when using the hybrid system compared to having only geothermal energy as the heat source. The use of solar evacuated FPC-geothermal was studied by Buonomano et al. [199] for a trigeneration system. They conducted an analysis with TRNSYS for a hotel in Ischia and found that the ORC efficiency was 6%, the solar collector efficiency was 60% and the simple payback period was between 2.5 and 7.6 years. Calise et al. [200] used PTC-geothermal for a polygeneration system that produced fresh water, electricity, heating and cooling. The proposed system was investigated based on energy and economic analyses in different weather conditions. They found a payback period of 4.5 years. In a similar investigation, Calise et al. [201] found the maximum exergy efficiency in winter (up to 50%) while in summer the exergy efficiency was lower (up to 20%). The cost of electricity was estimated in the range of 0.148 €/kWh to 0.172 €/kWh. Islam and Dincer [202] also investigated a similar system for heating, cooling, drying and power generation. The energy and exergy efficiencies were 51% and 62% respectively. Moreover, Heberle et al. [203] considered from economical and technical perspectives an ORC system for power generation using PTC-geothermal. The system efficiency was 10% and the lowest LCOE was 145 $/MWh. Bassetti et al. [204] developed an ORC power system using PTC-geothermal and TES. The system efficiency was 6.3% in hybrid mode while it was 5.3% in the geothermal-only mode. Li et al. [205] investigated a solar-geothermal-driven ORC system using two-stage evaporation. It was concluded that the performance of the system could be improved by using a two-stage serial ORC system driven by dual-level heat sources. The maximum exergy efficiency of the system was 27%.

3.9.2 Solar-biomass

Solar-biomass hybrid systems are also common in the literature and this section describes them, while table 10b gives a brief summary of these systems. Zourellis et al. [206] developed a cogeneration ORC system using PTC-biomass (see Fig. 26). They found that with a collector area of close to 30 000 m^2, the maximum electricity produced was 15 MW. Moreover, Karellas and Braimakis [207] investigated a hybrid system (PTC-biomass) including an ORC system and a vapour compression cycle (VCC) for polygeneration. The energy and exergy efficiencies were 5.54% and 7.56% respectively. Patel et al. [208] investigated an ORC-based trigeneration system driven by solar-biomass for cooling and heating. The use of SDC technology led to the highest solar fraction followed by PTC and LFR. The minimum payback period of the system with the use of biomass was 7.5 years. In another study, Yue et al. [209] developed a drying system that was powered by solar irradiation and biomass. They found that the net power of the system increased by increasing the moisture content and temperature of the outlet air of the drying system. Pantaleo et al. [210] investigated a hybrid system (PTC-biomass) for heating, cooling, and power generation. They examined different design scenarios and found the system to be financially viable. In another work, Boyaghchi and Chavoshi [211] studied an FPC-biomass hybrid system for power generation and heating at two temperature levels. Water/CuO nanofluid was used as the solar working fluid and the system had an exergy efficiency of 39.8%. Pantaleo et al. [212, 213] investigated a PTC-biomass hybrid trigeneration system. An ORC system was used at the bottom of the cycle for power generation. The LCOE ranged from around 100 €/MWh to above 220 €/MWh. Bufi et al. [214] thermodynamically optimised a hybrid PTC-biomass system. Toluene was recommended as the most suitable working fluid with a system efficiency of 30.3%. Pantaleo et al. [215] techno-economically investigated combined Brayton and ORC power plants using PTC-biomass. The global efficiency of the system with large PTC and TES was around 25%. In another investigation, Bellos et al. [216] considered polygeneration (using PTC-biomass) for producing power, cooling and heating at two temperature levels. The system was first optimised for steady-state conditions and then further investigated for performance during a typical year. The yearly energy and exergy efficiencies of the system were 51.26% and 21.77% respectively. Morrone et al. [217] investigated a hybrid ORC system (PTC-biomass) for cogeneration. They compared the hybrid ORC system with solar-only and biomass-only systems. It was concluded that the hybrid ORC system allowed for better utilisation of the low solar radiation levels and the system energy efficiency was around 67%.

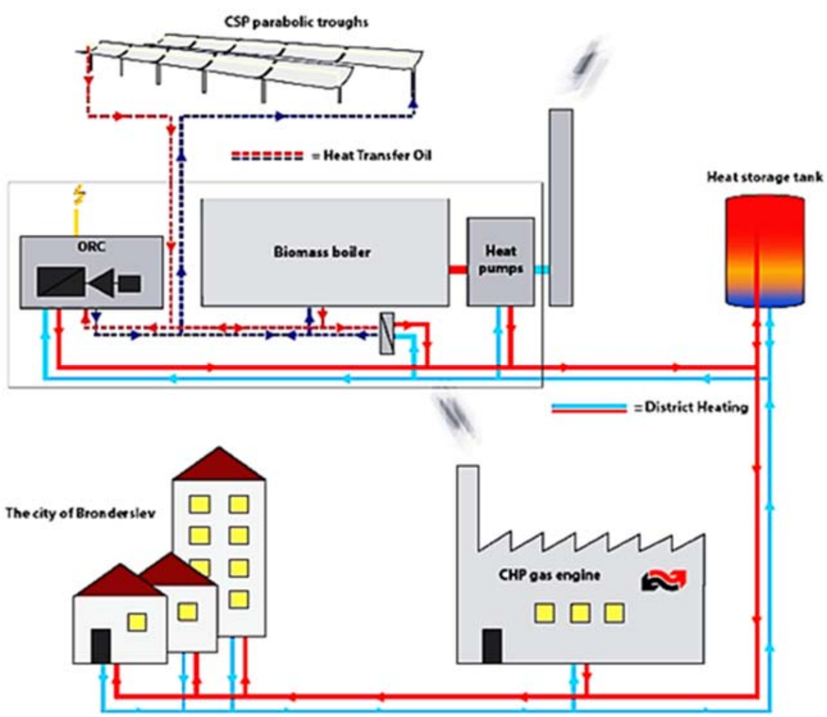


Figure 26. Hybrid system with solar energy and biomass furnace [206].

Biogas has also been considered in hybrid systems. Soares and Oliveira [218] developed a hybrid PTC-biogas system for power generation. The annual system efficiency was 37.4% and the hybrid mode was the most efficient. In another interesting study, Mosaffa et al. [219] suggested a novel polygeneration layout for power, heating, methanol and hydrogen, using ST-biogas. Moreover, the system was thermodynamically and exergo-environmentally considered. The authors concluded that the heat source temperature was an effective parameter for improving system performance. The energy and exergy efficiencies of the hybrid system were around 70% and 63% respectively.

3.9.3 Other hybrid systems

The use of alternative hybrid systems is presented in the present section and Table 10c includes the respective results. LNG and waste heat have also been investigated for feeding an ORC in combination with solar energy. Mehrpooya et al. [220] proposed a hybrid solar-LNG ORC system for power generation (see Fig. 27). The regenerative ORC was optimised and its exergy efficiency was found to be 14.4%, an increase of 5.7% compared to the reference scenario. Moreover, financial analysis proved a yearly income of 3.61 M$. Bellos and Tzivanidis [221] developed an ORC system fed by solar PTC and waste heat (see Fig. 28). Different ORC working fluids were considered and the system showed maximum performance with toluene (up to 19.7%). Moreover, Kane et al. [222] experimentally investigated a hybrid power system (using LFR and diesel engine waste heat) in cascade configuration with two ORCs. The system could produce heating and cooling when needed. The total system efficiency was 41% in hybrid mode and 7.7% in solar-only mode. Another interesting idea is the combination of thermal collectors and PV, which was investigated by Rahbar et al. [223]. A direct absorption tubular configuration was applied with PV cells on its outer surface. The authors used nanofluids to enhance the absorption inside the tubular receiver of the PTC. An ORC was coupled to the system and the final configuration presented an overall efficiency of 20.5%, while the CPVT-only system had an efficiency of 17.8%. Lastly, Li et al. [224] considered a hybrid system (solar-LNG) for power generation using an ORC system. The authors compared FPC and ETC and found that ETC performed the best. A system efficiency of 6% was found with isopentane/R125 as the working fluid in the ORC.

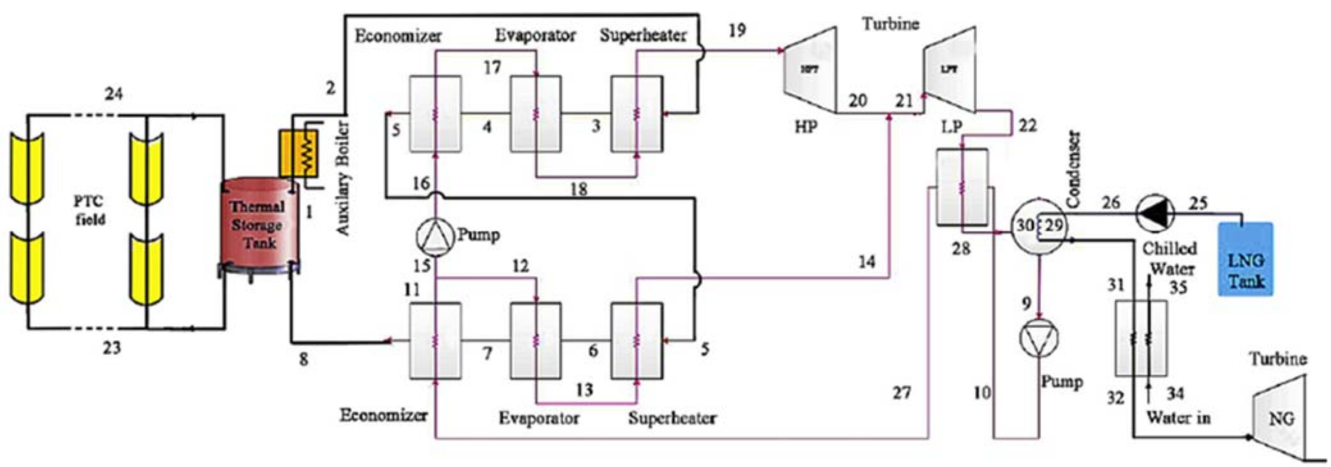


Figure 27. Hybrid system with PTC and LNG tank [220].

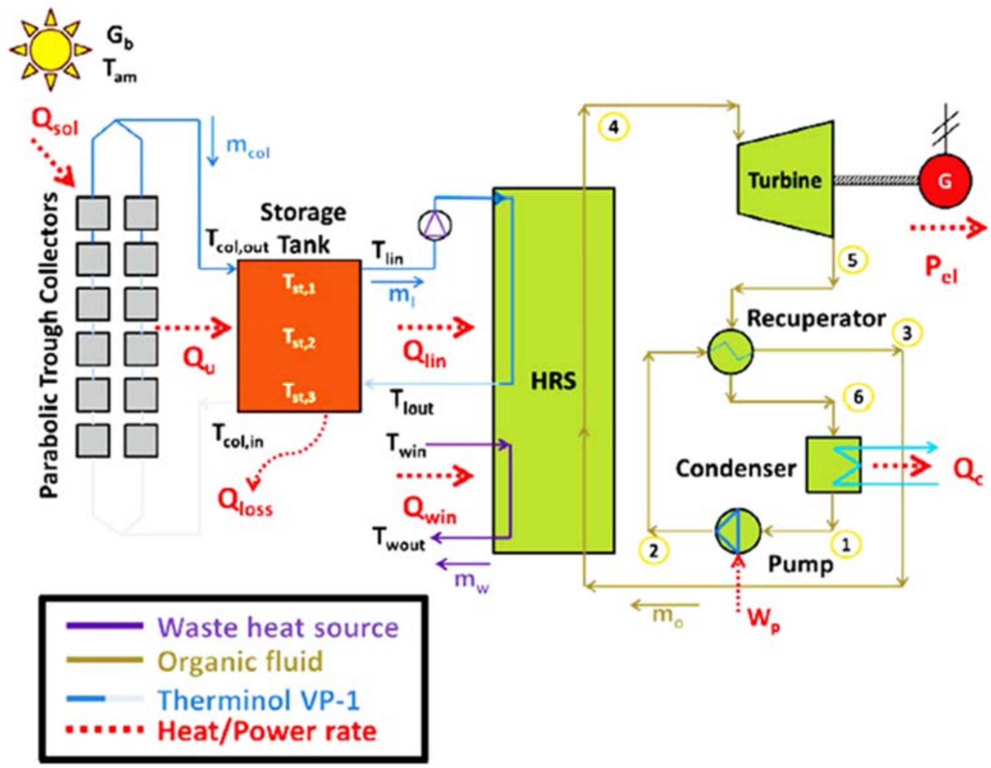


Figure 28. Hybrid system with solar energy and waste heat [221].

3.9.4 Summary

A summary of hybrid ORC systems in solar applications is presented in Tables 10a, 10b and 10c. Solar energy showed a high potential to be integrated with other resources for the purpose of producing clean energy. Researchers have investigated hybrid ORC systems powered by solar-geothermal, solar-biomass, solar-diesel engine and solar-LNG. The main aim of the hybridisation was to increase the reliability as well as the first and second law efficiencies of the systems. Research studies focused on the impact of hybridisation, the amount of thermal and electrical energy produced and, in some polygeneration systems, the amount of fresh water, hydrogen, or methanol produced, as well as the costs involved. In all cases, the hybrid systems proved to be more efficient with lower expense. Moreover, it has to be said that a great part of the literature has been focused on solar-geothermal and solar-biomass ORCs.

Overall, there is still vast opportunity for further research on hybrid systems. For example, determining the optimum proportion of each energy source to run the ORC unit, finding the best types of solar collectors to be coupled with another source of energy and testing a wide range of ORC and solar collector working fluids have not been studied comprehensively. Moreover, geographical features, one of the most important parameters which have a profound effect on the configuration of systems and the final cost of products, have not been taken into consideration in most of the studies. This parameter sheds light on the availability of each resource in each area, social and economic conditions as well as the conventional source of energy in each region. This information assists researchers to present their results far more accurately and realistically and opens the door to the commercial exploitation of renewable energy. Moreover, there is a need for conducting more experimental studies, especially studies with an ST or SDC coupled with geothermal or biomass heat sources.

Table 10a. Summary of hybrid solar-geothermal ORC systems.

Authors	Brief title	Highlights	Ref.
Astolfi et al. (2011)	PTC-geothermal coupled to ORC.	The LCOE produced was 145-280 €/MWh.	[195]
Tempesti and Fiaschi (2013)	ETC-geothermal coupled to ORC.	R245fa was found to be the best organic fluid.	[196]
Ghasemi et al. (2014)	PTC-geothermal coupled to ORC.	Maximum system efficiency of 17.9%.	[197]
Ayub et al. (2015)	PTC-geothermal coupled to ORC.	Maximum hybrid system efficiency of 8%, while for the solar-only case the maximum efficiency was 6.3%.	[198]
Buonomano et al. (2015)	Evacuated FPC-geothermal coupled to ORC.	The ORC electric and solar collector efficiencies were 6% and 60% respectively.	[199]
Calise et al. (2016)	PTC-geothermal for polygeneration.	Payback period of 4.5 years.	[200]
Calise et al. (2016)	PTC-geothermal for polygeneration.	Maximum exergy efficiency of 50% in winter and 20% in summer. The LCOE was in the range of 0.148 €/kWh to 0.172 €/kWh.	[201]
Islam and Dincer (2017)	PTC-geothermal for polygeneration.	The energy and exergy efficiencies were 51% and 62% respectively.	[202]
Heberle et al. (2017)	PTC-geothermal coupled to ORC.	The system efficiency was 10% and the lowest LCOE at 145 $/MWh.	[203]
Bassetti et al. (2018)	PTC-geothermal coupled to ORC.	The system efficiency was 6.3% in the hybrid mode and 5.3% in geothermal-only mode.	[204]
Li et al. (2018)	Solar-geothermal coupled to two-stage ORC.	Maximum exergy efficiency of 27%.	[205]

Table 10b. Summary of hybrid solar-biomass ORC systems.

Authors	Brief title	Highlights	Ref.
Zourellis et al. (2018)	PTC-WHR for cogeneration.	Maximum electric power output of 15 MW.	[206]
Karellas and Braimakis (2016)	PTC-biomass for trigeneration with ORC-VCC.	System energy and exergy efficiencies were 5.54% and 7.56% respectively.	[207]
Patel et al. (2017)	Solar-biomass (PTC, LFR or SDC) for trigeneration.	Payback period of 7.5 years.	[208]
Yue et al. (2017)	Solar-biomass drying system.	Increased moisture and temperature of the outlet air from the drying system would lead to electricity increase.	[209]
Pantaleo et al. (2017)	PTC-biomass for trigeneration.	Financially viable investment.	[210]
Boyaghchi and Chavoshi (2017)	FPC-biomass for cogeneration.	Maximum exergy efficiency of 39.8%.	[211]
Pantaleo et al. (2017)	PTC-biomass for trigeneration.	The LCOE ranged from around 100 €/MWh to above 220 €/MWh.	[213]
Bufi et al. (2017)	PTC-biomass for cogeneration.	System efficiency of 30.3% with toluene.	[214]
Pantaleo et al. (2018)	PTC-biomass coupled to combined cycle.	The global efficiency of the system with large PTC and TES was around 25%.	[215]
Bellos et al.	PTC-biomass for	The annual energy and exergy efficiencies were 51.3%	[216]

(2018)	polygeneration.	and 21.8% respectively.	
Morrone et al. (2018)	PTC-biomass for cogeneration.	System energy efficiency of 67%.	[217]
Soares and Oliveira (2017)	PTC-biomass coupled to ORC.	Annual system efficiency of 37.4%.	[218]
Mosaffa et al. (2019)	ST-biogas for polygeneration.	The energy and exergy efficiency of the hybrid system was around 70% and 63% respectively.	[219]

Table 10c. Summary of various hybrid ORC systems.

Authors	**Brief title**	**Highlights**	**Ref.**
Mehrpooya et al. (2017)	PTC-LNG coupled to ORC.	The optimised exergy efficiency was 14.4%.	[220]
Bellos and Tzivanidis (2018)	PTC-WHR coupled to ORC.	Maximum performance with toluene (up to 19.7%).	[221]
Kane et al. (2003)	LFR-WHR coupled cascade ORCs.	System efficiency of 41% in hybrid mode and 7.7% in solar-only mode.	[222]
Rahbar et al. (2019)	DASC-CPVT coupled to ORC.	Overall efficiency of the combined system was 20.5% while it was 17.8% in the CPVT-only system.	[223]
Li et al. (2016)	Solar-geothermal (FPC or ETC) for trigeneration.	ETC led to the highest efficiency of 6% (higher than FPC).	[224]

3.10 TES in solar-ORC systems

Solar irradiation is a variable heat source that presents a need for TES in order to eliminate heat source fluctuations. The use of TES allows the system to operate at approximately steady-state conditions and to operate close to the nominal point where the various subsystems have been sized [225]. Moreover, the use of a storage system makes the storage of useful heat, during the hours of high solar irradiation, and its utilisation later in the afternoon possible. Usually, a TES is designed for a few hours (4 to 8 hours) in order to develop systems with relatively high capacity factors. There are many ways of storing thermal energy in ORCs. Sensible storage is usually done by using storage tanks, while latent heat storage is performed by using PCM.

3.10.1 Sensible storage

Kutlu et al. [46] investigated a system with sensible storage. The system included a single water storage tank. In another work, Bassetti et al. [204] found that the use of two storage tanks in a solar field (see Fig. 29) was able to increase the annual power output by about 19% compared to the case without storage. Moreover, Pantaleo et al. [212] considered the use of a storage system between a primary and a bottoming solar-driven ORC. They found that having a storage system with molten salt between the two cycles was beneficial for the performance of the total configuration. Rodriguez et al. [133] compared the use of two tanks and of a single thermocline tank. They found that both configurations had similar thermal performance but that the thermocline was more cost-effective (30% lower cost). Li et al. [190] developed a novel system for TES using a direct steam generation solar technology with a payback period of around 5 years. Furthermore, Patil et al. [125] compared a solar-ORC using TES with a solar PV system using battery storage. They found that the solar-ORC had a lower LCOE and higher reliability than the PV system using batteries.

3.10.2 Latent heat storage

The use of latent heat storage makes it possible to store useful heat at preferable temperature levels without superheating, which reduces solar thermal efficiency and adds extra thermal losses. Moreover, a PCM can store large amounts of heat with a relatively small volume, allowing for more compact systems. However, the use of latent heat storage through PCM adds an extra cost to the system and also creates possible limitations to the reliability of the storage system. A proper design is therefore needed to develop a cost-effective and reliable system. Lakhani et al. [226] designed a solar-ORC with latent heat storage in the solar field loop. They found that the discharging efficiency of the stored energy was about 83%. Manfrida et al. [227] developed a model for simulating the latent heat storage in a solar-ORC. They found that a proper design with PCM storage allowed the system to operate for about 80% of the day. Lastly, Alvi et al. [53] studied the use of a direct and indirect PCM storage system in a solar-ORC system (see Fig. 30). They found that the direct system was more efficient than the indirect storage system.

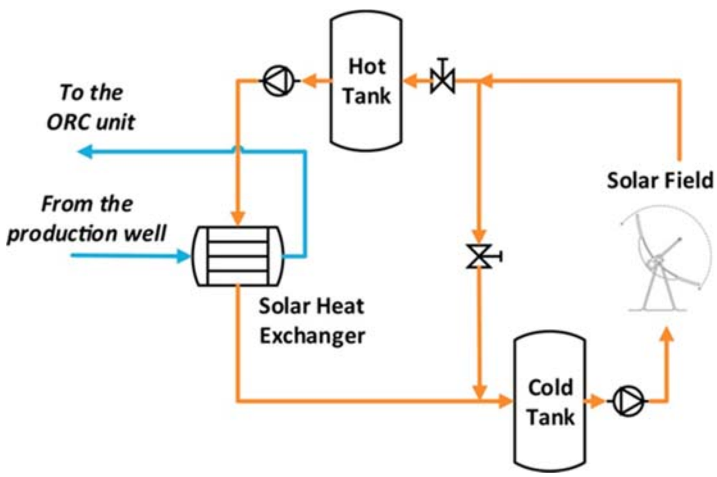
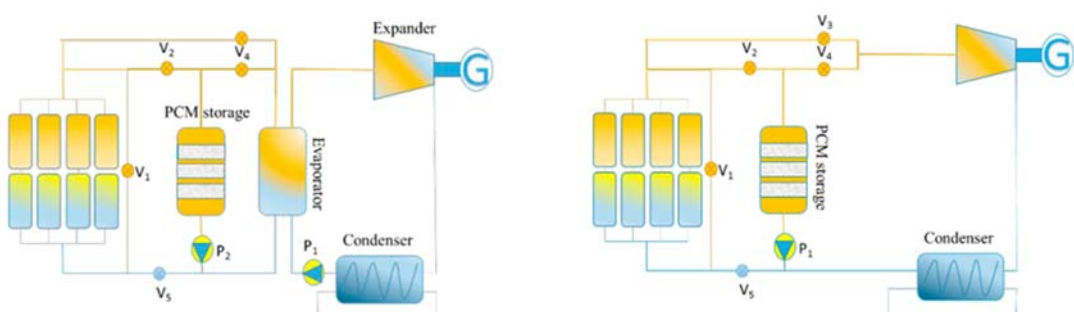


Figure 29. A sensible heat storage system with two storage tanks [204].



(a) **(b)**

Figure 30. Solar-ORC with PCM storage: (a) indirect system, and b) direct system [53].

4 Further discussion and suggested directions for future research

The presented review summarised the literature on ORC systems driven by solar-thermal collectors. Valuable conclusions have been extracted from this compilation of work and are discussed in this section, especially concerning solar collector selection along with issues relating to hybridisation and storage.

4.1 System performance

The first part of this review paper regards the non-concentrating solar-ORC systems. These systems present low simplicity due to the lack of tracking mechanism, low investment cost but also low efficiency. Therefore there is a need for installing high collecting areas in order to produce significant electricity amounts. Thus, the research has been expanded to solar-concentrating systems coupled to ORC in order to achieve higher system efficiencies. However, concentrating systems present a higher complexity due to the need for tracking systems and are also associated with increased investment costs. Concentrating systems also do not show improved performance in regions of high diffuse irradiance. However, they can lead to better performance in both energy and exergy terms if the solar conditions allow for this (requires a relatively good solar resource with clear-sky conditions). Specifically, linear concentrating systems are a reliable choice and numerous studies have, for this reason, considered PTCs, while a smaller number of studies have considered ETCs and LFRs. High-quality PTCs lend the possibility of operating at high temperatures (of up to 400-500°C) with reasonable optical and thermal efficiencies. PTCs therefore also account for the lion's share of the solar-ORC literature due to their maturity and performance in good solar conditions. In lower solar resource areas and/or more cloudy climates (in which the diffuse radiation component is more significant), studies have suggested that ETCs can have a similar performance to PTCs, but with a lower cost and complexity [13, 173]. On the other hand, LFRs have an interest due to their lower capital cost and lower fatigue loads because of the non-movable absorber parts. Reported thermal efficiencies with PTCs are generally above 20%, while LFRs lead to lower performance, especially at high latitudes. Various studies have considered different techniques for enhancing the performance of LFR-based ORC systems. The CPC, which is similar to the PTC, has a low concentration ratio and in some cases can operate without tracking. This technology is not as common in ORC applications, and also does not lead to high system efficiencies due to the limitations in its operating temperature.

The use of solar concentrating collectors in ORC systems for cogeneration, trigeneration, or polygeneration was also found in the literature. PTCs are a common option for solar-driven polygeneration units and lead to high energy and exergy efficiencies. Point-focal concentrating systems in particular are ideal for polygeneration. SDCs and STs can operate at higher temperatures than PTCs. This increases their exergetic performance and allows them to be applied in high-temperature applications for producing special useful outputs such as hydrogen.

The literature review also considered hybrid systems (a combination of solar energy with other energy sources, and more specifically geothermal energy, biomass and waste heat recovery). Hybrid systems are usually high capacity-factor systems thanks to the different and in many cases complementary, energy input profiles. Moreover, TES is an important element for achieving continuous operation or operation during a large portion of the day. Usually, TES systems rely on sensible storage that gives the possibility of storing energy for 4-8 hours daily, but various PCMs have also been proposed depending on the storage temperature.

Economic and financial assessments indicate that solar-ORC systems can be more viable and promising as part of wider polygeneration systems and with concentrating collectors in locations with high solar potential. The capital cost of these systems is relatively high but can be reduced with the maturing of the technology. Compared to PV technology, solar-ORC systems have higher costs; however, they can lead to higher energy and exergy performance, and also offer the opportunity for TES and polygeneration, at a lower overall cost. Solar-ORC can therefore be a competitive technology with its own advantages and disadvantages depending on the application, the needs of the end-user and the cost of electricity in every case. More specifically, it has been found that the PTC-ORC system leads to lower LCOE compared to PV technology, for the same capacity [125].

Comparing the LCOE of different solar-ORC technologies, it should be mentioned that the use of LFR leads to the highest LCOE and therefore it is not the recommended design [118]. On the other hand, PTC is more promising with lower LCOE [118]. The LCOE of PTC-ORC systems is usually listed in literature as 0.18 $/kWh [169]. CPC-ORC systems has an LCOE of 0.21 $/kWh [88] and is a better choice than using FPC or ETC. Moreover, the combination of PTC with other renewables reduces the LCOE. The use of a PTC-geothermal ORC presents an LCOE of 0.15 $/kWh [203], while the combination of PTC with biomass coupled to an ORC can reduce the LCOE to 0.1 €/kWh [212].

Lastly, it is important to discuss the control strategy of ORCs. PID controllers are usually used, as was done by Ni et al. [117] where 24% performance enhancement was found. Quolin et al. [228] investigated three different PID control strategies: the constant evaporating temperature strategy, the optimised evaporation temperature strategy and the pump speed strategy. It was found that the optimised evaporation temperature strategy is the best. In another work, Pang et al. [229] considered different PID control cases. It was concluded that a variable frequency device has to be applied in small ORCs and also that the superheat control methodology is a good choice in order to control the working mass flow rate. Moreover, PID control is the usual choice in solar-ORC [117] and geothermal-ORC [230] units.

4.2 Limitations of solar-ORCs

Solar-ORCs are promising systems with acceptable efficiency which can also be included in wider polygeneration systems for producing numerous useful outputs. However, there are technological limitations that remain and these can be used to motivate further research and development. Firstly, solar-ORC systems have high capital costs, especially in small-scale applications. Moreover, there is a need to identify high-performance turbine or expansion devices in order to achieve high overall efficiencies, including at part-load and off-design operation. This fact is important especially in small-scale systems in order to make them financially competitive with alternatives.

Another critical issue regards the selection of high-performance working fluids. There is a growing requirement for using fluids with zero ODP and low GWP, as well as fluids with low toxicity and flammability. However, it is not an easy task to find optimal working fluids with these characteristics and also with high efficiency. This has led to a significant research activity by many research groups. In low-temperature systems, natural refrigerants such as R290, R600 and R600a seem to be suitable candidates, while at higher temperatures, working fluids such as toluene, cyclohexane, MDM and MM seem to lead to the best performance. To conclude, in every case, there is a need for a working fluid investigation that takes into account different aspects of the application amongst other constraints.

4.3 Future work

Although commercially the technology has been facing challenges from low-cost PV, current research on solar-ORC systems is internationally cross-cutting and rapidly gaining traction. Therefore, the field is open and there is great potential for further research. Based on the present review of the literature, it is our view that the goal of future studies should be to determine the design and operation design characteristics and features of the most efficient and cost-effective solar-ORC technologies for deployment in different applications, regions and for different (local) needs. On the solar collector side, there is a need for performing more studies on suitable collectors that have not been studied in great detail when integrated with ORC technology. For example, studies on the use of CPCs and LFRs can be performed as these are popular choices, but also on ETCs which have not been extensively studied and have been shown to be promising in some cases. Moreover, there are only a few studies about alternative solar technologies with ORC systems, such as solar stills and solar chimneys, so these solar technologies can also be considered for future research.

Another critical aspect of future research regards energy storage. The most usual system involves sensible TES, while there are also other alternatives. The use of PCMs, for example, as well as of thermocline-bed sensible storage with rocks, or thermo-chemical storage are interesting alternatives that can be particularly suitable in this application and demand further investigation. PCMs, in particular, have attracted attention and led to a number of published studies, however, there is great scope to expand our knowledge in this area. For thermo-chemical storage, there is a need for studies on feasibility in solar-ORC applications as this enables longer-term (inter-seasonal) storage (storage during the summer and exploitation later in the year). The cost of the storage has to be taken into consideration in each analysis.

Lastly, the most important challenge for the future is to create commercial solar-ORC systems that can compete with other power generation systems with the real potential for substituting fossil-fuel systems. There is a need for performing more experimental studies in full-scale systems in order to create the basis for developing low-cost commercial products. The development of solar-ORC technology as part of wider polygeneration systems is a way to achieve sustainability in future energy systems in the building sector or in local communities that present high energy needs for cooling, heating and electricity. This is a particularly promising avenue for further research, especially since the technology readiness levels here are much lower. Moreover, there is a need for making ORC technology a well-known and socially acceptable technology. Proper dissemination of information in the industrial society, regarding the advantages of ORC coupled to renewables, has to be performed in order for this technology to be expanded into many markets. The advantages of ORC technology have to be presented well. More specifically, the compact design, small to high capacities, the reasonable pressure levels compared to the water-steam cycle and the low superheating degree are some of the advantages of this upcoming technology.

5 Conclusions

In this paper, a comprehensive review was presented related to solar-ORC systems for power generation, and also for the provision of additional energy vectors (heating, cooling) or other useful outputs (e.g., fresh water and hydrogen). Firstly, a wide range of different solar collectors that can be coupled to ORC systems was presented. Specifically, FPCs, ETCs, CPCs, LFRs, PTCs, SDCs and STs were reviewed in the context of solar-ORC systems. The review also extended to hybrid systems with dual-energy inputs (specifically solar-geothermal, solar-biomass and solar-WHR), and highlighted issues relating to TES which arise naturally in this application.

The present review work indicates that system efficiencies of over 20% can be achieved with PTCs, which is an effective choice in this application for achieving good efficiency at a reasonable cost. Other linear concentrating technologies and even non-concentrating technologies also appear as promising options in certain cases. Non-concentrating technologies appear especially promising in cooler and more overcast climates with reasonable efficiencies but at lower cost and complexity. Hybridisation of the solar input with other energy sources is an important avenue for creating a sustainable system with a high capacity factor and acceptable financial indicators. As a consequence, hybrid systems enable higher overall system efficiency (about 5%) compared to solar-only systems. TES is also important in allowing continuous power generation, which has motivated significant research on a range of storage solutions, with both sensible TES and PCMs being suitable options.

To conclude, solar-ORC technology is an excellent choice for sustainable and renewable power generation. This is also true for the generation of other useful products in polygeneration configurations, especially in distributed applications, which has shown good performance and which would benefit greatly from further techno-economic improvements. In the future, there is a need for conducting further research, especially experimental studies that would promote the commercial development and deployment of solar-ORC technology, focusing on improving efficiency but also, crucially, the financial proposition of these systems. Issues such as the selection of working fluids, expanders, solar collectors, storage technology as well as system configuration and optimisation remain important and need to be further pursued.

Nomenclature

C	Concentration ratio
G_b	Solar beam irradiance, W/m^2
h	Specific enthalpy, J/kg
LCOE	Levelised cost of electricity, €/kWh
m	Mass flow rate, kg/s
P_{el}	Electricity production, W
$P_{el,net}$	Net electricity production, W
Q_{in}	Input heat in the HRS, W
Q_{hs}	Heat input in the system, W
Q_{out}	Heat rejection to the ambient, W
T	Temperature, K
W_P	Pumping work consumption, W
W_T	Turbine work production, W

Greek Symbols

$\eta_{ex,sys}$	System exergy efficiency
$\eta_{is,T}$	Turbine isentropic efficiency
η_{mg}	Generator-mechanical efficiency
η_{orc}	Organic Rankine cycle efficiency
η_{sys}	System efficiency
η_{th}	Thermal efficiency of the heat source
Ψ_{hs}	Exergy factor

Subscripts and Superscripts

am	Ambient
is	Isentropic
hs	Heat source
hs,in	Heat source inlet
hs,out	Heat source outlet
sun	Sun

Abbreviations

CCHP	Combined cooling, heating and power production
CHP	Combined heating and power production
CPC	Compound parabolic collector

CPV	Concentrating photovoltaic
CPVT	Concentrating photovoltaic/thermal
CSP	Concentrating solar power
DASC	Direct absorption solar collector
ETC	Evacuated tube collector
FPC	Flat plate collector
GWP	Global warming potential
HRS	Heat recovery system
LFR	Linear Fresnel reflector
ODP	Ozone depletion potential
ORC	Organic Rankine cycle
PEMFC	Proton-exchange membrane fuel cell
PID	Proportional–integral–derivative (controller)
PCM	Phase change materials
PTC	Parabolic trough collector
PV	Photovoltaic
RC	Rankine cycle
RO	Reverse osmosis
SDC	Solar dish collector
ST	Solar tower
TES	Thermal energy storage
WHR	Waste heat recovery

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