A Review on Solar Collector and Solar Organic Rankine Cycle (ORC) Systems

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***Abstract*—Solar-driven organic Rankine cycle (ORC) has been drawing increasing attention due to its high potential in energy conversion efficiency. The two core components of thermal application systems of solar energy are solar collectors and thermal energy storage systems, and many studies have been published. ORC also has attracted much attention in recent years due to its potential in reducing consumption of fossil fuels, relaxing environmental problems, and its favorable characteristics to exploit low-temperature heat sources. This paper provides a review of the latest developments and advances in solar thermal applications of solar collectors and thermal energy storage systems, and solar-driven ORC systems. Various types of solar collector systems and solar ORC systems, and their working fluids are reviewed and discussed.**

***Index Terms*—solar collector, heat storage, organic rankine cycle (ORC), working fluid**

I. Introduction

Since worldwide energy demand has been rapidly increasing but the fossil fuel to meet the demand is being drained, for the past 20 years efficient uses of low-temperature energy source such as geothermal energy, exhaust gas from gas turbine system, biomass combustion, waste heat from various industrial processes, and solar energy have attracted much attention and researches about them become more and more important. The organic Rankine cycle (ORC) and the power generating system using binary mixture as a working fluid have been focused as they are proven to be the most feasible methods to achieve high efficiency in converting the low-grade thermal energy to more useful forms of energy. ORC is a Rankine cycle where an organic fluid is used instead of water as working fluid. Particularly in low temperature applications many benefits may be obtained by using ORC instead of steam Rankine process [1]-[4].

By powerful nuclear fusion reaction, the Sun produces staggering amounts of energy and much of that energy is dispersed in space and practically all of it is lost. The energy intercepted by the Earth over a period of one year is equal to the energy emitted in just 14ms by the Sun. The Sun releases an enormous amount of radiation energy to its surroundings and when the energy arrives at the surface of the Earth, it has been attenuated twice by both the atmosphere (6% by reflection and 16% by absorption) and the clouds (20% by reflection and 3% by absorption), as shown in Fig. 1 [5]-[7]. Solar collectors and thermal energy storage components are the two core subsystems in solar thermal applications. A solar collector which is the special energy exchanger converts solar irradiation energy either to the thermal energy of the working fluid in solar thermal applications. Solar collectors need to have good optical performance in order to absorb heat as much as possible. For solar thermal applications, solar irradiation is absorbed by a solar collector as heat and then is transferred to the working fluid. The heat carried by the working fluid can be used to either provide domestic hot water or to charge a thermal energy storage tank from which the heat can be drawn for use later [5], [8].

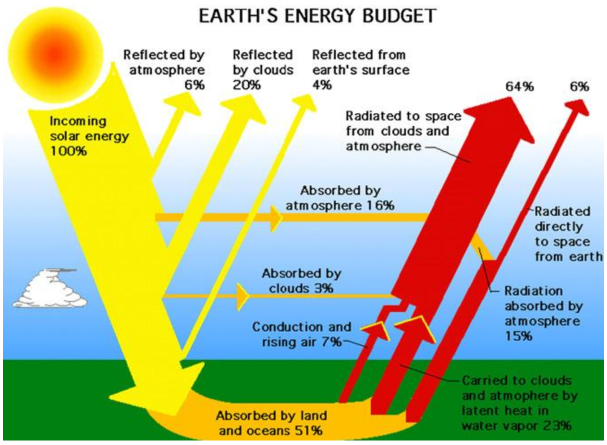

Figure 1. The Earth's energy budget [5]-[7].

After the thermal energy is collected by solar collectors, it needs to be efficiently stored when later needed for a release. Thus, it becomes of great importance to design an efficient energy storage system. Thermal storage is one of the main parts of a solar heating, cooling, and power generating system. If the solar system must operate continuously, the heat storage is necessary. For some applications intermittent operation is acceptable, but most other uses of solar energy require operating at night and when the sun is hidden behind clouds. The energy storage system has an enormous influence on overall system cost, performance, and reliability [9].

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Providing cooling by solar energy is one of the key solutions to the energy and environmental issues. There are presented theoretical basis and practical applications for cooling systems within various working fluids assisted by solar energy and their recent advances. Thermally powered refrigeration technologies are classified into two categories. One is the sorption technology including open and closed systems, and the other is the thermo-mechanical technology including ejector system. Solid and liquid desiccant cycles represent the open system. The liquid desiccant system has a higher thermal coefficient of performance (COP) than the solid desiccant system [10]. The solar thermal Brayton cycle has also shown the potential, merits and challenges to the energy issues, since it can be very competitive in terms of efficiency, cost and environmental impact. Thus, many studies have been published on the performance and optimization of the cycle [11].

In recent years, ORC has become a field of intense research and appears as a promising technology for conversion of heat into useful work or electricity. The heat source can be of various origins such as solar radiation, biomass combustion, ground heat source or waste heat from factories. Unlike in the steam power cycle, where vapor steam is the working fluid, ORC employs refrigerants or hydrocarbons. The economics of a Rankine system is strictly linked to the thermodynamic properties of the working fluid and a bad choice could lead to a low efficient and expensive plant [12]. Therefore, in this paper are presented theoretical basis and practical applications for technologies of solar collectors and solar thermal storage systems and especially solar-driven ORC within various working fluids. Various types of solar collector systems and solar ORC systems for various applications are reviewed and discussed.

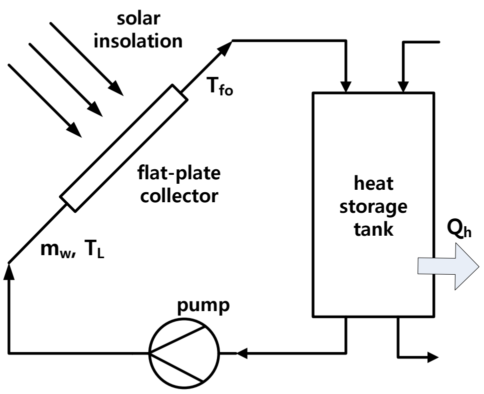

Figure 2. Schematic diagram of the solar collector and thermal storage system.

II. Solar Collector Systems

Solar collectors and thermal energy storage components are the two core subsystems in solar thermal energy systems as shown in Fig. 2. The thermal storage subsystems require high thermal storage density with small volume and low construction cost, excellent heat transfer rate in order to absorb and release heat at the required speed. Whilst solar collector is a device that absorbs the incoming solar radiation, converts it into heat, and transfers the heat to a fluid flowing through the collector. Thus solar collectors need to have good optical performance in order to absorb heat as much as possible. The solar collectors may be categorized as two types of non-concentrating and concentrating. A non-concentrating collector has the same area for intercepting and absorbing solar radiation, whereas a sun-tracking concentrating solar collector usually has concave reflecting surfaces to intercept and focus the sun's beam radiation to a smaller receiving area, thereby increasing the radiation flux. Concentrating collectors are suitable for high-temperature applications [9].

The flat plate solar collectors are usually permanently fixed in position and therefore need to be oriented approximately. A typical flat plate collector consists of glazing covers, absorber plate, insulation layers, recuperating tubes filled with heat transfer fluid and other auxiliaries. A glass cover on the upper surface and insulation at the bottom and sides reduce thermal losses. Air is present in the space between the metal absorber and transparent cover. The flat metal plate serves as a heat exchanger that absorbs solar radiation, converts it into heat and transfers the heat to a flowing fluid. The heat can be used directly if water is used as the transfer fluid or transferred to water in a storage tank using a heat exchanger if a solar fluid is used [13].

A storage tank in a solar system has an important function of the improvement of utilization of collected solar energy by providing thermal capacitance to alleviate the solar availability and load mismatch and improve the system response to sudden peak loads or loss of solar input. Solar energy can be stored in liquids, solids, or phase-change materials (PCM). Though the collector loop may use water, oils, water-glycol mixtures, or any other heat transfer medium as the collector fluid, water is the most frequently used storage medium for liquid systems,. This is because water is inexpensive and non-toxic and it has a high storage capacity, based on both weight and volume. Air systems typically store heat in rocks or pebbles, but sometimes the structural mass of the building is used. It is important that the temperature of the fluid delivered to the load should be appropriate for the intended application. The lower the temperature of the fluid supplied to the collectors, the higher is the efficiency of the collectors [9].

Farahat *et al*. [14] developed an exergetic optimization of flat plate solar collectors to determine the optimal performance and design parameters of these solar to thermal energy conversion systems. They carried out a detailed energy and exergy analysis for evaluating the thermal and optical performance, exergy flows and losses as well as exergetic efficiency for a typical flat plate solar collector under given operating conditions. In the analysis, the geometric and operating parameters are the absorber plate area, dimensions of solar collector, pipes' diameter, mass flow rate, fluid inlet, outlet temperature, and the overall loss coefficient, etc. They developed a simulation program for the thermal and exergetic calculations and the results of the computational program were in good agreement with the experimental measurements noted in the previous literature. From the exergetic optimization under given design and operating conditions, the optimum values of the mass flow rate, the absorber plate area and the maximum exergy efficiency were obtained.

The efficiency of a solar collector is a key factor for the performance of thermal facilities. As the weather conditions vary continuously during the day, the instant collector efficiency depends not only on the components employed in its construction but also on the actual environmental conditions, the hot water temperature and aging. Rodríguez-Hidalgo [15] performed an experimental research to describe the transient behavior of a flat plate collector field under outdoor working conditions. They assembled a transient collector model using thermal resistances and capacitances and added three thermocouples to measure the center point temperature of the glass cover, box back surface and absorber plate of one of the collectors. They calculated the useful heat and thermal losses by applying a dynamic energy balance under the transient regime. The working parameters were recorded during an entire year for periods of 10 min. The model was experimentally validated by comparing its results to the instant collector temperatures and heat fluxes that were obtained from the experimental database. Being the operating conditions unlike, differences throughout the day became evident.

They [16] also performed an experimental research on a solar facility with a nine-year-old, on-campus field with $50m^2$ area of flat plate solar collectors. They developed a transient model adapted to the characteristics of this facility. The efficiency normalization curve (ENC) operating conditions for the steady-state test were different from the working conditions and significant differences between the ENC and the model based predictions were found and quantified. The significance of the transient behavior was compared with the thermal inertia proposed in the EN-12975:2006 standard for the quasi-dynamic test. Using the model capabilities to predict the collector performance under transient working conditions, the influence of the operating conditions on the collector efficiency and on the useful heat produced is studied individually. The relevance of those conditions was ranked as the wind (velocity magnitude and direction) was the most influential, followed by the aging of the collector surfaces, convective heat losses, thermal inertia and the incident angle of irradiance.

The development of sustainable energy services like the supply of heating water may face a trade-off with a comfortable quality of life, especially in the winter season where suitable strategies to deliver an effective service are required. Dagdougui *et al*. [17] investigated the heat transfer process as well as the thermal behavior of a flat plate collector evaluating different cover configurations. They formulated a complete model taking into account various modes of heat transfer in the collector to investigate the impact of the number and types of covers on the top heat loss and the related thermal performance, and thus to support decision makers about the most cost-effective design. The proposed model can also be used to investigate the effect of the different parameters which may affect the performance of the collector. They also formulated and implemented a two objective constrained optimization model to evaluate the optimality of different design approaches. Their goal was to support decision makers in the definition of the optimal water flow and of the optimal collector flat area in order to give a good compromise between the collector efficiency and the output water temperature.

Tang *et al*. [18] constructed and tested two sets of water-in-glass evacuated tube solar water heater (SWH) for comparative studies of performance. Both SWHs were identical in all aspects but had different collector tilt-angle from the horizon with the one inclined at 22^o (SWH-22) and the other at 46^o (SWH-46). Experimental results showed that the collector tilt-angle of SWHs had no significant influence on the heat removal from solar tubes to the water storage tank, both systems had almost the same daily solar thermal conversion efficiency but different daily solar and heat gains, and climatic conditions had a negligible effect on the daily thermal efficiency of systems due to less heat loss of the collector to the ambient air. These findings indicated that, to maximize the annual heat gain of such solar water heaters, the collector should be inclined at a tilt-angle for maximizing its annual collection of solar radiation. Experiments also showed that increasing the collector tilt-angle of SWHs had no positive effect on the thermosiphon circulation of the water inside tubes.

Gang *et al*. [19] proposed a low-temperature solar thermal electric generation based on the compound parabolic concentrator (CPC) of small concentration ratio and ORC. Two-stage collectors and heat storage units were adopted to improve heat collection efficiency, and the technologies of CPC and ORC were analyzed and feasibility of the system was demonstrated.. Organic fluid was preheated by flat plate collectors prior to entering a higher temperature heat exchanger connected with the CPC. The two-stage heat storage units composed of two types of phase change material (PCM) with diverse melting temperatures. They built mathematic models for heat transfer and thermodynamics of the system. Coupling relationship among the proportion of FPC to CPC, the melting temperature of the first-stage PCM and the overall collector efficiency was established. They investigated the benefits of the preheating concept and cascaded heat storages in detail in comparison with the single-stage system. The results showed that the increase in collector efficiency of the two-stage system was appreciable.

Cruz-Peragon *et al*. [20] provided a general methodology to validate a collector model with undetermined associated complexity, which serves to characterize the device by means of critical coefficients, such as the film convection transfer coefficient, plate absorptance or emmitance. An intermediate complex collector model with 2D finite-difference method was proposed. Both steady and transient states were analyzed under different operating conditions based on Newton's method optimization. The results depicted a robustness of the overall proposed method as starting point to optimize models applied to solar collectors.

Palacios *et al*. [21] investigated thermal mixing caused by the inflow from one or two round, horizontal, buoyant jets in a water storage tank, which is part of a thermal solar installation. They carried out a set of experiments in a rectangular tank with a capacity of $0.3m^3$, with one or two constant temperature inflows. As a result, they developed two correlations based on temperature measurements. One of the correlations predicts the size of a zone of homogenous temperature, referred to herein as the mixing zone, which develops when a single hot inflow impinges on the opposite wall of the tank. The other identifies the degree of mixing resulting from the interaction between a hot inflow and a cold inflow located below the hot one. The correlations are combined with energy balances to predict the amount of hot water available in a tank with open side inlets and the corresponding temperatures of the outflows.

III. SOLAR ORC

In recent years, organic Rankine cycle (ORC) has attracted much attention, since it is considered as a promising technology for conversion of heat into useful work or electricity. The heat source can be of various origins such as solar radiation, biomass combustion, ground heat source or waste heat from industries. In ORC refrigerants or hydrocarbons are used as working fluids instead of water used in the conventional Rankine cycle. Selection of working fluid and working conditions of the ORC has a great effect on the system operation and its energy efficiency.

Tchanche *et al*. [12] analyzed thermodynamic characteristics and performances of different fluids for selection as working fluids in a low-temperature solar ORC. They found that the fluids favored by the pressure values are isentropic fluids, butanes, n-Pentane and refrigerants R152a, RC318 and R500. On the other hand low volume flow rates are observed for R32, R134a, R290, R500 and ammonia. Rayegan and Tao [22] considered 117 organic fluids and compared the fluids based on their molecular components, temperature-entropy diagram and fluid effects on the thermal efficiency, net power generated, vapor expansion ratio, and exergy efficiency. They found that collector efficiency improvement and use of the regenerative ORC instead of the basic cycle reduce irreversibility of a solar ORC.

Delgado-Torres and García-Rodríguez [23] carried out a theoretical analysis that the thermal energy required by a solar ORC is supplied by means of stationary solar collectors. They considered twelve substances as working fluids of the ORC and four different models of stationary solar collectors including flat plate collectors, compound parabolic collectors and evacuated tube collectors. They evaluated the operating conditions of the solar ORC that minimizes the aperture area needed per unit of mechanical power output of the solar cycle for every working fluid and every solar collector. They [24] also considered the coupling between the low-temperature solar ORC and seawater and brackish water reverse osmosis desalination units with four working fluids. They evaluated the volumetric flow of fresh water produced per unit of aperture area of stationary solar collector. They also analyzed the influence of condensation temperature of the ORC and regeneration's process effectiveness on the productivity of the system.

Jing *et al*. [25] investigated a low temperature solar thermal electric generation system mainly consists of compound parabolic concentrators (CPC) and the Organic Rankine Cycle (ORC) working with HCFC-123. They developed mathematical formulations to study the heat transfer and energy conversion processes and carried out the numerical simulation based on distributed parameters. The influences of the collector tilt angle adjustment, the connection between the heat exchangers and the CPC collectors, and the ORC evaporation temperature on the system performance are investigated. They found that the three factors have a major impact on the annual electricity output and should be the key points of optimization.

Tchanche *et al*. [26] performed an exergy analysis of micro-organic Rankine heat engines to identify the most suitable engine for driving a small scale reverse osmosis desalination system. Three modified engines derived from simple Rankine engine using regeneration were analyzed through the exergy-topological method based on the combination of exergy flow graphs, exergy loss graphs, and thermo-economic graphs. They found that the most critical components include evaporator, turbine and mixing units, and a regenerative heat exchanger has positive effects only when the engine operates with dry fluids.

Gang *et al*. [27] proposed a new solar thermal electric generation system with regenerative Organic Rankine Cycle for use of low-temperature source. The system consisted of small concentration ratio compound parabolic concentrators (CPC) and a regenerative ORC. The system has advantages of the innovative configuration such as effectively reducing heat transfer irreversibility and permitting the use of thermal storage with phase change materials (PCMs). The numerical simulation of the heat transfer and power conversion processes based on distributed parameters showed that the regenerative cycle has positive effects on the ORC efficiency but negative ones on the collector efficiency due to increment of the average working temperature of the first-stage collectors, so it is necessary to evaluate the overall electricity efficiency when regenerative cycle is adopted.

Wang and Zhao [28] performed an analysis of low-temperature solar Rankine cycles for power generation using zeotropic mixtures. Because there is an obvious temperature glide during phase change for zeotropic mixtures, an internal heat exchanger (IHE) is introduced to the Rankine cycle. They showed that utilizing zeotropic mixtures can lead to a significant increase of thermal efficiencies when superheating is combined with

IHE and can extend the range of choosing working fluids for low-temperature solar Rankine cycles.

Nafey and Sharaf [29] designed and carried out performance calculations of the cycle consisted of thermal solar collectors including Flat Plate Solar Collector (FPC), Parabolic Trough Collector (PTC), and Compound Parabolic Concentrator (CPC) for heat input, and expansion turbine for work output, condenser unit for heat rejection, pump unit, and Reverse Osmosis (RO) unit. They modeled the proposed process units and showed a good validity with literatures. By the exergy and cost analysis for saturation and superheated operating conditions, they also evaluated exergy efficiency, total exergy destruction, thermal efficiency, and specific capital cost for direct vapor generation (DVG) process. They showed that toluene and water achieved minimum results for total solar collector area, specific total cost and the rate of exergy destruction.

Small-scale solar thermal cogeneration shows promise as an effective way to get increased benefit out of a given solar availability, since it does not waste potential during summer after the water capacity is heated. Towmey *et al*. [30] tested a scroll expander in a small ORC and calibrated a static expander model. The calibrated model was then incorporated into a larger dynamic model of a solar thermal cogeneration system as shown in Fig. 3. They conducted an annual simulation using a collector area of 50 m^2 and showed that the scroll expander has a maximum isentropic efficiency of 59% while the ORC efficiency was 3.47%, the total energy produced is 1710 kWh, and the hot water available was on average 2540 L/day, and it was possible to shift the time period that the system could produce power to match the peak demand period by adjusting the solar store volume.

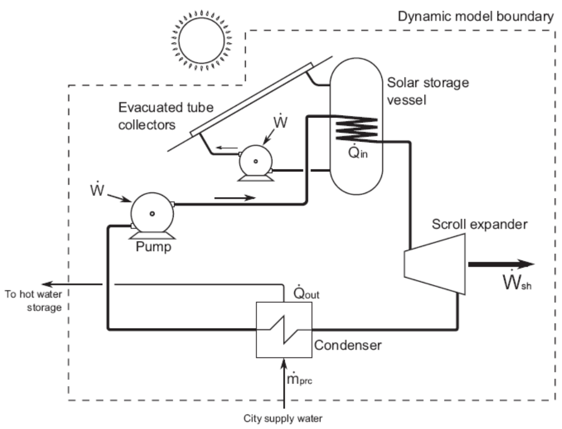

Figure 3. Solar ORC system configuration [30].

Desalination driven by renewable energies is an interesting technology in isolated areas. Its feasibility and reliability are guaranteed by innumerable designs implemented and experiences carried out, mainly focused on small capacity systems. Penate and Garcia-Rodriguez [31] investigated the optimum solar desalination system with a seawater reverse osmosis desalination unit powered by an ORC heated by a parabolic trough solar field. As the Rankine cycle proposed was designed to provide the total electricity demand of the desalination plant, the system would be suitable for a standalone operation due to all the energy requirement is supplied by the solar system.

He *et al*. [32] built a model for a typical parabolic trough solar thermal power generation system with ORC. With this model, they examined the effects of several key parameters, including the interlayer pressure between the absorber tube and the glass tube, the flow rate of high temperature oil in the absorber tube, solar radiation intensity and incidence angle, on the performance of the parabolic trough collector field based on the meteorological data. The study showed that the heat loss of the solar collector increases sharply with the increase in the interlayer pressure at beginning and then reaches to an approximately constant value. The variation of heat collecting efficiency with the flow rate is quite similar to the variation of the heat loss with the interlayer pressure. However, the solar radiation intensity and the incident angle exhibit opposite effect on the collecting efficiency.

By the theoretical and experimental studies Marion *et al*. [33] showed the potential of producing mechanical power by a system combining a solar thermal collector with an ORC. They developed a theoretical model based on heat transfer equations and predicted the thermal equilibrium state of a small-scale glazed flat plate collector for different operational conditions. They showed that the expected net mechanical power strongly depends on the fluid mass flow rate and the optimum flow is a linear function of the solar radiation. Reducing the collector heat losses appears as the most relevant solution before the choice of the working fluid to improve the overall installation performance.

For utilizing of the solar energy over a low temperature range with low cost, Wang *et al*. [34] presented a regenerative ORC with flat-plate solar collectors to collect the solar radiation energy. A thermal storage system was employed to store the collected solar energy and provided continuous power output when solar radiation is insufficient. They conducted parametric analysis to examine the effects of some thermodynamic parameters on the system performance using different working fluids and optimized with the daily average efficiency. They showed that under the actual constraints, increasing turbine inlet pressure and temperature or lowering the turbine back pressure could improve the system performance and a higher turbine inlet temperature with saturated vapor state could obtain the better system performance. Compared with other working fluids, they also showed that R245fa and R123 are the most suitable working fluids for the system due to their high system performance and low operation pressure.

Astolfi *et al*. [35] analyzed a combined concentrating solar power system and a geothermal binary plant based on a supercritical ORC. Besides utilization of an intermediate enthalpy geothermal source, a solar parabolic trough field was included in the plant, introducing an additional high temperature heat source for the cycle and increasing power production. The off-design performance analysis of the power cycle was performed and an hour-by-hour simulation was then carried out to estimate the yearly production using a detailed solar field model. Finally, a differential economic analysis was performed to determine the cost of the additional electricity generated with the solar source. Since plant should be operated to achieve the highest conversion efficiency of the additional heat available, an optimal combination of maximum temperature and mass flow rate is required for any value of the additional heat. Fig. 4 represents by the two boundary lines and the envelope of constant maximum temperature curves.

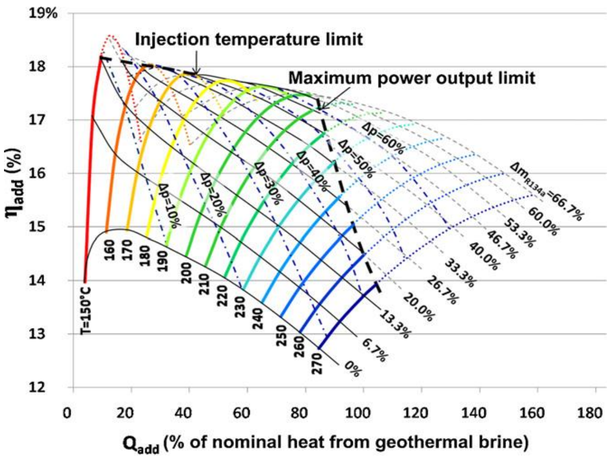

Figure 4. Additional heat conversion efficiencies obtainable by exploiting the additional heat source [35].

Li *et al*. [36] proposed a cogeneration system producing electricity and freshwater by a solar field driven supercritical SORC coupled with a desalination unit. The parabolic trough solar collectors in the proposed system could produce 700kW thermal energy with temperatures up to 400 ℃ at peak conditions. The SORC used hexamethyldisiloxane as the working fluid and could achieve cycle efficiency close to 21%. The RO unit specific energy consumption decreases due to the elevated temperature of the preheated seawater. Based on variable incident solar radiation, the proposed system had two modes of operation as electricity only and water-electricity co-generation. This system could reduce the negative impact of intermittent solar energy without thermal energy storage by converting solar energy to desalinated water.

Pikra *et al*. [37] presented a series of activities in developing a concentrated solar power plant which includes the conceptual design of the small-scale system with the capacity of 10kW in Indonesia. The electrification ratio in Indonesia by the end of 2011 was about 74%, which means that 26% of the population does not have electricity. Indonesian Institute of Sciences (LIPI) is developing small scale concentrated solar power plant using ORC that can be operated in remote, isolated areas or small islands. Some constraints of electrification in these areas are the cost of integrated grid construction is relatively high, the limitation of energy resources and the population of the area is relatively small. Research in concentrated solar power with parabolic trough has been carried out by LIPI since 2010 and a stand-alone power unit by utilizing local energy resources will be constructed. A hybrid system of solar thermal and biomass energy can be a suitable choice to solve the electricity problem in the area, since the daily average intensity is about 4.8kWh/m^2/day so the potential intensity of solar energy in some areas of Indonesia is relatively good.

Bu *et al*. [38] developed a thermodynamic model to develop a coupled ORC and vapor compression cycle (VCC) for ice maker driven by solar energy. Four working fluids of R123, R245fa, R600a and R600 were selected and evaluated to identify suitable working fluids which may yield high system efficiencies. Besides, the effects of generation temperature and condensation temperature on the system performance were also analyzed. In terms of power efficiency and expander size, R600 and R600a are more suitable working fluids for ORC. Also, R600a and R600 are more appropriate working fluids for VCC in terms of pressure ratio and coefficient of performance. In terms of overall efficiency and ice production per square meter collector per day, R123 is most suitable working fluid for ORC/VCC. The generation temperature and condensation temperature have important effects on overall efficiency and ice production. There is always an optimal generation temperature at which overall efficiency and ice production can achieve the maximum values, while the generation temperature can be controlled by changing the mass flow rate of working fluid for ORC. In addition, the system performance and payback period should be comprehensively considered so as to decide to adopt air cooled or water cooled condenser due to having different condensation temperature.

Casati *et al*. [39] investigated thoroughly on thermal storage systems tailored to high-temperature ORC power plants, stemming from the observation that the direct storage of the ORC working fluid is effective thanks to its favorable thermodynamic properties. They introduced a concept of complete flashing cycle (CFC) as a mean of achieving an unmatched system layout simplification, while preserving conversion efficiency, which is a variant of the Rankine cycle, whereby the vapor is produced by throttling the organic working fluid from liquid to saturated vapor conditions. The proposed turbo-generator achieved an estimated 25% efficiency, which corresponded to a value of 18% in design conditions for the complete system.

Recent interest in small-scale solar thermal combined heat and power (CHP) power systems has coincided with demand growth for distributed electricity supplies in areas poorly served by centralized power stations. One potential technical approach to meeting this demand is the parabolic trough solar thermal collector coupled with an ORC heat engine. Quoilin *et al*. [40] presented the design of a solar ORC being installed in Lesotho for rural electrification purpose. The system was consisted of parabolic though collectors, a storages tank, and a small-scale ORC engine using scroll expanders. They developed a model of each component taking into account the main physical and mechanical phenomena occurring in the cycle and based on experimental data for the main key components. The model allowed sizing the different components of the cycle and evaluated the performance of the system. Different working fluids were compared, and two different expansion machine configurations of single and double stage were simulated.

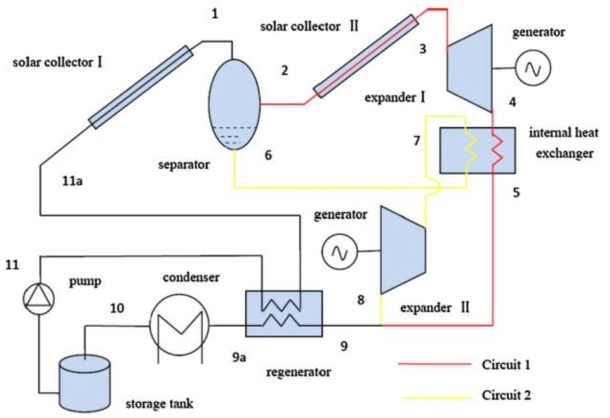

Figure 5. Schematic diagram of ALSRC system [41].

Bao *et al.* [41] proposed an auto-cascade low-temperature solar Rankine cycle (ALSRC) system as shown in Fig. 5. The system is different from the single-stage low temperature solar Rankine cycle (SSLSRC) system because it consists of two solar collectors, two expanders, a regenerator, and an internal heat exchanger. The working fluid used for the system is the zeotropic mixture of isopentane and R245fa. The main advantages of the ALSRC system is that heat from the exhaust stream of the expanders are reclaimed twice, once using an internal heat exchanger and another time using a regenerator. Results showed that the thermal efficiency of the system was significantly higher than that of SSLSRC system.

IV. Conclusion

This paper has presented a review of the latest developments and advances in solar collector system and solar-driven organic Rankine cycle (ORC). The solar collector and thermal energy storage subsystems are two core subsystems of solar thermal applications. Both the non-concentrating types and concentrating types of solar collectors have been discussed. The thermal storage tank in a solar system has an important function of the improvement of utilization of collected solar energy by providing thermal capacitance to alleviate the solar availability and load mismatch. The great efforts have been made by the many researchers to develop the better solar collector systems. ORC has been considered as a promising technology for conversion of low-grade heat into useful work or electricity. The potential of producing mechanical power or electricity by a system combining a solar thermal collector with an ORC has been shown by the theoretical and experimental studies.

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