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Chapter 19

Concentrated Solar Energy-Driven Multi-Generation
Systems Based on the Organic Rankine Cycle Technology

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CHAPTER 19

Concentrated Solar Energy-Driven Multi-Generation Systems Based on the Organic Rankine Cycle Technology

*Nishith B Desai** and *Fredrik Haglind*

1. Introduction

Design of energy efficient, environmentally friendly and economically viable systems is important for sustainable development. Among the various technology options based on renewable energy sources, concentrated solar power (CSP) systems are considered to be technologies in the development stages. Many small to large-scale power plants (a few kW_e to a few MW_e) based on the CSP technology exist in different sun-rich regions worldwide. Due to the high capital cost and high levelized cost of energy (LCOE), CSP plants have not captured a large market share like those of solar photovoltaic (PV) and wind power plants. Concentrated solar power plants with cost-effective thermal energy storage can work as a base load plant with a high capacity factor. In contrast, solar PV and wind power plants with large-scale battery storage are not cost-effective. Patil et al. (2017) reported that the levelized cost of electricity (LCOE) for solar photovoltaic systems with battery storage is about 36.8% higher than that of the parabolic trough collector-powered organic Rankine cycle system with thermal energy storage. Concentrated solar power plants can also avail of the advantage of producing heat and other products, and thus work as a cogeneration, trigeneration or multi-generation unit. In contrast, solar PV and wind power plants cannot be used for heat production; therefore, the sub-systems for cooling and/or heating and/or desalination should be electricity-driven. Shalaby (2017) recommended avoiding the use solar photovoltaic systems with batteries to drive RO desalination systems because of the high capital and running costs. Commonly-used small to medium-scale, dispatchable (on demand) distributed generation systems are diesel generator-based or biomass-based systems. Biomass- and diesel-based multi-generation units can have electrical or thermal energy-driven sub-systems, depending on the resulting cost of utilities. For isolated regions and islands, the cost of electricity generation is high, as the diesel is imported from the nearby port. The use of biomass is a major concern in places with water scarcity, due to the large water footprints of biomass energy sources (Gerbens-Leenes et al., 2009).

Multi-generation systems achieve a higher efficiency and a higher energy utilization factor than plants producing only electricity (Karellas and Braimakis, 2016). Concentrated solar energy-driven

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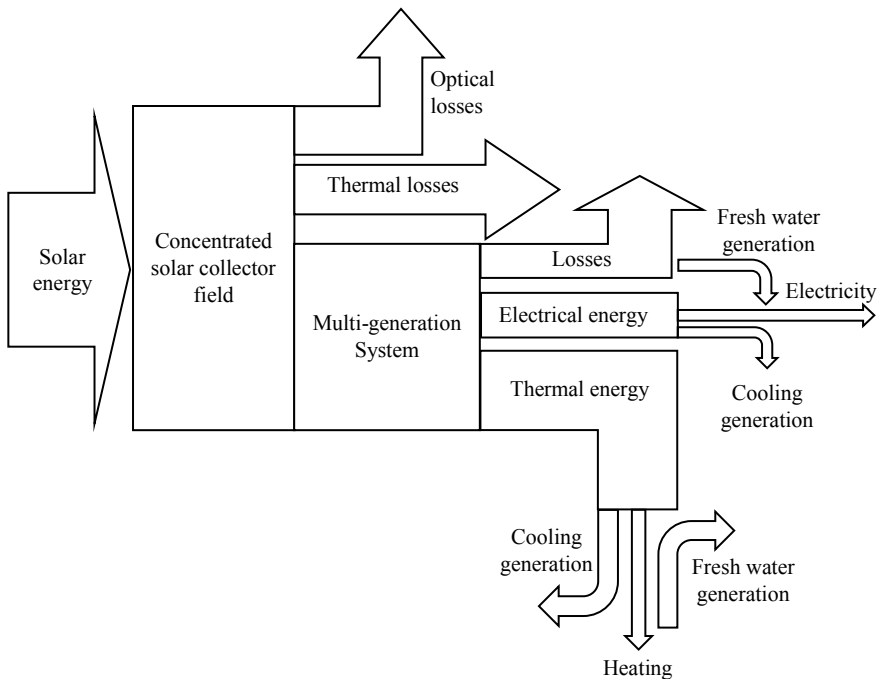


Figure 1. Representation of possible energy conversion routes of concentrated solar thermal energy-powered multi-generation systems.

multi-generation systems are also suitable for decentralized installations. Integrated systems powered by concentrated solar energy and biomass energy make up a promising option (Mathkor et al., 2015). Wu et al. (2019) proposed the integration of a concentrated solar thermal energy and power cycle system with a conventional combined cooling, heating and power system. A representation of possible energy conversion routes of concentrated solar thermal energy-powered multi-generation systems is shown in Figure 1. In the case of a typical parabolic trough collector field, the optical losses (including shading and blocking, cleanliness, shielding by bellows) are about 37% and the thermal losses (including thermal losses from piping) are about 18% (Heller, 2017). For small to medium-scale applications (a few kW_e to a few MW_e), organic Rankine cycle power systems have been demonstrated to be efficient solutions for multi-generation plants (Astolfi et al., 2017; El-Emam and Dincer, 2018). Organic Rankine cycle (ORC) power systems can be effectively used for energy sources, like concentrated solar power, biomass, waste heat, geothermal, and ocean thermal. The main advantages of organic Rankine cycle power systems employing dry and isentropic working fluids are the high isentropic efficiency of the turbine at design and part-load conditions, quick start-up, long life-time of the components, low mechanical stresses in turbine blades, automatic and unmanned operation, low operation and maintenance costs, and flexibility and ability to follow variable load profiles (Algieri and Morrone, 2012). All the mentioned characteristics make ORC units particularly suitable for supplying the electricity demand for a vapor compression refrigeration system and/or for a reverse osmosis system or the thermal energy (using high temperature working fluid vapor available at the exhaust of turbine) demand for a vapor absorption refrigeration system and/or for a water distillation system. When designed for multi-product purposes (thermal energy-driven), the system is designed with a condensation pressure higher than that of systems designed for power generation only. Hoffmann and Dall (2018) reported that the levelized cost of electricity for a solar power tower integrated Rankine cycle increases by 8.8% when used for co-generation. This is because the condensing stream leaving the turbine should be at a higher temperature in order to act as an energy source for the cogeneration application. The revenue generated from the other product (heat, fresh water, or cooling) may compensate for this low efficiency.

In this chapter, different concentrated solar energy-driven multi-generation systems based on the organic Rankine cycle technology for small to medium-scale applications are reviewed. Power generation systems are discussed in section 2. Systems generating power, fresh water and heating are presented in section 3. Section 4 describes power, cooling and heating systems. Design considerations and issues in CSP-driven multi-generation systems using ORC technology are presented in section 5. Finally, concluding remarks are given in section 6.

2. Power Generation

Parabolic trough collector (PTC)-based CSP plants, using a conventional synthetic thermal oil as a heat-transfer fluid (HTF), are the most mature CSP technology. Solar power tower (SPT) technology and linear Fresnel reflector (LFR) technology with flat mirrors and simple structure are proposed as promising alternatives to the PTC-based CSP plants. The solar power tower technology is cost-effective for large-scale applications ($> 50 \text{ MW}_e$). The linear Fresnel reflector technology has a lower optical efficiency (Nixon and Davies, 2012; Xie et al., 2012) and requires a much higher area of installation compared to that of a PTC-based CSP plant of the same capacity (Desai and Bandyopadhyay, 2015). The paraboloid dish system is the least applied concentrated solar power technology for power generation, relative to the other technologies.

The conventional steam Rankine cycle is widely used in commercial concentrated solar power plants. Depending on the capacity of the CSP plant and steam conditions at the inlet of the turbine, the thermal efficiency of the steam Rankine cycle is in the range of 20% to 40%. Modular CSP plants with a few kW_e to a few MW_e capacity offer solutions in industrial as well as off-grid applications. For such plants, ORC power systems have been demonstrated to be an efficient solution for electricity production (Quoilin et al., 2013). Existing concentrated solar energy-powered organic Rankine cycle-based commercial/medium-scale plants ($> 500 \text{ kW}_e$) for different applications are listed in Table 1 (NREL, 2019; Petrollese et al., 2018; Turboden, 2019; Wendt et al., 2015). In addition, there are a few micro and small-scale CSP-ORC plants, mainly built for research and development purposes, which are not commercially viable and are, therefore, not included in the list.

A simplified schematic of a typical concentrated solar thermal energy-driven organic Rankine cycle power system is given in Figure 2. The system can be equipped with a thermal energy storage for storing the excess energy. When the stored energy is available, the ORC power system runs at full load. However, when the storage is at a minimum level and solar radiation is not sufficient, the heat transfer fluid mass flow rate is adjusted such that the solar field outlet temperature is controlled. The power system mass flow rate and turbine power output are also affected by the variations in the heat transfer fluid flow rate. Part-load efficiencies of the equipment are lower than the design condition efficiencies, and therefore, appropriate models need to be used for predicting the performance of the system. A summary of previous works on medium-scale (a few hundred kW_e to a few MW_e) concentrated solar thermal energy-powered organic Rankine cycle power systems is given in Table 2. It can be observed that the parabolic trough collector and linear Fresnel reflector are typically used for medium-scale plants. Recently, a novel nanostructured polymer foil-based concentrated solar power system, which avails the advantages of low capital cost, low operation and maintenance cost, and two-axis tracking, has been analyzed (Desai et al., 2019a; Desai et al., 2019b). This system uses a nanostructured focusing plastic film that is adhered to a glass plate.

It is important to select a proper working fluid for an organic Rankine cycle power system for cost-efficient utilization of any available heat source. For low and medium-grade heat sources, the dry and the isentropic fluids are the preferred organic working fluids, as the condition at the outlet of the turbine is always either saturated or super-heated vapor, avoiding expansion in the two-phase region (Hung, 2001; Lui et al., 2004). The promising organic working fluids for CSP-based plants are n-pentane, isopentane, hexamethyldisiloxane (MM), toluene and cyclohexane; see Table 2. In commercial, medium-scale actual plants ($> 500 \text{ kW}_e$) n-pentane, MM or isobutene are used as working fluids in the ORC system; see Table 1. Apart from the techno-economic performance, environmental, safety, health, and legislative aspects need to be considered in the final selection of the working fluid for the ORC power system.

Table 1. List of concentrated solar energy-powered organic Rankine cycle-based commercial/medium-scale actual plants (> 500 kW_e) for different applications (NREL, 2019; Petrollese et al., 2018; Turboden, 2019; Wendt et al., 2015).

Name (Location)	Start year	Solar field	Solar field area (m ²)	Storage	Application (net capacity)
Saguaro Power Plant (Arizona, USA)	2006	PTC	10,340	–	Electricity generation (1 MW _e) (currently non-operational).
Rende-CSP Plant (Calabria, Italy)	2014	LFR	9,780	–	Electricity generation (1 MW _e). The facility is combined with an already operating biomass-based plant (14 MW _e).
Airlight Energy Ait-Baha Pilot Plant (Ait Baha, Morocco)	2014	PTC	6,159	Packed-bed rock (5 h)	Electricity generation from CSP and waste heat from cement industry (hybrid plant) (2 MW _e).
Stillwater GeoSolar Hybrid Plant (Fallon, USA)	2015	PTC	24,778	–	Electricity generation. About 17 MW _{th} from CSP combined with geothermal energy producing 33 MW _e . Additionally, 26.4 MW _e of a solar photovoltaic plant.
Aalborg CSP-Brønderslev CSP with ORC project (Brønderslev, Denmark)	2016	PTC	26,929	–	Combined heat and electricity production from CSP (16.6 MW _{th}) and biomass combustion (hybrid plant) (3.8 MW _e).
Ottana Solar Facility (Sardinia, Italy)	2017	LFR	8,600	Two-tank direct	Power generation (0.6 MW _e), additionally 0.4 MW _e of solar PV.

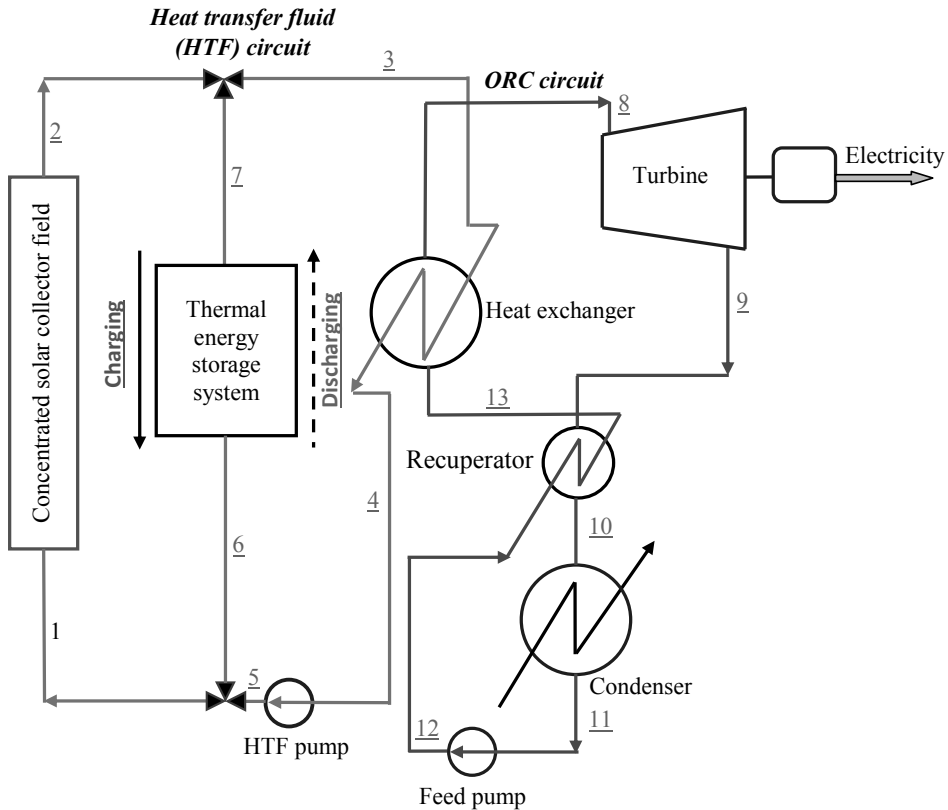


Figure 2. Simplified schematic of a typical concentrated solar thermal energy-driven organic Rankine cycle power system.

Table 2. Summary of previous works on medium-scale concentrated solar power generation based on the organic Rankine cycle technology.

Authors	Solar field	Storage	ORC capacity/working fluids	Max. temp. of ORC/HTF	Remarks
Casartelli et al. (2015)	PTC, LFR	–	2.94 MW _e and 3.57 MW _e (Toluene)	295 °C (ORC)	For cost parity, the cost of the LFR solar field should be about 50% of PTC solar field.
Cooco and Serra (2015)	LFR	Two-tank direct, thermocline	1 MW _e (Siliconic oil)	305 °C (ORC)	The cost of energy for a thermocline storage system is 420 €/MWh and for the direct two-tank system 430 €/MWh.
Cooco and Cau (2015)	PTC, LFR	Two-tank direct	1 MW _e (Siliconic oil)	305 °C (ORC)	Cost of energy (1 MW _e , 2 h storage): LFR-based plant: 380 €/MWh; PTC-based plant: 340 €/MWh.
Rodríguez et al. (2016)	LFR	Two-tank, thermocline	1 MW _e (Cyclopentane)	300 °C (ORC)	Specific cost for a thermocline storage system (€/kW _{th}) is about 33% on average lower than that of the conventional two-tank storage system.
Desai and Bandyopadhyay (2016)	PTC, LFR	–	1 MW _e (R113, n-pentane, Cyclohexane, MDM, MM, Heptane, Toluene, R245fa, and other)	337 °C (ORC)	Cost of the LFR field to reach cost parity with a PTC-based plant: for SRC-based plants: 48% of PTC field cost; for ORC-based plants: 58% of the PTC field cost; the Steam Rankine cycle is a preferred option.
Garg et al. (2016)	PTC	Packed bed	500 kW _e (Isopentane, R152a, butane, isobutene, R245fa, and other)	275 °C (HTF)	Hybrid plants (5, 50 and 500 kW _e) powered by waste heat and solar thermal energy. Isopentane is the preferred working fluid.
Tzivanidis et al. (2016)	PTC	Single tank direct	1 MW _e (Cyclohexane, toluene, water, MDM, and other)	270 °C (HTF)	Techno-economically, Eurotrough ET-150 is a better solution compared to other PTC technologies. Cyclohexane is the preferred working fluid.
Russo et al. (2018)	LFR	Thermocline	1 MW _e (Not given)	300 °C (HTF)	For thermocline storage, forced circulation of molten salts is better compared to the natural circulation.
Javanshir et al. (2018)	SPT	–	Butane, ethanol, isobutene, R11, R141b	350 °C (ORC)	For a max cycle temperature lower than 300 °C, an ORC system (with R141b) is a better option. For high temperature, combined cycles are the better option.
Bellos and Tzivanidis (2018)	PTC	Single tank direct	238 kW _e to 845 kW _e (Toluene, cyclohexane, MDM, n-pentane)	300 °C (HTF)	Hybrid solar-waste heat-powered system. Toluene is the preferred working fluid.
Petrollese and Cooco (2019)	LFR	Two-tank direct	716 kW _e to 730 kW _e (MM, n-heptane, toluene)	222 °C (ORC)	Multi-scenario approach for the plant design. MM is the preferred working fluid.
Desai et al. (2019a)	Foil-based	Two-tank indirect	1 MW _e (n-pentane, MM)	225 °C (ORC)	A foil-based CSP plant can reduce the LCOE by up to 40% compared to the PTC-based CSP plant.

In ORC power systems, the expander is the most important component as it has the most effect on the techno-economic performance of the system. Expanders for the ORC power system can be grouped into two types: (i) turbo expanders (axial and radial turbines), and (ii) volumetric expanders (scroll expanders, screw expanders, reciprocation piston expanders, and rotary vane expanders). Turbines with an organic working fluid can reach a very high isentropic efficiency with only one or two stages. In systems with high flow rates and low pressure ratios, axial turbines (100 kW_e to a few MW_e) are the most widely used. In contrast, radial-inflow turbines are suitable for the systems with low flow rates and high pressure ratios. However, with decreasing power output and, hence, turbine size, the rotational speed increases proportionally. Therefore, for the low power range (mainly using radial-inflow turbines, < 100 kW_e), it is necessary to design an adequate bearing system and to employ a high-speed generator and power electronics. Radial outflow turbine design allows a high volume flow ratio with the constant peripheral speed along the blade span (Zanellato et al., 2018). Radial-outflow turbines can be used for small to medium-scale applications with an advantage of reduced rotational speed, allowing direct coupling to a generator (Maksiuta et al., 2017). In systems with a capacity less than 50 kW_e, the turbines cannot be used due to high rotational speed and high cost (Imran et al., 2016). Reciprocating piston expanders (Wronski et al., 2019) and screw expanders (Bao and Zhao, 2013) can be used for small capacity plants. Scroll expanders and rotary vane expanders can be used in small or micro-scale ORC power systems (Bao and Zhao, 2013).

Apart from the expander, the heat exchangers (evaporator, recuperator, and condenser) represent a significant share of the total ORC system cost. Temperature driving force (pinch point temperature difference) and pressure drops are key performance parameters regarding heat transfers, and each heat exchanger in the power system should be sized based on these parameters. The most commonly used heat exchangers for ORC power systems are shell and tube heat exchangers (for large-scale power systems) and plate heat exchangers (for small-scale power systems, due to compactness) (Quoilin et al., 2013). Organic Rankine cycle feed pumps should meet the requirements of efficiency, controllability and low net pressure suction head. In addition, the ORC power system should be leak-proof, because the organic fluids are expensive (compared to water) and can be toxic, flammable, and have high values of global warming potential and/or ozone depletion potential. In a conventional steam Rankine cycle system, the pump electricity consumption is very low compared to the power output (low back work ratio). On the other hand, in an ORC power system, the irreversibility in the pump can reduce the overall cycle efficiency significantly (Quoilin et al., 2013).

As for the thermal energy storage technologies, the most widely-used systems for CSP-driven organic Rankine cycle systems are the conventional indirect two-tank molten salt storage technology (for large capacity) and the direct thermal oil storage technology (for small capacity). Sensible thermal energy storage using a single tank packed-bed that consists of solids (such as rocks) as the heat storage medium and a heat transfer fluid in direct contact with the solids has also been analyzed in the literature (Cocco and Serra, 2015; Russo et al., 2018). The latent heat thermal energy storage is still at the proof of concept stage because of the low thermal conductivity, resulting in slow charge and discharge processes.

2.1 Thermodynamic analysis

2.1.1 Solar collector field

The solar collector field useful heat gain, \dot{Q}_{CL} , can be calculated as follows:

$$\dot{Q}_{CL} = \eta_{o,CL} \cdot f_{clean} \cdot DNI \cdot IAM \cdot A_{p,CL} - U_{l,1} \cdot (T_{m,CL} - T_a) \cdot A_{p,CL} - U_{l,2} \cdot (T_{m,CL} - T_a)^2 \cdot A_{p,CL} \quad (1)$$

where $\eta_{o,CL}$ is the optical efficiency of the solar collector field, $U_{l,1}$ and $U_{l,2}$ are the heat loss coefficients based on the aperture area of the solar collector field, $A_{p,CL}$ is the aperture area of the solar collector field, $T_{m,CL}$ is the mean temperature of the solar collector field, T_a is the ambient temperature, and DNI is the direct normal irradiance. The incidence angle modifier (IAM) represents the reduction of the optical efficiency due to the incidence angle in parabolic trough collector fields and due to the incidence and

the transversal angles in linear Fresnel reflector fields. The IAM for the system with two-axis tracking (paraboloid dish) is one. The cleanliness factor (f_{clean}) is the ratio of the optical efficiency in average dirty conditions to the optical efficiency with the same optical element in clean condition.

2.1.2 Organic Rankine cycle power system

The organic Rankine cycle feed pump increases the pressure of the working fluid (from state 11 to 12 in Figure 2). The power consumption of the pump, \dot{W}_p , is computed as follows:

$$\dot{W}_p = \frac{\dot{m}_{ORC} \cdot (h_{12s} - h_{11})}{\eta_{is,P}} \quad (2)$$

where \dot{m}_{ORC} is the mass flow rate of the organic working fluid, $\eta_{is,P}$ is the isentropic efficiency of the feed pump, and h_i denotes specific enthalpy at i -th state point. The index s refers to a state achieved after an isentropic compression/expansion.

The organic working fluid in the liquid state at the maximum operating pressure (state 13) enters the heat exchanger. In the heat exchanger, heat is transferred from the high temperature heat transfer fluid, heated through the solar collector field, to the organic working fluid. Typically, this heat exchanger consists of three parts, a preheater, evaporator, and superheater. The heat transfer rate in the heat exchanger, \dot{Q}_e , is given as follows:

$$\dot{Q}_e = \dot{m}_{ORC} \cdot (h_8 - h_{13}) \quad (3)$$

The power output of the turbine, \dot{W}_T , and the gross electric output, $\dot{W}_{el,gross}$, are calculated as follows:

$$\dot{W}_T = \dot{m}_{ORC} \cdot (h_8 - h_{9s}) \cdot \eta_{is,T} \quad \text{and} \quad \dot{W}_{el,gross} = \dot{W}_T \cdot \eta_g \quad (4)$$

where $\eta_{is,T}$ is the isentropic efficiency of the turbine and η_g is the generator efficiency.

In the case of dry organic working fluids, the state point after the expansion in the turbine is superheated. The organic liquid at state 12 enters a recuperator (this component is optional) where the low-pressure organic fluid vapor from the turbine (state 9) supplies heat. Finally, the turbine exhaust is condensed in a condenser after part of its heat has been transferred in the recuperator. The heat transfer rate in the condenser, \dot{Q}_c , is calculated as follows:

$$\dot{Q}_c = \dot{m}_{ORC} \cdot (h_{10} - h_{11}) \quad (5)$$

3. Power, Fresh Water Generation and Heating

Reasonable water and electricity supply policies are of vital importance for the development of locations where there is inadequate water. Solar photovoltaic systems or diesel generator systems using reverse osmosis (RO) for fresh water generation are commonly used for a few kW_e to a few MW_e capacity plants, for simultaneous generation of electricity and fresh water. For dispatchable (on demand) electricity and fresh water generation in isolated regions and on islands, diesel generator-based systems are used. With respect to CSP-based electricity and fresh water generation systems, steam Rankine cycle power systems (Palenzuela et al., 2015), organic Rankine cycle power systems (Astolfi et al., 2017), or supercritical carbon dioxide Brayton cycle power systems (Sharan et al., 2019) can be used for power generation, and reverse osmosis systems (El-Emam and Dincer, 2018) or thermal energy-driven desalination systems (Astolfi et al., 2017) can be used for fresh water generation. Simplified schematics of a typical concentrated solar thermal energy-driven organic Rankine cycle-based electricity system with reverse osmosis-based desalination system and thermal energy-driven desalination systems are shown in Figures 3 and 4, respectively. A summary of previous works on concentrated solar power-based cogeneration systems using the ORC technology and desalination system (reverse osmosis or thermally driven) is given in Table 3.

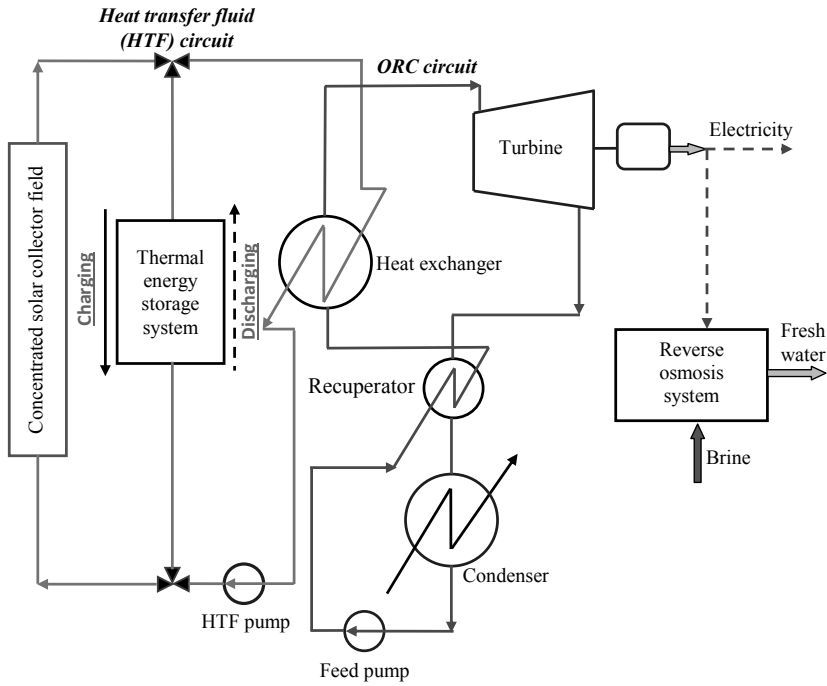


Figure 3. Simplified schematic of a typical concentrated solar thermal energy-driven organic Rankine cycle-based electricity and reverse osmosis-based desalination system.

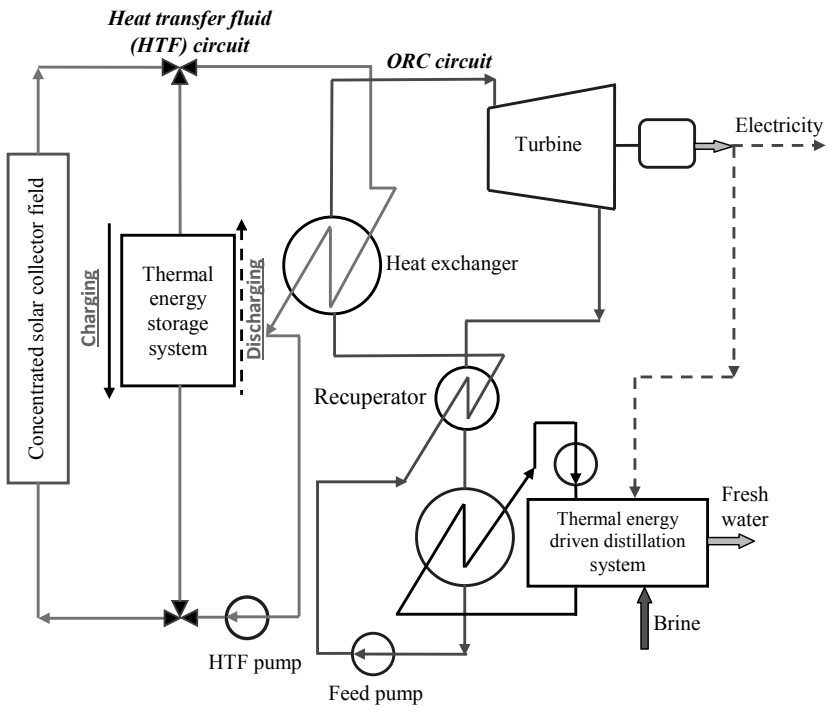


Figure 4. Simplified schematic of a typical concentrated solar thermal energy-driven organic Rankine cycle-based electricity and thermal energy-driven desalination system.

Table 3. Summary of previous works on concentrated solar energy-powered electricity and fresh water generation systems based on the organic Rankine cycle technology.

Authors	Solar field	Storage	ORC capacity/working fluids	Max. temperature of ORC/HTF	Desalination system	Remarks
DeIgado and Garcia (2007)	PTC	–	100 kW _e (Toluene, Octa-methylcyclotetrasiloxane, MM)	365 °C (HTF)	RO	Toluene is a promising working fluid, based on thermodynamic analysis of the system.
Bruno et al. (2008)	FPC, ETC, PTC	–	11.72 kW _e and 27.82 kW _e (Isopentane, n-propilbenzene, tribromomethane, dibromomethane, ethylbenzene, and other)	400 °C (ORC)	RO	Solar thermal energy-based fresh water generation cost: 4.32 €/m ³ to 5.5 €/m ³ . PV-RO-based fresh water generation cost: 12.83 €/m ³ to 14.85 €/m ³ . Isopentane and n-propilbenzene are promising working fluids.
Nafey and Sharaf (2010)	FPC, CPC, PTC	–	998 kW _e to 1131 kW _e (Toluene, dodecane, nonane, octane)	300 °C (HTF)	RO	System with direct vapor generating solar collectors. Toluene is a promising working fluid for PTC-based plants (with fresh water generation cost: 0.903 \$/m ³).
Nafey et al. (2010)	PTC	–	347 kW _e to 662 kW _e (Toluene)	340 °C (HTF)	RO	Fresh water generation cost (seawater desalination): 0.59 \$/m ³ to 0.89 \$/m ³ .
Sharaf et al. (2011)	PTC	–	394 kW _e to 1123 kW _e (Toluene)	350 °C (HTF)	MED-TVC, MED-MVC	Plant using a multi-effect distillation system with thermal vapor compression (MED-TVC) is better than the mechanical vapor compression (MED-MVC).
Karellas et al. (2011)	PTC	–	250 kW _e (R134a)	113.5 °C (ORC)	RO	Hybrid system integrating solar PV and CSP-ORC. Minimum cost of fresh water production is about 6.52 €/m ³ for Chalki Island, Greece.
Sharaf (2012)	PTC	–	Not mentioned (Toluene)	350 °C (HTF)	RO, MED, MED-TVC, MED-MVC	A CSP-ORC-system with RO desalination is the best alternative (with fresh water generation cost: 0.57 \$/m ³).
Li et al. (2013)	PTC	–	100 kW _e (MM)	400 °C (HTF)	RO	Supercritical ORC-systems have higher thermal efficiency than a subcritical ORC-system.
Mathkor et al. (2015)	PTC	–	1 MW _e (Cyclopentane)	189 °C (ORC)	Single effect desalination	Hybrid system by CSP and biomass energy using an ORC-unit (1 MW _e), single absorption chiller (682.3 kW and a single effect desalination unit (234 m ³ /day). Exergy efficiency: 41.7%.
Astolfi et al. (2017)	PTC	Thermo-cline	Up to 5 MW _e (n-pentane)	300 °C (HTF)	MED	Hybrid system powered by a CSP-ORC, solar PV, and DG-set with RO and MED-units. Fresh water generation cost: 1.43 \$/m ³ to 2.15 \$/m ³ .
El-Emam and Dincer (2018)	PTC	Two-tank indirect	200 kW _e to 500 kW _e (n-octane)	340 °C (ORC)	RO	Polygeneration using an ORC-unit, vapor absorption cooling unit, desalination unit, and electrolyzer. Optimum exergy efficiency and cost rate: 30.3% and 278.9 \$/h.
Desai et al. (2019b)	Foil-based	Two-tank indirect	1 MW _e (n-pentane, MM, cyclopentane, isopentane, toluene)	238 °C (ORC)	MED	Lowest LCOE for cyclopentane (0.17 €/kWh _g) and lowest levelized cost of water for MM (0.91 €/m ³).

Toluene (Delgado-Torres et al., 2007), R134a (Karellas et al., 2011), isopentane (Bruno et al., 2008), MM (Li et al., 2013), and n-octane (El-Emam and Dincer, 2018) were proposed as promising organic working fluids for CSP-driven ORC systems with RO desalination. For concentrated solar thermal energy-driven ORC-systems with a thermal energy-driven desalination system, n-pentane (Astolfi et al., 2017), toluene (Sharaf, 2012), and cyclopentane (Mathkor et al., 2015; Desai et al., 2019b) were proposed as promising organic working fluids.

The parabolic trough collector is the most widely-used CSP technology for ORC-based cogeneration systems (El-Emam and Dincer, 2018). Recently, a nanostructured polymer foil-based concentrated solar collector technology was analyzed as a promising alternative compared to a PTC-based system for ORC power systems integrated with a multi-effect distillation (MED) desalination system (Desai et al., 2019b). The assumptions related to the solar irradiation, capital cost of the sub-systems and electricity consumption significantly influence the techno-economic performance of the cogeneration system. The concentrated solar thermal energy integrated MED-system is less expensive than a RO-based desalination system (Ghobeity et al., 2011; Sharan et al., 2019). Depending on seawater salinity, membrane configuration and efficiencies of components, the specific electricity consumption for reverse osmosis systems is about 3.5 kWh_e/m³ to 5 kWh_e/m³ (IRENA, 2012; Sharan et al., 2019). For multi-effect seawater distillation systems, the specific electricity consumption is about 1 kWh_e/m³ to 1.5 kWh_e/m³ (Alfa Laval, 2018).

4. Power, Cooling and Heating

Conventional vapor compression refrigeration systems (VCRS) powered by electrical energy are widely used for cooling applications. Such systems can be powered by electrical energy produced by a concentrated solar thermal energy-based organic Rankine cycle power system. A low-grade thermal energy-driven vapor absorption refrigeration system (VARS) can also be integrated as a bottoming cycle to an organic Rankine cycle power system. A simplified schematic of a typical concentrated solar thermal energy-driven organic Rankine cycle-based vapor compression or absorption refrigeration system is given in Figure 5. A summary of previous works on CSP-driven ORC-based cooling and/or heating systems is given in Table 4.

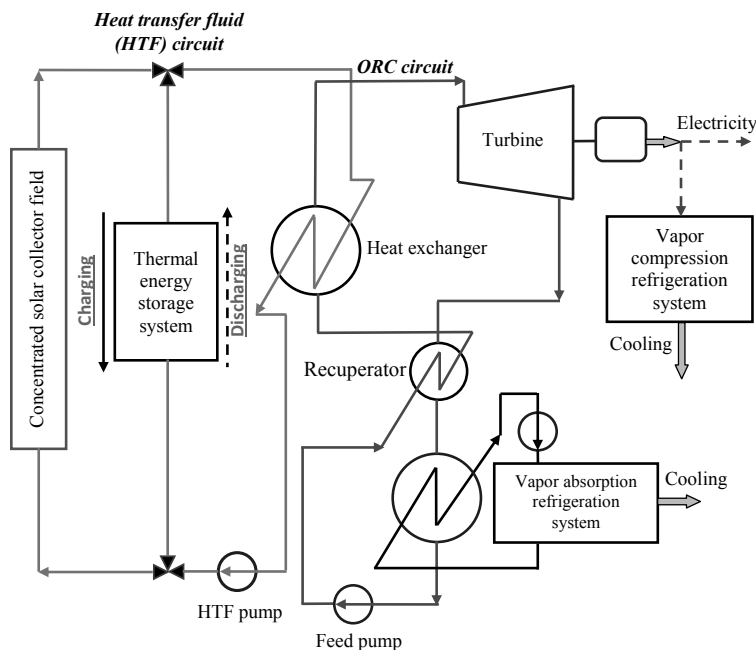


Figure 5. Simplified schematic of a typical concentrated solar thermal energy-driven organic Rankine cycle-based electricity and vapor compression or absorption refrigeration system.

Table 4. Summary of previous works on CSP-driven ORC-based cooling and/or heating systems.

Authors	Solar collector	ORC capacity/working fluids	Cooling system/refrigerants	Remarks
Al-Sulaiman et al. (2011a)	PTC	500 kW _e (n-octane)	VARS (LiBr-H ₂ O)	Exergy efficiency of trigeneration system: 20% for solar mode, 7% for storage mode, and 8% for solar-storage mode.
Al-Sulaiman et al. (2011b)	SOFC-Biomass-solar thermal	500 kW _e (n-octane)	VARS (LiBr-H ₂ O)	Energy efficiency of trigeneration system: 90% for solar mode, 90% for biomass mode, 76% for solid oxide fuel cell (SOFC) mode.
Buonomano et al. (2015)	Solar thermal and geothermal	6 kW _e (R245fa)	VARS (LiBr-H ₂ O)	Cooling capacity: 30 kW; heating capacity: 87 kW _{th} . System efficiency: 69.4% for trigeneration mode, 6.4% for only power mode. Payback period range: 2.5 y to 7.6 y.
Karellas and Braimakis (2016)	PTC and biomass	1.42 kW _e (R134a, R152a, R245fa)	VCRS (R134a, R152a, R245fa)	Cooling capacity: 5 kW, heating capacity: 53.5 kW _{th} . Solar-ORC thermal, electrical and exergy efficiency: 6%, 3%, and 7%. COP of VCRS: 3.88, payback period: 7 y.
Patel et al. (2017)	PTC/LFR/dish and biomass	10 kW _e (n-pentane, Toluene, R245fa)	Cascade VARS-VCRS	Fully biomass-based system better than solar-biomass system. LFR as a solar field and n-pentane as an ORC working fluid are the more appropriate choices.
Bellos and Tzivanidis (2017)	PTC	89.3 to 177.6 kW _e (Toluene, n-octane, MDM, MM, etc.)	VARS (LiBr-H ₂ O)	Toluene is the more suitable working fluid with exergy efficiency of 29.42%. For toluene, net power output: 177.6 kW _e , heating capacity: 398.8 kW _{th} , cooling capacity: 947.2 kW.
Bellos et al. (2018a)	PTC and biomass	8.2 kW _e (Toluene, n-octane, MDM, MM, n-heptane, cyclohexane)	VCRS (R141b, R 600, R161, R600a, and other)	Cooling capacity: 5 kW, low-temperature (50 °C) heating capacity: 7.91 kW _{th} , high temperature (150 °C) heating capacity: 5 kW _{th} . Toluene is the more suitable refrigerant. Payback period: 5.13 y.
Bellos et al. (2018b)	PTC and waste heat	146.8 kW _e (Toluene, n-octane, MM, n-pentane)	VARS (LiBr-H ₂ O)	Simple payback period: 4.86 y. Cooling capacity: 413.6 kW, heating capacity: 947.1 kW _{th} . Toluene is the more suitable refrigerant.
Villarini et al. (2019)	LFR, CPC	25 kW _e (NOVEC 649)	VARS	Cooling capacity: 17.6 kW. Energy performance of LFR-ORC-system very sensitive to location compared to CPC-ORC-system.
Bellos and Tzivanidis (2019)	PTC	10 kW _e to 15 kW _e (Toluene, n-octane, MM, n-pentane)	VARS (LiBr-H ₂ O)	Toluene and n-octane are the preferred refrigerants when the heat rejection temperature is about 125–135 °C.

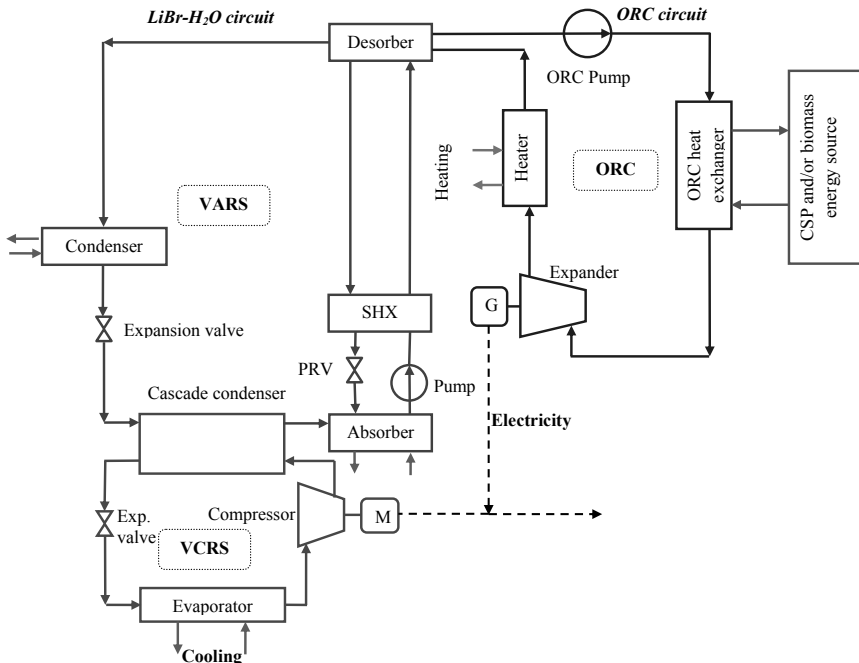


Figure 6. Simplified schematic of a typical organic Rankine cycle-based electricity and cascaded vapor compression and absorption refrigeration system (Adopted from Patel et al., 2017).

A bottoming VARS using lithium bromide-water ($\text{LiBr-H}_2\text{O}$) as a refrigerant is limited to space cooling at a commercial level (Tassou et al., 2010). Vapor absorption refrigeration systems with ammonia-water ($\text{NH}_3\text{-H}_2\text{O}$) are less advisable for food applications due to toxicity, flammability, low boiling point temperature difference of refrigerant and absorbent, low coefficient of performance and incompatibility with materials (Deng et al., 2011). Integrated systems based on adsorption cooling and liquid desiccant cooling technologies are still at the research and development phase (Jradi and Riffat, 2014).

Concentrated solar thermal energy-powered organic Rankine cycle systems integrated VARS, which works on thermal energy, are typically limited to space cooling. On the other hand, ORC-integrated VCERS, which works on electrical energy, can be used for refrigeration applications. Patel et al. (2017) proposed a concentrated solar thermal energy and biomass energy-powered ORC unit with a cascaded refrigeration system, as shown in Figure 6. In such a system, the electricity and heat duty requirements of the VCERS and VARS are fulfilled by the ORC-unit, combining the advantages of both systems. The cascaded system achieves low temperature (up to $-20\text{ }^\circ\text{C}$) cooling and requires much lower electricity compared to the vapor compression refrigeration system (Patel et al., 2017).

5. Design Considerations

The key aspects of designing CSP-integrated ORC-unit-based multi-generation systems optimally are briefly covered in this section.

5.1 Solar irradiation data

The duration and intensity of the solar irradiation affect the performance, capacity factor, and economic viability of the system significantly. The sizing and configuration of the system also depend on the solar irradiation. Local factors like fog and pollution level, dust/sand storms, wind speeds and their variations also need to be considered when selecting the place of installation.

5.2 Solar collector field and thermal energy storage

Concentrated solar collector type and size and thermal energy storage type and size need to be carefully selected, as both these systems have major shares in the capital cost of the complete system. Optical efficiency and overall heat loss coefficients are crucial parameters for concentrated solar collector fields and improvements in these parameters often increase the solar field cost. The use of thermal energy storage facilitates delivery of the utilities according to the need by absorbing the variations due to fluctuations in the solar irradiation. For off-grid locations, where there are no available central grids, integration of other energy sources, fossil fuel based or biomass based, may be needed to meet the utility demands.

5.3 Organic Rankine cycle power system and other sub-systems

The selection of cycle configuration, component types and designs, and working fluid is important for efficiently converting solar thermal energy into multiple products. All these parameters are dependent on the application type and maximum capacity requirement. The other products (cooling, heating, fresh water) should be selected based on the needs of the region. The primary need (electricity, cooling, heating or fresh water) of the place is of vital importance for successful implementation. The cooling and desalination systems can be thermal energy driven or electrical energy driven, and the selection depends on the techno-economic analysis. Integration of thermal energy driven systems with an organic Rankine cycle power system enables a high energy utilization factor and high overall system efficiency. However, in such a system, the net power output is lower compared to only power generating systems with a condensing turbine. Therefore, the selection of an ORC power system and other sub-systems should be done carefully.

5.4 Load characteristics

The system design needs to be based on a detailed analysis of the part-load characteristics of the components of the multi-generation systems. Due to the mismatch between supply and demand, the major challenge is to provide a dilute and variable nature of solar energy input to the various demands. Moreover, it needs to be addressed that the actual system performance may differ from that of the design predictions due to the system inertia causing delays during the start-up and shut-down phases.

5.5 System configuration and control

For optimal system configuration, all of the aforementioned parameters need to be considered carefully. The process controls of the CSP-driven multi-generation systems based on the ORC technology should be designed as a subset of the overall plant control strategy. A proper system configuration and control provide desired products to the consumers cost-effectively and reliably.

5.6 Cost

Concentrated solar collector powered medium-scale dispatchable multi-generation energy systems with thermal energy storage are typically more costly than fossil fuel based and biomass based systems. However, factors like availability of fossil fuels and biomass as well as high carbon footprints for the former and high water footprints for the latter are the major drawbacks of these technologies.

6. Concluding Remarks

In this chapter, concentrated solar thermal energy-driven multi-generation systems based on the organic Rankine cycle technology were reviewed. Power generation, cogeneration, trigeneration, and multi-

generation systems were discussed, and their possible configurations were presented. Issues related to the system design were addressed.

For solar organic Rankine cycle systems, parabolic trough collector and linear Fresnel reflector technologies are typically used. For cost parity, the cost of the linear Fresnel reflector technology ($\text{€}/\text{m}^2$) should be about 50% to 60% lower than that of the parabolic trough collector technology. A recently analyzed nanostructured polymer foil-based concentrated solar field is a promising alternative for small to medium-scale organic Rankine cycle systems.

For fresh water generation applications, thermal energy driven multi-effect distillation is a better option than the electrical energy driven reverse osmosis system. The type of components (expander, heat exchangers and pump) and working fluid of the organic Rankine cycle power system should be decided based on the solar collector field data, type of application, and capacity of the system.

For cooling applications, depending on the temperature needed, either the electrical energy driven conventional vapor compression refrigeration systems or the thermal energy driven vapor absorption refrigeration systems can be used. The recently investigated cascaded refrigeration system is a promising alternative; however, it is currently at the research stage and no commercial plant exists as of yet.

The selection of type and size of the concentrated solar field, thermal energy storage, organic Rankine cycle power system, and other sub-systems is of vital importance for attaining a cost-effective solution. Solar irradiation data and load characteristics affect the overall system configuration and controller design.

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Nomenclature

$A_{p,CL}$	aperture area of the solar collector field (m^2)
DNI	direct normal irradiance (W/m^2)
h	specific enthalpy (J/kg)
IAM	incidence angle modified
\dot{m}	mass flow rate (kg/s)
\dot{W}	power (W)
\dot{Q}	heat rate (W)
T	temperature ($^{\circ}\text{C}$)
$U_{l,1}$	first-order heat loss coefficient based on aperture area ($\text{W}/(\text{m}^2\cdot\text{K})$)
$U_{l,2}$	second-order heat loss coefficient based on aperture area ($\text{W}/(\text{m}^2\cdot\text{K}^2)$)

Greek symbols

η	efficiency
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Subscripts

a	ambient
c	condenser
CL	collector
e	evaporator
g	generator

<i>i</i> s	isentropic
<i>m</i>	mean
<i>o</i>	optical
<i>P</i>	pump
<i>T</i>	turbine

Abbreviations

CSP	concentrated solar power
HMDS	hexamethyldisiloxane
HTF	heat transfer fluid
LFR	linear Fresnel reflector
ORC	organic Rankine cycle
PTC	parabolic trough collector

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