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Solar Collectors and Photovoltaics as Combined Heat and Power Systems: A Critical Review

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Abstract

A main method to increase the solar energy utilization efficiency is to combine heat and power generation together. In this paper, a critical review of the literature on solar combined heat and power systems (CHP) is conducted, which includes solar photovoltaic/thermal systems, concentrated photovoltaic/thermal systems, and various combination with different solar collectors and applications. It shows that there are serious gaps in this field, which calls for more research. The modeling and analysis of the electrical parts of the CHP systems are not adequate, and there are limited studies on the economic and exergy assessments of the solar concentrating CHP systems. The solar collectors for combined CHP were focused on optimizing the performance of the maximum average useful power generation and minimum total heat transfer area, little environment impact analysis was conducted. Careful exergy, economic and environmental analysis on both electronic and thermal performance is suggested, especially for large CHP system.

Keywords: Combined heat and power; photovoltaic/thermal; concentrating collectors; flat collectors.

Contents:

1. Introduction

Energy and environment are the two main concerns of our future, and developing sustainable renewable energy technologies becomes more and more imperative. Among all the renewable sources, solar energy is the most promising one due to its abundance and environmentally friendly nature[2]. To resolve the reliability and accessibility problems of solar energy, hybrid power generations are used broadly, [4]. A main method of increasing the productivity of solar systems is to extend them to combined heat and power generation (CHP) [5]. Solar CHPs could reduce the greenhouse gas emissions far faster than the conventional solar energy devices, and maximize the economic and environmental value of the energy derived from the sun.

Firstly, in 1976, Wolf [6] analyzed the performance of a hybrid system of solar photovoltaic and flat plate thermal collector for residential applications in New Mexico. The performance of combined solar heat pump arrangements including series, parallel and dual source were analyzed by the TRNSYS software , which showed that the parallel configuration was the most practical combined setup, because of the higher thermal performance at a given collector area over the hot season [7]. In 1986, a hybrid solar closed-cycle gas turbine, consisting of a parabolic dish reflector with focal-mounted heat exchangers and a centralized prime-mover, was analyzed to meet the needs of a small urban/industrial community. The proposed cogeneration had substantial placement flexibility as it was free from the needs of natural gas, oil, and cooling water [8]. In another work, an actively cooled combined photovoltaic-thermal technology consisting of a linear solar concentrator and a tubular absorber was analyzed [9]. In 1991, a combination of an air heater and photovoltaic was analyzed. The optimum area of the solar cells, necessary to generate sufficient electrical energy for the pump, was calculated for different configurations of the air heater [10].

Kalogirou [11] simulated a hybrid photovoltaic–thermal (PVT) solar energy plant composed of a normal PV panel with a finned heat exchanger embedded at the back. In another work, a novel hybrid solar/gas scheme was developed for cooling/heating and electricity generation of buildings. The setup, including of an ejector heat pump cycle with a Rankine cycle, was driven by solar energy and a gas burner as a supplement [12]. Zhang and Wang [13] proposed and described a novel hybrid of solid adsorption–ejector refrigeration and heating system. In the proposed combined configuration, the absorber was driven by a solar compound parabolic concentrating collector, and a zeolite–water working pair was chosen. In another study, the design and construction of a hybrid heat pipe solar collector/CHP were conducted. The thermodynamic and heat transfer analysis of this design was studied to compare the proposed device with conventional electricity and heating systems. Also, the experimental data were measured in a building at the University of Nottingham [14,15]. Kalogirou and Tripanagnostopoulos [16] simulated hybrid PV/T solar systems, composed of polycrystalline silicon (pc-Si) and amorphous silicon (a-Si) PV modules, with TRNSYS. In this study, a domestic thermosyphonic system and a larger active system were considered. The results indicated that the hybrid units had a better chance of success when the overall energy production of the units was increased. The same case was studied for an industrial process heating system. The results indicated that the electrical production of the polycrystalline solar cells was more than the amorphous ones, but the solar thermal fraction was slightly lower [17].

In 2012, Carmeli et al. [18] compared different configurations of hybrid CHP systems with renewable energy sources. The first small-scale concentrating solar power plant with parabolic trough collectors was presented by Krüger et al. [19] for producing cooling, heating, and power.

Kasaeian et al. [20] prepared an optimal model for PVT systems by the genetic algorithm to increase both electrical and thermal efficiency. A novel CSCHP (Concentrated Solar Combined Heat and Power Plant) was presented by Han et al. [21] including solar trough collector, power generator and exhaust heat utilization for building scale. In another work, an evaluation of hybrid systems was presented, and different designs of hybrid systems were studied [22]. Recently, in 2017, Kasaeian et al. [23] have empirically studied the influence of changing the mass flow rate and channel conditions on the operation and efficiency of an air-cooled PVT. In another work, a research group examined the electrical output of a solar CHP with an organic Rankine cycle engine with various organic working fluids, for the UK climate [24].

A general and up-to-date review of concentrating photovoltaic/thermal (CPVT) technologies was proposed [25,26]. This review is divided into two sections; the first section of the article was about the CPVTs' specifications and the design factors, and the second section covered the CPVTs' published research, utilization areas, commercial enterprises, performance evaluation, and research outlooks.

Different types of solar thermal collectors and their applications were overviewed in an interesting review paper by Kalogirou [3]. The thermal and thermodynamic analysis of solar thermal collectors including flat-plate, evacuated tube, compound parabolic, parabolic trough, parabolic dish, Fresnel lens and heliostat field collectors were surveyed. Also, various applications of these collectors including solar water heating, space heating and cooling, refrigeration, industrial process heating, desalination, solar thermal power, furnaces and chemistry systems were presented [3]. A review of the literature on the solar energy-based heat and power plants has been done in 2017 [27], which considered the CHP plants, powered by renewable energies, to produce electricity and hot water for the end use. These plants included two configurations namely solar-only and solar-hybrid with solar PV, solar concentrating and non-concentrating collectors [27]. In order to fill this gap of knowledge, a critical review of the literature on solar combined heat and power systems is conducted in this work to advance our understanding in this field. The review includes solar PVT and CPVT, solar concentrating and flat collectors, with a focus on the most recent publications .

2. PVT CHPs

Obviously, solar energy can be used as the source of thermal energy and electrical energy. PVT systems are capable of converting solar radiation into electrical and thermal energy, simultaneously, which makes it more efficient compared to the current PV systems [28]. Due to many advantages of PVTs such as supply both electrical and thermal demand at the same time, and being cost-effective, the applications of these systems are being expanded [29]. The PVT systems consist of two parts: a solar cell which converts the sunlight into electricity and a solar thermal collector, mounted at the back of the PV panel, for collecting the thermal energy. Water or air are usually applied as the cooling fluids for the solar panels [1,30,31]. Therefore, this configuration enhances the operation of the panels, and improves the efficiency.

It has established that increasing the solar cell temperature by one degree centigrade decreases the efficiency of monocrystalline (c-Si) and polycrystalline (pc-Si) silicon solar cells by about 0.45%, and about 0.25% for the amorphous silicon (a-Si) cells [16]. Many researchers have analyzed the PVTs in terms of efficiency and the relation between the temperature of the panels and efficiency [32–35]. With this regard, Medrano et al. [36] investigated the efficiency, and the economic and environmental aspects of the integration of three distributed generation (DG) systems (high-temperature fuel cells, micro-turbines, and photovoltaic solar panels). In 2012, Carmeli et al. [18] compared different configurations of the hybrid distributed generation systems consisting of a CHP energy source and one or more renewable energy source. Also, a high-level control strategy was proposed to provide the electrical load demands, and improve the system performance. By using the genetic algorithm, Kasaeian et al [20] prepared an optimal model for PVT collectors to increase both electrical and thermal efficiencies ss. The design parameters and the temperature of the inlet air were also analyzed in this paper. In another study, an exergy and energy investigation on an air PVT collector was presented, and the effect of using glass cover was studied [37]. Also, Yazdanpanahi et al. [38] assessed the exergy efficiency of a PVT water collector, and simulated the performance of the PVT collector. The thermal and electrical performances of a modified photovoltaic/thermal solar collector were investigated experimentally. In another study, the electrical and thermal efficiencies of a modified PVT configuration were assessed empirically. In this assessment, the effect of the mass flow rate on the electrical and thermal efficiency were studied, and it was demonstrated that increasing the mass flow rate improved the thermal performance, but did not have an impressive effect on the electrical efficiency [39]. In 2017, Slimani et al. [40] presented an electrical-thermal model for three different photovoltaic/thermal collectors and photovoltaic modules in order to compare the efficiencies of the proposed configurations. These systems included a photovoltaic module, a conventional hybrid solar air collector, a glazed hybrid solar air collector and a glazed double-pass hybrid solar air collector. The results showed that the glazed double-pass hybrid solar air collector, the glazed hybrid solar air collector, the conventional hybrid solar air collector and the photovoltaic modules had the highest efficiency, respectively. Proell et al. [41] conducted an empirical research on the structure of compound parabolic concentrator PVT collectors with the aim of analyzing the efficiency of this configuration.

In order to reduce the waste of CHP systems, Nosrat and Pearce [42] proposed an absorption chiller to utilize the produced thermal energy of the system for cooling their PV-CHP unit. In 2015, Niederhäuser et al. [43] introduced a novel method with the aim of reduction in electrical power losses. This method worked with respect to the weather forecast and production information in order to have the optimum production. The impact of this method on the energy consumption was also investigated. Tourkov and Schaefer [44] provided a combination of a PVT collector and an ORC (Organic Rankine Cycle) to utilize the heat losses and enhance the overall efficiency.

Nowadays, according to the environmental and economic concerns, it is important to pay attention to optimizing the energy systems in order to reduce the greenhouse emissions and expenses. Charalambous et al. [45] focused on the optimization of a PVT collector in order to reduce the system expenditure. To reach this goal, some changes in the structure of the collectors were applied. In the same field, Chua et al. [46] analyzed a CCHP consisting a microturbine, a photovoltaic-thermal and a fuel cell, by applying the multi-criteria analysis method. The system was investigated in aspects of energy saving, environmental impact, and operational cost minimization. Nosrat et al. [47] presented a comparison between a PV-CHP, a PV-CCHP, and a conventional centralized power plant by means of the PV trigeneration optimization model method. The results of the simulation indicated that both CHP and CCHP configurations were effective in reducing the greenhouse emissions. In 2014, Nosrat et al. [48] evaluated the greenhouse gas emission of CHPs in the residential sector. In this research, it was indicated that the development of the hybrid PV and CHPs could reduce the CO_2 emissions by 21-62% (3000 to

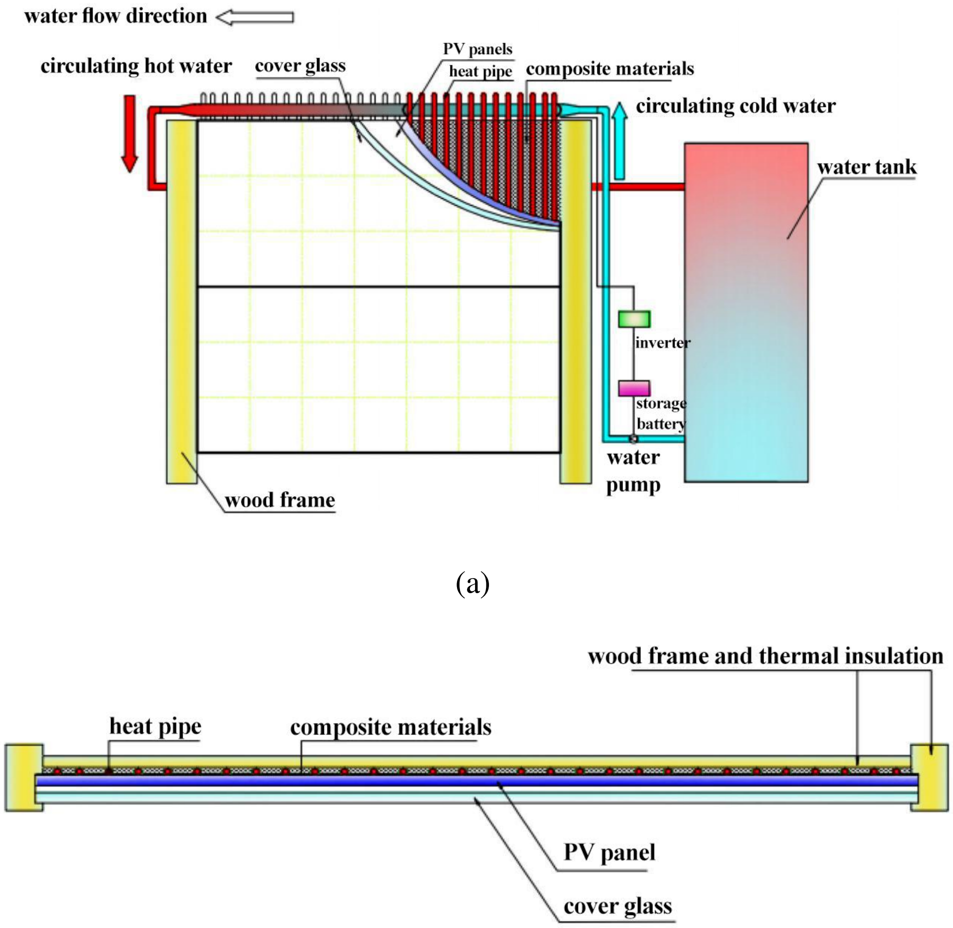
9000 $kg\ CO_{2e}/year$) based on the loads type. A CCHP was analyzed from the energy-ecological point of view, and the advantages and disadvantages of the thermo-ecological cost method were presented in comparison to the thermo-economic analysis method [49]. Akikur et al. [50] presented an investigation on cogeneration systems consisting solar photovoltaic and three different modes of the reversible solid oxide fuel cell. In this research, a numerical model was provided for simulating the thermal and electrical energy production. In another research, Yousefi et al. [51] assessed the application of CCHP micro-grids in buildings, and indicated the optimal capacity of the system. For this purpose, two different scenarios were considered and analyzed from the energy production, economic and environmental points of view.

The use of CHP configurations in the residential sector has been expanded in the recent years. The energy consumption in buildings is around 30%-40% of the total energy consumption in the world [52]. Therefore, it is essential to present an optimal model for CHPs in the residential parts. With this regard, Mohamed et al. [53] assessed the operation of a micro-CHP, then presented a new general model for the micro-CHP in buildings. A comparison between three different hybrid systems in the building sector was provide, and it was shown that the hybrid renewable systems, which contained PV panels, had the best operation [54]. In another study, a photovoltaic/natural gas hybrid system was studied and the operations of this unit were evaluated [55]. It was shown that this system was able to provide all of the electrical, thermal and cooling needs of the building of the studied area.

One of the significant points that should be considered in the construction of CHPs is specifying the optimal size of the system. Brandoni and Renzi [56] demonstrated the factors of the optimal sizing of solar-based hybrid systems, and illustrated the importance of optimal sizing in the residential sector. A simulation of a household-scale CHP hybrid system, which contained photovoltaic and battery arrays, was also presented [57]. In this paper, the ability of the systems to supply the energy demand of three regions in the U.S. was investigated, and it was shown that the arrangement and placement of the PVT modules affected the system operations. Sun et al. [58] evaluated the impact of the connection methods and the tilt angle of PVT modules on the performance, and presented a guidance for installing PVTs. In another study, an analysis and simulation was presented for the building-integrated photovoltaic thermal (BIPVT) configuration with respect to changes in the weather conditions [59]. Also, a model for a combined heat and power photovoltaic, fuel cell and wind turbine micro-grid was provided, considering all variable parameters [60]. This model could enhance the efficiency of the CHP system. The outcome of this research showed a 90% reduction in the total power loss of the test network, by using the introduced method, compared to the total power loss without optimization.

In an economic assessment of hybrid systems, different hybrid designs were studied and the optimal design was demonstrated, considering a number of constraints [22]. Aste et al. [61] proposed a numerical model for water-PVTs simulating, which involved the required parameters for the system performance prediction. They verified the model with the empirical results, then tested the model for three different places in Europe. In another research, a modification design of BIPVT roofing collectors was presented and validated with experimental results. It was shown that both electrical and thermal efficiencies of the presented panels were enhanced and the total energy efficiency ($\eta_T = \eta_{pv} + \eta_{thermal}$) could reach to 79.8%, 77.3% and 75.2% under the solar irradiances of 620 W/m^2, 800 W/m^2 and 1000 W/m^2, respectively [62]. By utilizing the TRNSYS software, Hazami et al. [63] evaluated the annual expenses and the energy and exergy efficiencies of a PVT collector in the residential sector in Tunisia. The evaluation of this article demonstrates that the exergetic and electrical efficiencies of the considered PVT configuration could increase by 2.5% and 3%, respectively.

Many researchers have investigated the performance of heat pipes with nanofluids in controlling the temperature of PVT collectors [64–66]. Nanofluid is composed of nanometer-sized solid particles (lower than 100 nm at least in one dimension), which are dispersed in heat transfer fluids such as water, oil and ethylene glycol [67]. It has been shown that nanofluids could increase the thermal conductivity of the liquids, and enhance the cooling capability of the fluid [68,69]. On this issue, Khanjari et al. [70] tested different compounds of nanofluid in order to enhance the heat transfer in PVT panels. The results of the simulation indicated that using these fluids had a positive effect on the system performance. Wang et al. [71] combined the heat pipe building-integrated PVT collectors (HP-BIPVT) with phase change material storage devices and metal wires to improve the system efficiency in dwelling sector. The introduced configuration could improve the efficiency and reduce the heat waste, furthermore, it could increase the heat storage capacities. The HP-BIPVT configuration was comprised of the PVT module, inverter, battery, water tank, water pump and piping, as illustrated in Fig. 1. Kim et al. [72] coupled a heat-recovery ventilator with an air-PVT collector which could improve the efficiency. The performance of the proposed configuration was compared with the air-PVT without ventilator. Also, an empirical study was performed on a PVT panel to indicate the potential of extension of PVTs. The impact of the air flow rate and the depth of the collector on the performance of a PVT air system were investigated. It was demonstrated that the collectors with smaller depth had a more sensibility to the air mass flow rate, but it had better performance at high ΔT [73]. In 2017, Kasaeian et al. [23] empirically studied the influence of changing the mass flow rate and channel condition on the operation and efficiency of an air-cooled PVT. It was indicated that decreasing the depth of channels improved the thermal performance. In another research, Khanjari et al. [74] compared two different fluids and indicated that the performance of the system, using Al_2O_3-water, was better than the case using pure water. Liu et al. [75] utilized microencapsulated phase change slurry in PVT collectors, to increase the heat transfer and enhance the thermal and electrical efficiencies of the system.



(a)

(b)

Fig. 1. (a) Schematic of the proposed HP-BIPVT configuration, (b) Plan view of the PVT module [71] [Reprinted with permission from Elsevier]

Table 1 shows a summary of the studies about photovoltaic thermal systems. Surveying the papers, which concentrated on PVTs, demonstrates that the number of simulation and modeling articles are more than the experimental studies. Some of the studies are focused on the optimization of the PVTs in order to increase the efficiency. However it is essential to consider electrical simulation to optimize the electrical parts of the system, for enhancing the total efficiency. Assessing the papers indicates the lack of attention to analyzing the optimal connection mode, and integration of PVT collectors to the electric grid. The optimal sizing is another important matter in designing the energy systems, which has not been paid attention in the literature.

Table 2. Summary of the studies about photovoltaic thermal systems

Author(s)	**Brief title**	**Highlights**	**Significant Action**	**Ref.**
Kalogirou and Tripanagnostopoulos (2006)	Providing domestic hot water	Investigating a photovoltaic thermal using TRNSYS software in domestic scale.	Simulation	[16]
Kalogirou (2001)	Using TRNSYS for modeling	Analyzing and simulating a PVT collector in order to determine the efficiency of the system.	Modeling and Simulation	[11]
Medrano et al. (2008)	Integration of distributed generation	Investigating the efficiency, economic and environmental aspect of the integration of three DG technologies.	Simulation and Assessment	[36]
Kasaeian et al. (2013)	Modeling an air-cooled PVT.	Modeling and optimizing of an air-cooled PVT, and calculating the design parameters and the temperature of inlet air.	Modeling and Optimization	[20]
Nosrat and Pearce (2011)	Dispatch strategy and model	Proposing an absorption chiller to utilize the produced thermal energy of the system for cooling a PV-CHP.	Simulation	[42]
Charalambous et al. (2011)	Optimization of PVT collector	Optimizing the PVT system in order to reduce the expenditure. To reach this goal, some changes in the structure of the collectors were applied.	Mathematical analysis and Optimization	[45]
Carmeli et al. (2012)	Control strategies and configurations	Comparing different configurations of hybrid distributed generation configurations and providing a control strategy to supply the electrical load demands.	Analysis	[18]
Chua et al. (2012)	Integrating renewable energy technologies	Analyzing a CCHP system consisted of a micro-turbine, photovoltaic-thermal and fuel cell. This configuration could supply the energy demand of a commercial building.	Modeling, Evaluation and Analysis	[46]
Nosrat et al. (2013)	Performance of trigeneration	Presenting a comparison between PV-CHP, PV-CCHP and conventional centralized power plant systems.	Optimization and Assessment	[47]

Kasaeian et al. (2013)	Energy and exergy analysis	Investigating the energy and exergy efficiency of an air PVT collector. Studying the influence of the application of glass cover on the total performance.	Modeling and Analysis	[37]
Nosrat et al. (2014)	Simulations of greenhouse gas emission	Evaluating the greenhouse gas emission of CHPs. It was illustrated that the extension of hybrid PV and CHP systems could reduce the CO_2 emissions by 21-62%.	Modeling and Optomization	[48]
Akikur et al. (2014)	Analysis of a cogeneration unit	Investigating and simulating cogeneration systems consisting solar photovoltaic and three different modes of reversible solid oxide fuel cell.	Assessment and Modeling	[50]
Mohamed et al. (2014)	Selection of micro-cogeneration	Analyzing and presenting a new model of micro-CHP in buildings, and calculating the factors of the overall weighted matching index (WMI).	Modeling	[53]
Brandoni et al. (2014)	Simulation of hybrid systems	Providing a comparison between three different hybrid systems in the building sector. The hybrid renewable systems, containing PV panels, had the best arrangement.	Comparison studying, Modeling, and Optimization	[54]
Niederhäuser et al. (2015)	Innovative solar heating	Introducing a novel optimization method in order to reduce the energy waste. This method operated with respect to the weather forecast.	Simulation and Optimization	[43]
Ondeck et al. (2015)	Optimal operation of a residential PVT	Studying a photovoltaic/natural gas hybrid device which could provide all of the electrical, thermal and cooling needs.	Modeling and Feasibility study	[55]
Tourkov and Schaefer (2015)	Evaluation of PVT/ORC	Studying the combination of PVT collector and organic Rankine cycle, the proper working fluid was indicated.	Optimization and Analysis	[44]
Brandoni and Renzi (2015)	Optimal sizing of hybrid micro-CHP	Demonstrating the factors of optimal sizing of solar-based hybrid systems and indicating the importance of optimal sizing.	Optimal sizing and Analysis	[56]
Stanek et al. (2015)	Thermo-ecological assessment	Investigating CCHP facilities in terms of ecological. Also, an exergy analysis was presented to assess the performance. The advantages and disadvantages of TEC (thermo-ecological cost) method were illustrated.	Exergo-ecological analysis	[49]
Shah et al. (2015)	Performance of hybrid units	Simulating a household hybrid energy unit in three different regions in U.S by the HOMER software, and assessing the ability to supply the energy demand.	Simulation and Viability study	[57]
Sun et al. (2016)	Effect of tilt angle and connection mode	Studying the effect of tilt angle and connection mode of PVT modules on the operation, and proposing an instruction for installing the PVTs.	Experimental study and Simulation	[58]
Khanjari et al. (2016)	Investigation of using nanofluid	Testing different combinations of nanofluids in order to have the best heat transfer. By Ag-water nanofluid, the value of electrical and thermal exergy could reach to 137.9470 kW and 24.2384 kW.	Evaluation and Simulation	[70]
Wang et al. (2016)	Investigation of HP-BIPV/T	Applying the heat pipe building-integrated PVT collectors (HP-BIPVT) with using phase change material and metal wires to reduce the heat losses.	Design and Experimental study	[71]
Farshchimonfared et al. (2016)	Optimization and sensitivity analysis	Investigating the impact of air flow rate and depth of collector on the efficiency. The collectors with smaller depth were more sensible to air mass flow rate.	Optimization and Sensitivity analysis	[73]
Kim et al. (2016)	Performance of an air-type PVT	Presenting a heat-recovery ventilator, which coupled to an air-PVT, and comparing this configuration with the air-PVT collector without a ventilator.	Experimental analysis	[72]
Rounis et al. (2016)	Modeling under climatic conditions	Analyzing and modeling the Building-Integrated Photovoltaic Thermal (BIPVT) systems, considering the influence of changing weather conditions.	Comparison, Modelling and Numerical	[59]

Bornapour et al. (2016)	Optimal coordinated scheduling of CHP	Proposing a model for a combined heat and power photovoltaic, fuel cell and wind turbine micro-grid, considering all variable parameters.	Modelling and Evaluation	[60]
Rodríguez et al. (2016)	Economic feasibility	Presenting an economic assessment and studying different designs of hybrid systems. Proposing optimal configuration considering a number of constraints.	Life Cycle assessment and Comparison	[22]
Aste et al. (2016)	Performance monitoring and modeling	Proposing a numerical model for water-PVTs, simulating and verifying the model with empirical results, and testing the model for different places.	Modelling and Experimental validation	[61]
Chen and Yin (2016)	Fabrication and laboratory-based testing	Modifying the design of BIPVT roofing collectors, and increasing the efficiency of the PVT collectors.	Design and Experimental validation	[62]
Hazami et al. (2016)	Energetic and exergetic analysis	Investigating the cost and exergy efficiencies of a PVT system in Tunisia by utilizing TRNSYS software. Performing an empirical study to indicate the potential of the extension of PVTs.	Experimental analysis and Simulation	[63]
Saygin et al. (2016)	Evaluation of a modified PVT	Assessing the electrical and thermal efficiency of a modified PVT configuration, empirically.	Experimental study	[39]
Kasaeian et al. (2017)	Effects of forced convection	Studying the effect of changing the mass flow rate and channel conditions on the operation and efficiency of an air-cooled PVT.	Experimental investigation	[23]
Khanjari et al. (2017)	Evaluating the environmental parameters	Comparing two different fluids and showing that Al_2O_3-water nanofluid had positive effect on the efficiency.	Theoretical analysis	[74]
Yousefi et al. (2017)	Multi-objective optimal sizing	Assessing the application of CCHP micro-grids in building, and indicating the optimal capacity of the system.	Simulation and Optimal sizing	[51]
Slimani et al. (2017)	A detailed thermal-electrical model	Presenting an electrical-thermal model for three different photovoltaic/thermal collectors and photovoltaic modules.	Modeling and Experimental validation	[40]
Liu et al. (2017)	Performance evaluation of a novel PVT	Utilizing microencapsulated phase change slurry in PVT collectors, to increase the heat transfer and enhance the thermal and electrical efficiencies.	Simulation and Dynamic analysis	[75]

3. CPVT CHPs

In a concentrated photovoltaic system, lenses and curved mirrors are used to converge the sunlight into the solar panels. The increased solar energy intensity in CPVT leads to increased thermal and electrical performance in comparison with simple PVT collectors. Properly used, CPVT collectors could increase the overall solar energy efficiency and reduce the number of required solar cells. Mittelman et al. [76] analyzed an integrated system consisting a CPVT collector and a multi-effect evaporation (MEE) desalination plant. This combination could produce solar electricity and utilize the heat losses of the photovoltaic cells to desalinate water, simultaneously. The results of the simulation and the cost investigation showed that the proposed integrated plant could have a considerable benefit, comparing to the conventional solar desalination methods. A schematic of the CPVT-based MEE plant is shown in Fig. 2.

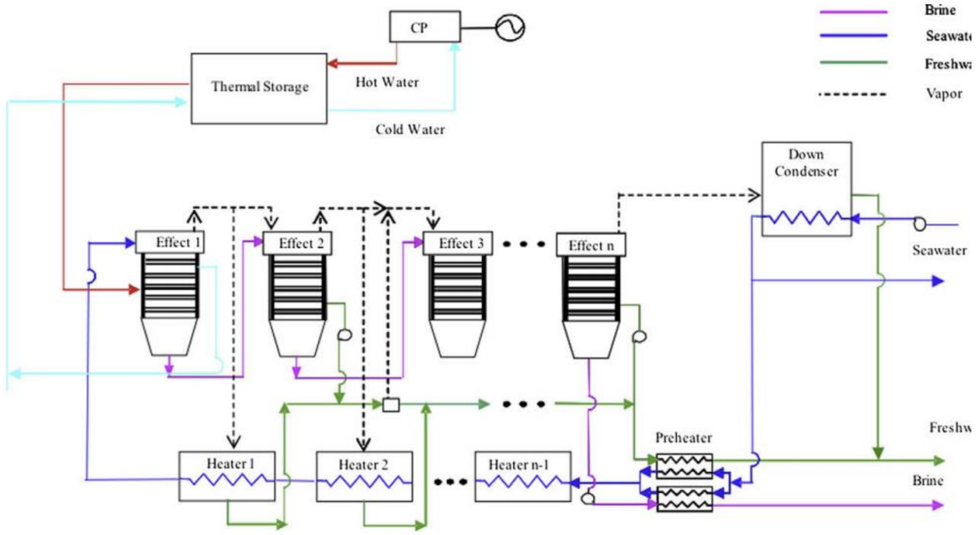


Fig. 2. Schematics of the CPVT-based MEE plant [76] [Reprinted with permission from Elsevier]

In 2010, Chowdhury et al. [77] provided a model to enhance the overall efficiency of a coupled CPVT solar collector by optimizing different influencing factors. In another study, Otanicar et al. [78] analyzed the efficiency of a coupled CPVT collector and indicated that, by changing some parameters including the band-gap of the PV material, solar concentration ratio, and the system thermal pattern, the efficiency could reach to 32.3%. Ji et al. [79] provided a one-dimensional steady model for a trough CPVT collector with a super cell array and a GaAs cell array. Helmers et al [80] provided an energy balance model for CPVT collectors. The results illustrated that, at the concentration ratios above 300 and at the temperatures up to 160 °C, the system reached a total efficiency of 75%. In 2013, Calise et al. [81] introduced an integrated system consisting a CPVT collector and a high-temperature solar heating and cooling (SHC), as shown in Fig. 3. The results of the simulation, by the TRNSYS software, were verified empirically.

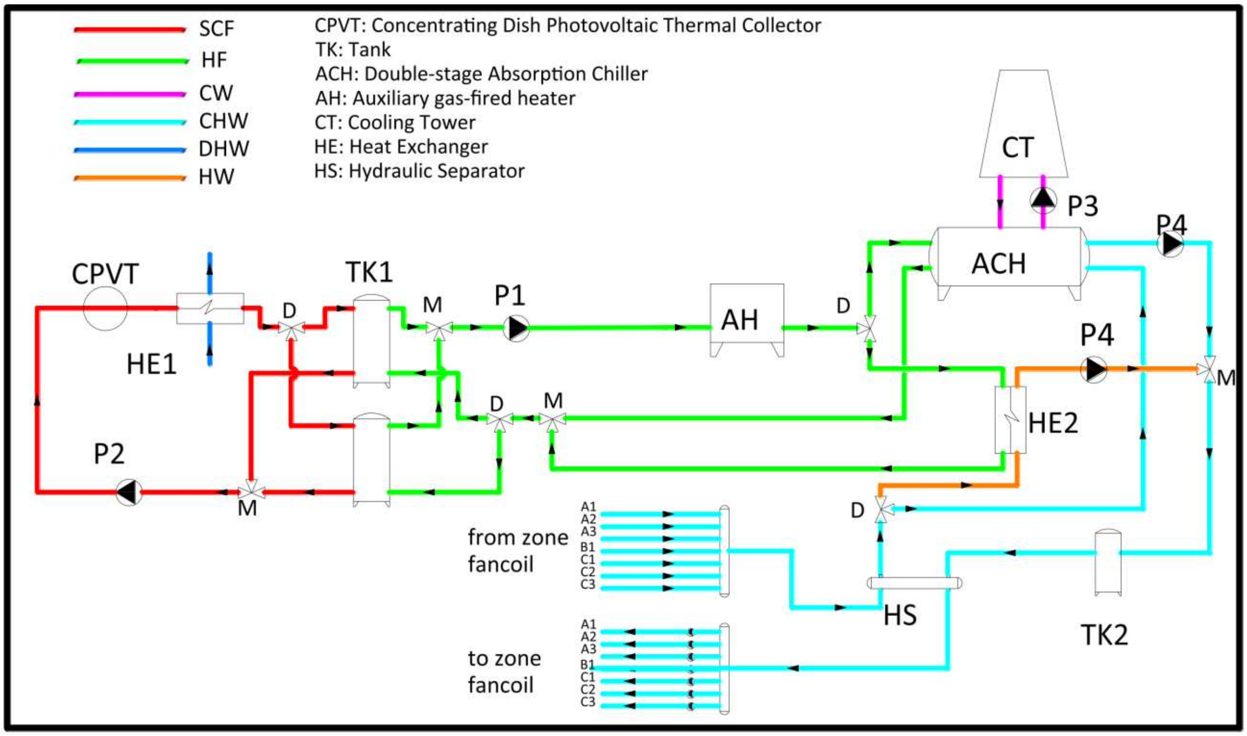


Fig. 3. Solar Trigeneration (ST) system [81] [Reprinted with permission from Elsevier]

Helmers and Kramer [82] presented a performance model for both non-concentrating PVT and concentrating CPVT collectors, considering the panel's realistic application conditionsBuonomanoa et al. [83] analyzed an integrated CHP comprising CPVT collectors and SHC systems, using a novel renewable poly-generation device. The results of economic assessment confirmed the effectiveness of the system. Calise et al. [84] proposed a prototype unit consisting of CPVT solar collectors with a parabolic dish concentrator and a planar receiver based on an ORC. Papadopoulos et al. [85] reviewed the current conditions of photovoltaic power generation centralizing CPVs. In this research, a solar polygeneration system (PROTEAS) was introduced to supply electricity, hot water, and air-conditioning, simultaneously. The PROTEAS is a novel solar polygeneration system, which can present a practical alternative to the conventional energy systems. Sharaf and Orhan [86] focused on assessing the components of the CPVT solar technologies, and provided comprehensive optimization models. In 2017, Tripathi et al. [87] analyzed three different series-connected CPVT collectors (partially covered N-CPVT collector, fully covered N-CPVT collector and convectional N-CPC collector). It was illustrated that, in terms of the demand of total thermal exergy and energy, the convectional N-CPC collector had some advantages in comparison with other cases.

The obvious constraint for large scale application of CPVT system is the cost. Due to the much higher construction cost of the CPVT systems, it is required to evaluate these cases in economic aspects carefully and selecting proper collectors becomes a very important issue. On this aspect, however there is not enough research to address the factors of selecting the appropriate collector, which will be reviewed below. Table 2 shows a summary of the studies about CPVT-based CHPs.

Table 2. Summary of the studies about CPVT CHPs

Authors	**Brief title**	**Highlights**	**Significant Action**	**Ref.**
Mittelman et al. (2009)	Water desalination with CPVT	Integrating a CPVT collector with an MEE desalination plant to produce solar electricity and desalinate water, simultaneously.	Simulation and Economic investigation	[76]
Chowdhury et al. (2010)	Efficiency of a CPVT collector	Modeling a CPVT collector system in order to improve the efficiency of CPVT collectors by changing in some factors.	Simulation and Analysis	[77]
Otanicar et al. (2010)	Parametric analysis of a coupled CPVT	Modeling a coupled CPVT collector in order to analyze the efficiency. The efficiency could reach to 32.3%.	Simulation and Parametric analysis	[78]
Ji et al. (2012)	Analysis of a Trough CPVT	Providing models for a trough CPVT collector and validating the models empirically with the aim of assessing the operation.	Modelling and Experimental	[79]
Helmers et al. (2012)	Modeling of CPVT	Providing a model and analyzing the performance of CPVTs. The results demonstrated a total efficiency of 75%.	Modelling and Analysis	[80]
Calise et al. (2013)	Dynamic simulation	Introducing an integrated system consisting of a CPVT collector and a high-temperature SHC.	Dynamic simulation and Economic analysis	[81]
Helmers and Kramer (2013)	Multi-linear performance model	Presenting and analyzing a performance model for PVT and CPVT systems which considered the condition of the panels.	Modelling	[82]
Buonomanoa et al. (2014)	A novel renewable poly-generation	Analyzing a CHP including CPVT and SHC systems. The results of the economic assessment confirmed the usefulness of the case.	Design, Dynamic simulation and Economic analysis	[83]
Calise et al. (2015)	Design and dynamic simulation	Providing a prototype combined system consisting CPVT collectors with parabolic dish concentrator and a planar receiver based on ORC.	Design and Dynamic simulation	[84]
Papadopoulos et al. (2015)	Innovative optics for CPVTs	Reviewing the current conditions of photovoltaic power generation centralizing CPVs. Introducing PROTEAS to supply electricity, hot water, and air-conditioning, simultaneously.	Reviewing	[85]
Sharaf and Orhan (2016)	Thermodynamic analysis	Investigating the performance of CPVT technologies. Assessing and simulating the components of the CPVT to indicate the optimal design.	Thermodynamic analysis, Simulation, and optimization	[86]
Tripathi et al.	Energy matrices and exergoeconomic analysis	Analyzing three different series-connected CPVT collectors. The convectional N-CPC collector had some advantages over the others.	Comparison and Evaluation	[87]

4. Concentrating Solar Thermal Collectors

Solar collectors, which convert the absorbed incident solar radiation into heat, are the key components of any solar systems. The generated heat is carried by a working fluid for different applications such as producing hot water or space conditioning, and stored in a storage tank for using at nights or cloudy days. Solar collectors are classified as the non-concentrating and concentrating ones. For the low and medium temperature applications, such as space heating and cooling, water heating, and desalination, flat collectors are mainly used. While for the high-temperature applications such as electricity generation, the concentrating solar collectors are applied [1]. To satisfy the power and heat demands simultaneously, the CHP configurations based on concentrating solar collectors can be used either in the solo-solar or solar hybrid units. To assure the independent supply of the heat and electric power from daylight and weather conditions, combining two devices is a technically and economically compatible solution. The concentrating solar thermal collectors and the CHP plants, using these collectors, have been widely studied over the last decades. These investigations include analyzing the concentrating collectors for various usages such as electricity, heating, and cooling.

4.1. Parabolic Trough Collectors

One of the key parameters for the enhancement of the solar energy conversion is to increase the solar collector's performance by optimizing the geometry of the collector, changing the working fluid and selecting proper materials for the absorber tube. Among all solar collectors, parabolic trough collector (PTC) is the well-performed one. A PTC consists of a reflector (parabolic trough mirror) and a receiver in the focal line of the reflector to collect the reflected radiation from the sun. A metal black pipe is placed along the focal line of the collector and covered with a glass tube to reduce the heat losses. The concentrated radiation reaches the receiver tube and heats the circulating fluid for converting the solar radiation into useful heat [88]. This type of collector is one of the solar linear concentrating collectors which can be used for the light structures in the range of 150-400 ℃.

In 2000, Omer and Infield [89] assessed the thermal performance of a two-stage solar energy concentrator including a parabolic trough and a compound parabolic concentrator for generating both heat and thermoelectric power (Fig. 4). The aim of designing this structure was to provide an effective concentration of the incident solar radiation without adjusting the tracking and inhibiting the heat loss from the absorber. The designed system was assessed by the computational fluid dynamic modeling, and an experimental validation was carried out by a laboratory scale system. The results from evaluating thermal conversion efficiency with tracking misalignment and collector tilt angle showed that the thermal radiation dominated the convective heat losses. So, the efficiency was very sensitive to the collector tracking misalignment angle, particularly for the angles greater than about 4℃.

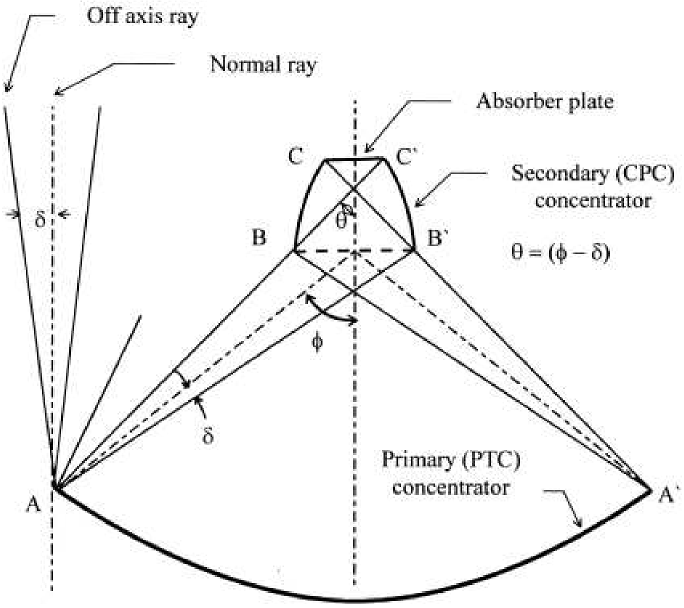


Fig. 4. Two-stage concentrator with a parabolic trough and a compound parabolic concentrator collector [89] [Reprinted with permission from Elsevier]

Al-Sulaiman et al. [90,91] proposed a solar parabolic trough collector and an ORC unit with two thermal storage tanks to improve the performance of a novel CCHP device, as shown in Fig. 5. They considered three modes of operation including solar, solar and storage, and storage alone, and examined the exergy performance by varying the pinch point temperature of ORC evaporator, the inlet temperature of ORC pump and the inlet pressure of the turbine. A single-effect absorption chiller and a heat exchanger were used in the trigeneration system to provide the necessary cooling and heating energy. The results revealed that using trigeneration increased the exergy efficiency noticeably. The maximum trigeneration-exergy efficiency was 20%, 8% and 7% for the solar, solar and storage, and for the storage mode, respectively.

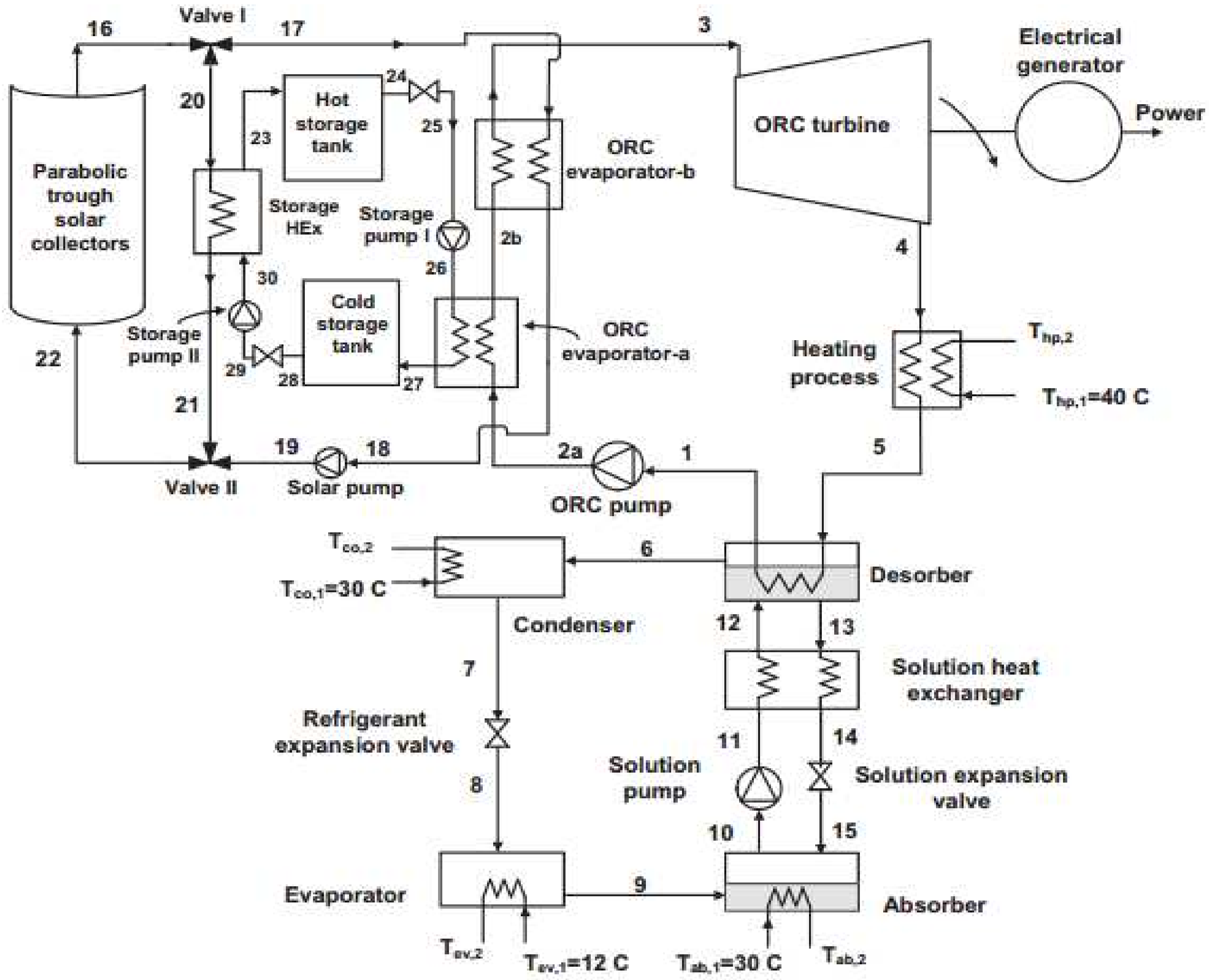


Fig. 5. Layout of solar parabolic trough CCHP plant [91] [Reprinted with permission from Elsevier]

Another similar research, with a stand-alone solar parabolic trough collector and a thermal storage, was carried out in 2014. The parabolic trough plant was simulated in the TRNSYS by coupling with the Solar Thermal Electric Components model library for meeting both electricity and heating loads in an isolated area of Egypt. Both solar and power cycle performances were modeled based on the solar energy data of the plant site. High transmission losses and costs were the main challenges for electrification in the selected area (Nile valley) [92]. The first small-scale concentrated solar power plant with parabolic trough collectors was presented by Krüger et al. [19] for producing cooling, heating, and power. The solar field, turbine and chiller ran jointly and produced electricity and chilled water. It was the first concentrating solar power plant in a power range below 100 kW electricity. The study revealed that the major obstacle for small scale solar thermal power production was the unavailability of the matched and cost efficient steam turbines or other Rankine expansion machines.

Also, many types of research have been done for developing the model of small-scale solar thermal trigeneration plants consisting parabolic trough collectors and ORC units [93–98]. Some other works have been carried out to analyze and assess the performance of parabolic trough CHP plants. Borunda et al. [99] studied a CSP plant, coupled with an ORC unit, applied for a textile industrial process in Almeria, Spain. The results showed that the system was a favorable alternative for the medium temperature CHP applications. Naccarato et al. [100] presented a numerical model of a linear parabolic trough collector, coupled with an ORC system, for combined energy and DHW (domestic hot water) production in Brindisi, Italy. The outputs showed that the co-generation of both electricity and heat enhanced the overall efficiency to 12-30%. Yuksel et al. [101] analyzed the thermodynamic performance of a solar-based multi-generation plant. The components of this system were parabolic trough collectors, a proton exchange membrane fuel cell, a double-stage organic Rankine cycle, and a quadruple effect absorption cooling system to produce power, space heating and cooling, DHW and hydrogen. In another study, a hybrid parabolic trough collector was analyzed for determining the optimum coupling conditions. Fig. 6 shows the parabolic solar trough collector, coupled with a Rankine cycle and a heat exchanger The parabolic trough solar collector reflects the heat coming from the sun by using a parabolic-shaped mirror onto a vacuum-sealed pipe, where the heat transfer fluid is heated up to high temperatures [102].

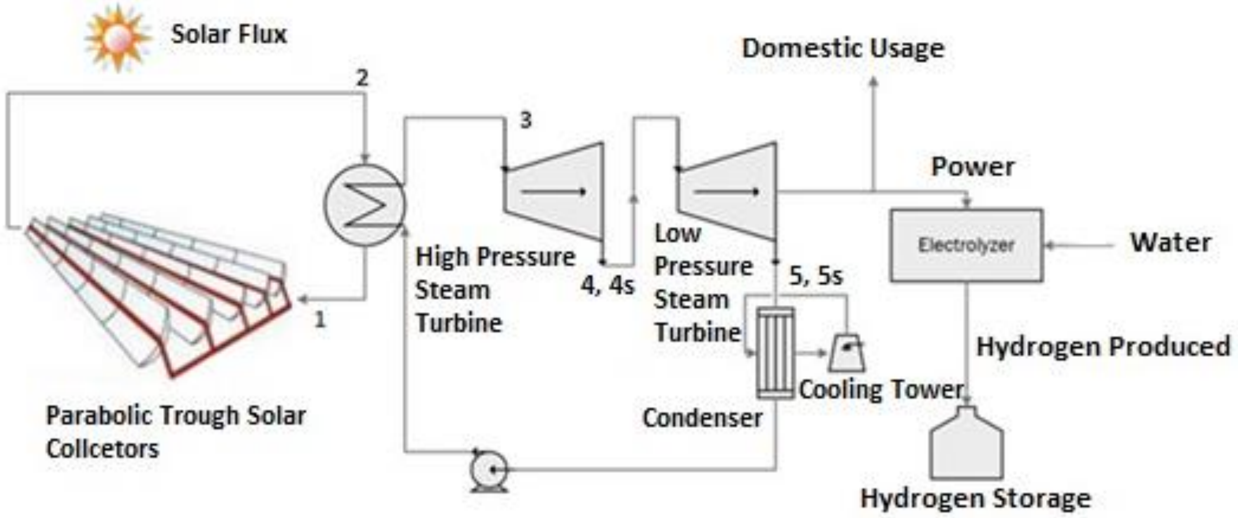


Fig. 6. Parabolic solar trough coupled with Rankine cycle [102] [Reprinted with permission from Elsevier]

In 2014, a concentrated solar combined heat and power plant scheme was presented by Han et al. [21]. The unit included a solar trough collector, a power generator and an exhaust heat utilization for building scale. The results indicated that the best exergy efficiency was near 30%, when the external environment was about 300 K. In 2016, a solar-based multi-generation was proposed to assess the energy and exergy performance of the system. The configuration was formed by a parabolic trough collector, two ORCs, an electrolyzer, a heat pump, a thermal storage unit, and two absorption chillers for producing power, heating, cooling, hydrogen, and dry biomass. The results showed that the overall energy and exergy efficiencies were 20.7% and 13.7%, respectively [103]. Another novel polygeneration plant was composed of parabolic trough collectors, a Kalina power cycle, an electrolyzer, an absorption refrigeration cycle, a hydrogen tank, and a thermal storage tank. This system was applied in a multi-unit building in Toronto, Canada for producing heating, cooling, power, and hydrogen. The proposed renewable-based system minimized the use of fossil fuels [104].

4.2. Parabolic Dish Collectors

One of the key methods to increase the temperature of the working fluid is to focus the sunlight to a focal point by means of parabolic dish collectors [105]. A parabolic dish reflector is a point-focus collector to track the sun in two axes and concentrate the solar energy onto a receiver at the focal point of the dish. To reflect the beam into the thermal receiver, the sun should be tracked by the dish structure. Also, in the case of CHP applications, the receiver absorbs the solar energy radiation, and converts it into thermal energy by a circulating fluid. The thermal energy can be converted into electricity by coupling an engine-generator directly to the receiver, or it can be transported to a central power-conversion system by pipes. The following studies have been conducted in the field of solar parabolic dish CHPs.

Cucumo et al. [106] used a life cycle assessment analysis on a micro-CHP with dish-Stirling. The outputs of the study indicated that the dish-Stirling devices had low impact in comparison with photovoltaics. Later in 2013, the 3E (energy, economic and environmental) analysis of a solar dish-Stirling CHP system, coupled with an HVAC, was carried out to meet the power, heating, hot water and cooling needs of a residential building. The results showed that using the solar dish-Stirling micro-CHP had a pleasant potential in the primary energy saving, carbon dioxide emission reduction and acceptable payback period. Also, for selecting the optimum size of the engine in some cities of Iran, the TOPSIS decision-making method was used. Among these cities, Tabriz had the highest overall efficiency and Bandar Abbas had better performance in the annual Stirling engine efficiency, the annual primary energy saving and annual carbon dioxide emissions reduction [107]. Grosu et al. [108] presented a micro-CHP system with Stirling engine, and the results showed that the direct method and the adiabatic model had good accuracy. Ferreira et al. [109,110] optimized a micro-CHP with a parabolic collector and a solar Stirling engine to produce heat and power. The main purpose of the paper was to maximize the annual worth of the CHP system. Fig. 7 shows a simplified layout of the micro-CHP with parabolic dish collectors.

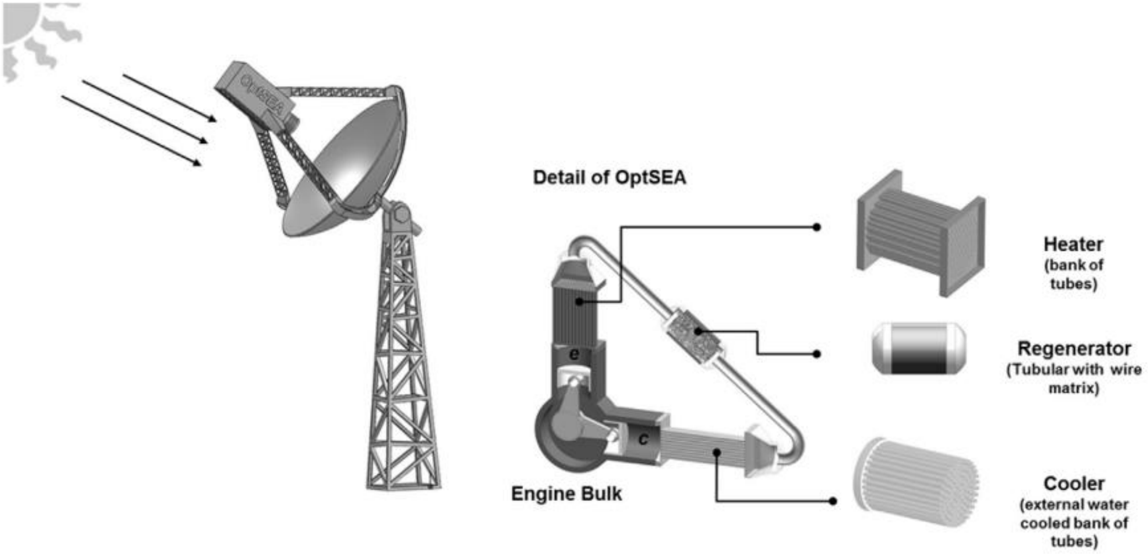


Fig. 7. Schematic of a micro-CHP with parabolic dish collector [109] [Reprinted with permission from Elsevier]

4.3. Fresnel Collectors

Linear Fresnel collectors are another types of concentrating collectors, which have linear receivers and reflectors. The reflectors concentrate the direct solar radiation onto a linear receiver to heat up and evaporate water. These collectors can be considered as the broken-up parabolic trough collectors, but unlike them, there is no obligation to be in the shape of parabolic. So, large absorbers can be constructed and the absorber does not have to move. The main benefit of these systems is the application of flat or elastically-curved reflectors which are cheaper in comparison with the parabolic glass reflectors. Moreover, these collectors are mounted close to the ground and decrease the structural requirements.

Iglauer et al. [111] investigated a CHP plant to provide the process heat for a paint shop convection ovens, along with electric power. The configuration was composed of a Fresnel collector, a micro gas turbine, and a thermal oil circuit. The results indicated that the consumption of fossil fuels was reduced by 35% at the nominal power, and the overall efficiency reached to the values beyond 90%. Fig. 8 shows an example schematic of the CHP with solar Fresnel collectors. Rady et al. [93] studied an integrated system using parabolic trough and LFC (linear Fresnel collectors) at different operation modes in typical winter and summer days, in Egypt. The results showed that the use of LFC caused a reduction in the operation hours of ORC and TDAC (Thermally Driven Absorption Chiller) by about 50% and 30%, respectively.

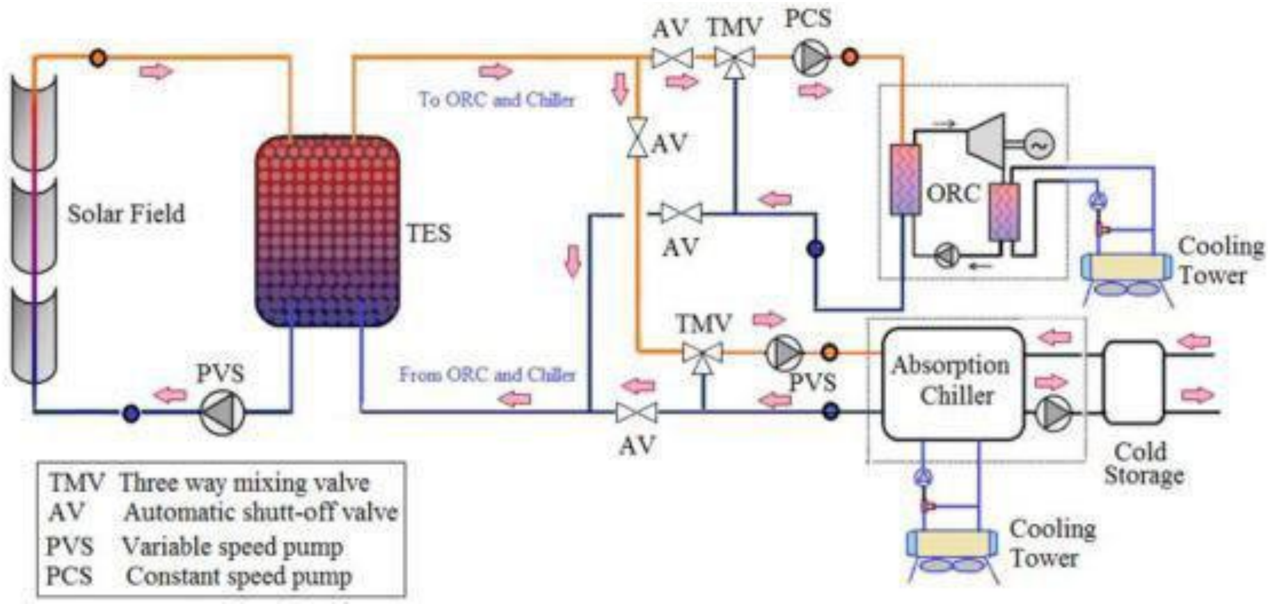


Fig. 8. Layout of the CHP with solar Fresnel collectors [93] [Reprinted with permission from Elsevier]

By reviewing these studies, it can be noticed that coupling solar parabolic trough collectors with other devices such as storage tanks, turbine and generator packages, and fuel cells could improve the performance of CCHPs, and make them competitive from the cost and environmental point of view. Also, some other novel studies have been done on the scale-up of polygeneration to provide the energy needs of multiunit buildings without depending on fossil fuels. Future work should be more practical to optimize the solar CHPs and pave the way of commercialization. Surveying the publications about dish-Stirling CHPs illustrates that almost all of the investigations in this context are on the basis of size optimization and life cycle analysis of the device. It is suggested to consider these systems with coupling other renewable energies to get a better performance. There is no article about simulation and mathematical modeling of dish-Stirling CHPs.

Table 3 shows the summary of the studies about solar concentrating collectors in CHP plants and reveals that most of the researches in concentrating CHP systems are about parabolic trough collectors due to their relative high efficiencies. There are a few articles about other types of concentrating collectors, and it is recommended to study the feasibility of these systems by the simulation software.

Table 3. Summary of the studies about solar concentrating collectors in CHP plants

Author	**Brief title**	**Highlight**	**Significant Action**	**Ref.**
Omer and Infield (2000)	Analysis of solar concentrator	Combination of a parabolic trough and a compound parabolic concentrator.	Designing, Modelling	[89]
Al-Sulaiman et al. (2011)	Exergy modeling trigeneration	Solar collectors and ORC evaporators as the key sources of the exergy reduction. Insignificant effect of the turbine inlet pressure.	Modeling, Exergy	[90]
Al-Sulaiman et al. (2012)	Assessment of parabolic trough	Solar mode with the highest energy efficiencies, and net electrical power. The lower efficiency of the solar mode in comparison with the solar and storage mode.	Modeling	[91]
Krüger et al. (2012)	Solar cogeneration parabolic trough	The first CSP plant in a power range of <100 kW. A package solution for reducing costs of small-scale CSP installations.	Designing, Modeling, Experimental	[19]
Abdelhady et al. (2014)	Design of solar co-generation	Performance and economic assessment of a stand-alone solar thermal co-generation plant using diathermic oil. Overcoming the electricity cut-offs in summer.	Designing, modeling	[92]
Crema et al. (2014)	Energy concentrated solar	The outputs of 1–3 kW electrical power and 3–9 kW thermal power were obtained.	Designing, Modeling, Experimental	[94]
Naccarato et al. (2014)	Optimization of organic Rankine cycle	Identifying the best power plant configuration for maximizing energy and hot water.	Optimization	[100]
Saadatfar et al. (2014)	Conceptual solar polygeneration	Better cycle efficiency by silver-nano pentane, compared with pentane.	Modeling	[95]
Bouvier et al. (2015)	Experimental solar parabolic trough	Increasing the efficiency with the elevation of ambient temperature and irradiance.	Modeling, Experimental	[96]
Almahdi et al. (2016)	Solar multigeneration	The increment of the cogeneration, trigeneration, and multigeneration efficiencies by a reduction in the ambient temperature.	Designing, Modeling	[103]
Borunda et al. (2016)	Organic Rankine parabolic trough	Reduction of the energy and exergy efficiencies by enhancing the solar fraction. Augment of the overall system efficiency by using waste heat as a heat source.	Modeling	[99]
Bouvier et al. (2016)	Experimental solar parabolic trough	Simplicity and cost reduction were the advantages.	Experimental	[97]
Ozlu et al. (2016)	Evaluation of solar multigeneration	Minimizing the use of fossil fuels and achieving better environmental quality.	Analysis	[104]
Yuksel et al. (2016)	Thermodynamic analysis	Increase in exergy efficiency by enhancing in ambient temperature	Modeling	[101]

Han et al. (2014)	Exergy for concentrated solar CHP	Supplying 23.8 kW power for building utilization.	Analysis, Exergy	[21]
Rady et al. (2015)	Designing a multi-generation unit	Small-scale multi-generation solar plant was applied for a medical center building. Improving the plant effectiveness by using appropriate control system and operational strategy.	Designing, Modeling	[93]
Karellas et al. (2016)	Cogeneration and trigeneration	A biomass boiler was coupled with a module of PTC. Demonstrating positive economic results even for the worst case scenarios.	Modeling, Exergy, Economic	[98]
Shahin et al. (2016)	Parabolic trough and heliostat	Enhancing the net power output and thermal efficiency by using a reheat system. The increment of the thermal efficiency by applying open feed water heaters.	Modeling	[102]
Cucumo et al. (2012)	Life cycle assessment	Low impact of dish-Stirling compared with photovoltaic. Favorable energy pay-back time in the case of complete reusing and recycling materials.	Analysis	[106]
Ferreira et al. (2012)	Techno-economic assessment	Development of optimization models for designing and techno-economic assessment of micro-CHP systems.	Economical assessment	[110]
Moghadam et al. (2013)	Solar Stirling micro CHP	Saving primary energy and reducing CO_2 with acceptable payback time.	Modeling	[107]
Grosu et al. (2015)	Stirling micro-cogeneration	Adiabatic model as the best model for representing the engine operation. Good accuracy of the direct method and the adiabatic model.	Modeling	[108]
Ferreira et al. (2016)	Solar-powered Stirling	High costs and large investment recovery periods as the most drawbacks of renewable micro-CHP systems.	Optimization Economic	[109]
Ferreira et al. (2012)	Techno-Economic Assessment	Development of optimization models for design and techno-economic assessment of micro-CHP systems.	Economical assessment	[110]
Iglauer et al. (2014)	Sustainable automobile manufacturing	Improving the economic viability of the solar thermal system. Promoting the dissemination of solar thermal technologies for industrial applications.	Designing, modeling	[111]

5. Flat Solar Thermal Collectors

5.1. Flat Plate Collectors

The flat-plate solar collector is the heart of solar thermal systems which has many applications in a medium temperature range from domestic to industrial sectors. A black flat surface collects as much energy as possible, and then the energy is transferred to water, air, or other fluids for further use. A few researchers have studied CHP systems based on flat plate collectors, recently.

In 2010, the dynamic performance of a solar-driven carbon dioxide power plant was analyzed. The daily and yearly performance of the setup, under the Swedish climatic conditions, was simulated. The results indicated that the proposed arrangement had a payback period of 12 years [112]. In another work with the combination of an organic Rankine cycle with an ejector refrigeration cycle, the multi-objective optimization of a solar-driven CCHP was carried out. The results indicated that the best performance of the CCHP with various requirements could be achieved because of the comprehensive solution set of multi-objective optimization. Fig. 9, shows the schematic diagram of the solar driven CCHP, which consists of a solar collector, a thermal storage tank and an auxiliary heater. The flat-plate collector was selected to collect solar radiation due to its low cost and wide application. A thermal storage tank was used to correct the mismatch between the supply of the solar energy and the demand of thermal source consumed by the CCHP subsystem, thus, the system operated continuously and stably. Water was the heat-transfer medium in the solar collection subsystem for its low cost and large heat capacity. The CCHP subsystem consists of a vapor generator, a turbine, an evaporator, a heater, a condenser, a recuperator, a throttle valve, an ejector, a pump, and several regulation valves which combine the organic Rankine cycle with an ejector refrigeration cycle [113]. Recently, in 2017, the electrical output of a solar CHP plant with an organic Rankine cycle engine has been examined. Various organic working fluids have been simulated and optimized for the UK climate. The results show that the proposed system could provide 32% of a usual household demand under the UK setting operations [24].

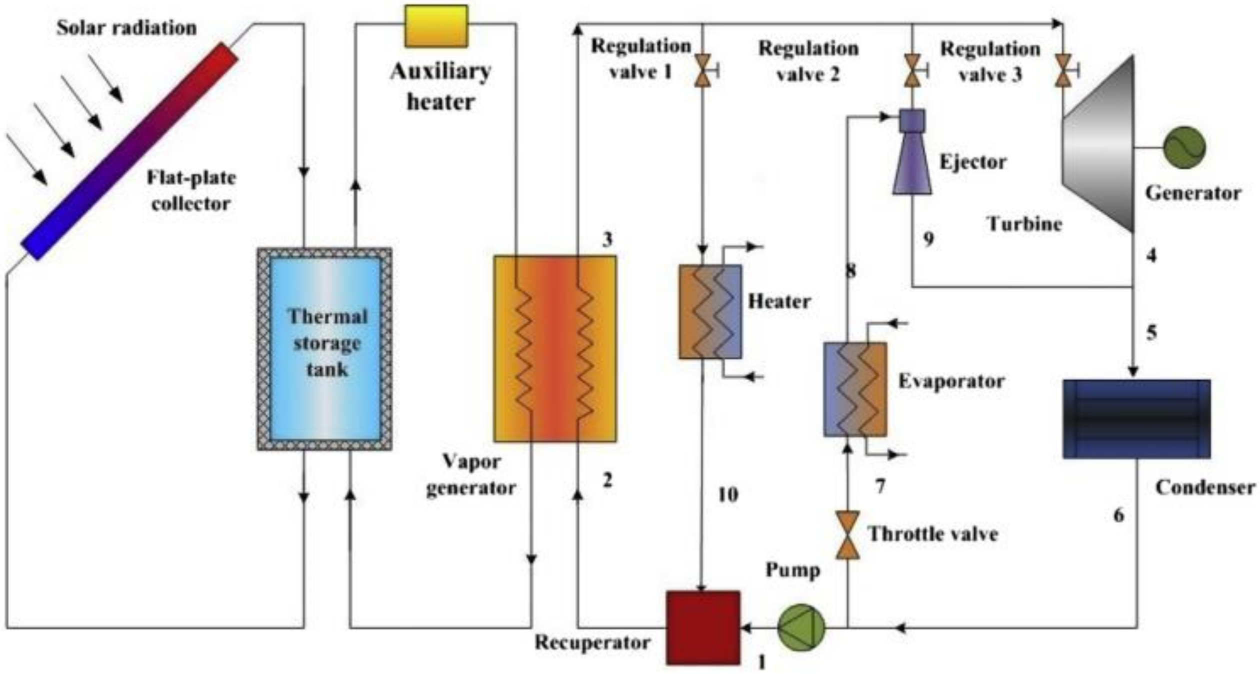


Fig. 9. Layout of a solar flat plate CCHP system [113] [Reprinted with permission from Elsevier]

5.2. Evacuated Tubes and Heat Pipes

Evacuated tube collectors (ETC) convert energy from the sun into a usable heat in a solar water/air heater [114]. This energy can be used for domestic and commercial hot water heating, pool heating, space heating, and air conditioning. While evacuated tube technology clearly surpasses flat panels for nearly all water heating applications, the advantages are truly dramatic when used for solar air conditioning, heating or commercial processes [115,116].

- *ETC*

Numerical investigations were presented for Rankine cycle-based solar systems which employed CO_2 as the working fluid [117,118]. Due to the capability of ORCs in utilizing the low-level heat losses, Schuster et al. [119] indicated some applications in some cases like solar desalination. Fig. 10 shows the photos of the solar driven reverse osmosis system. Tempesti et al. [120] compared two different configurations of ORC designs, and tested three different working fluids. With this regard, a system was considered which utilized geothermal and solar energy as the heat source. In another research, Twomey et al. [121] studied a solar thermal cogeneration system in residential scale, and analyzed a scroll expander in a small ORC. The output of this article demonstrated that the performance of the expander isentropic was satisfactory, and it could be enhanced by changing some mechanical parts. The total produced energy of the proposed configuration was 1710 kWh. Crema et al. [94] assessed the integration of evacuated tubes to a micro-CHP configuration, composed of CSP and Stirling engine system, in building sector. The proposed combination was satisfying in supplying the demands of the buildings. Calise et al. [122] analyzed an ORC-based solar CHP in terms of technical and economic issues and conducted a feasibility study to indicate the proper places. The outputs proved the practicality of the presented system.

Some researchers have investigated the hybrid CHPs with evacuated tubes. Yagoub et al. [123] carried out a study on the utilization of a hybrid solar-gas system based on Rankine cycle for an office building. In this study, two different working fluids (HFE-301 and n-pentane) were compared, and it was demonstrated that HFE-301 had more positive effect on electrical performance compared to n-pentane. Tempesti and Fiaschi [124] presented an economic investigation and evaluated three different working fluids (R134a, R236fa, and R245fa). The outcome of this analysis indicated that R245fa had the lowest electricity production cost and total cost, compared to other working fluids. A system, composed of evacuated tubes, flat solar collectors, and low-temperature geothermal wells was analyzed in the aspect of life cycle and environmental [125].

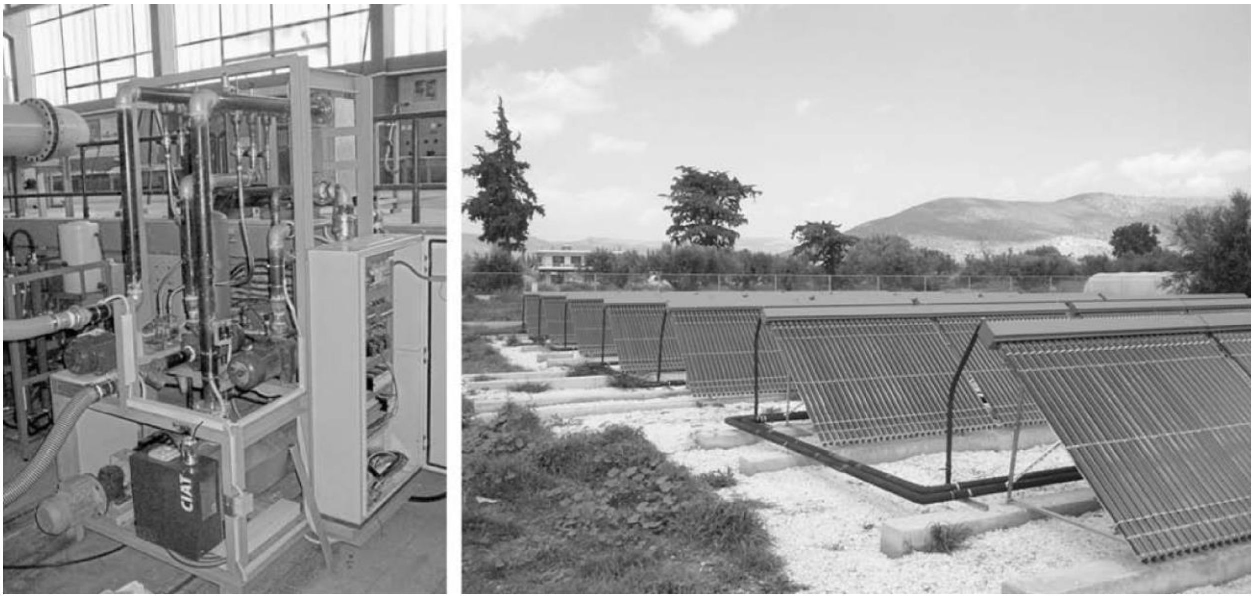


Fig. 10. A solar-driven RO-system [119] [Reprinted with permission from Elsevier]

- *Heat Pipes*

Firstly, in 2004, Riffat and Zhao [15,16] described the design and construction of a hybrid heat pipe solar collector/CHP. The thermodynamic and heat transfer analysis of this arrangement was studied to compare the proposed scheme with the conventional electricity and heating systems. Also, the experimental data were measured in a building at the campus of University of Nottingham. The results indicated that the primary energy consumption, the CO_2 emissions and the running cost of the hybrid configuration were lower than the conventional ones. Fig. 11 shows the schematic diagram of the hybrid heat pipe solar collector CHP.

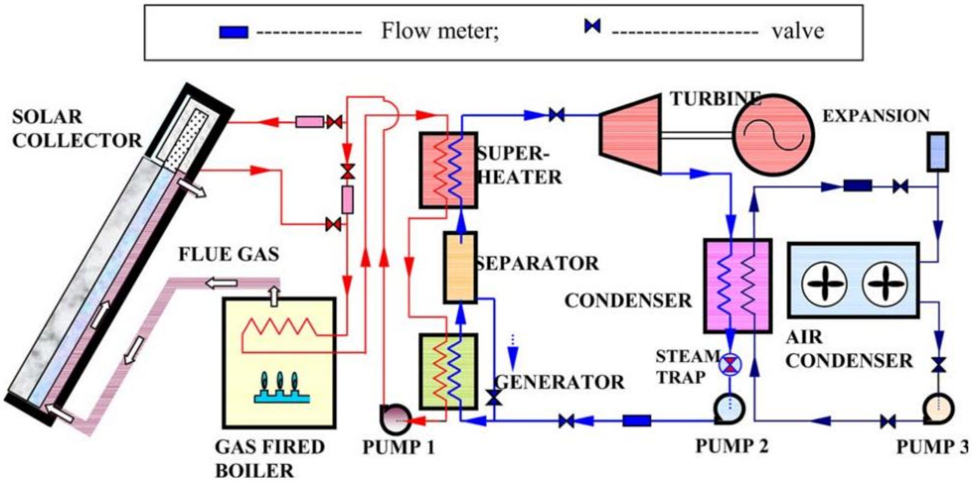


Fig. 11. Layout of the solar heat pipe CHP system [15] [Reprinted with permission from Elsevier]

In 2016, Wang et al. [126] evaluated the performance of a solar-natural gas hybrid CCHP technology with the aim of optimization of the CCHP configuration. The outcome of the analysis showed that the exergy efficiency could be increased by integrating the PV panels into the CCHP system, while the energy efficiency could be enhanced by integrating a solar heat collector.

By looking out the essays for solar flat CHPs, we found that most of them were about optimization for different climate zones, and only limited work about economic and environmental assessment. It is proposed to do more works for optimizing costs and payback periods of these CHPs. Table 4 shows the summary of the articles about solar flat plate collectors in CHP plants.

Table 4. Summary of the studies about flat collectors in CHP plants

Author	**Brief title**	**Highlight**	**Significant Action**	**Ref.**
Omer and Infield (2000)	Two-stage solar concentrator	Providing an effective concentration of the incident solar radiation without adjusting the tracking.	Designing, Modeling	[89]
Riffat & Zhao (2004)	Heat pipe solar collector	Integration of solar collector with the exhaust gas flue channels for utilizing both. As the working fluids, n-pentane and hydrofluoroether (HFEs) were utilized.	Designing, Modeling	[14,15]
Zhang et al. (2006), (2007)	Analysis of solar Rankine cycle	Studying a Rankine cycle-based evacuated solar collector system which employed CO_2 as working fluid.	Theoretical analysis	[117], [118]
Schuster et al. (2009)	Energetic, and economic investigation	Indicating the application of organic Rankine cycle in solar desalination process and analyzing the performance.	Simulation	[119]
Chen et al.(2010)	Dynamic simulation of a transcritical system	Essential influence of the expansion machine on the system performance.	Dynamic simulation	[112]

Twomey et al. (2013)	Dynamic performance estimation	Simulating and analyzing the expander isentropic efficiency. The performance of the expander isentropic efficiency was satisfactory, with the production of 1710 kWh total energy.	Dynamic modeling	[121]
Tempesti and Fiaschi (2013)	Thermo-economic assessment	Evaluating three different working fluids (R134a, R236fa, and R245fa). The results showed the superiority of R245fa.	Design and Economic	[124]
Mohammadkarim et al. (2014)	Investigation of solar ETC	Simulating evacuated tube solar water heating collector utilizing the TRNSYS software.	Simulation	[115]
Ruzzenenti et al. (2014)	Evaluation of environmental sustainability	Proposing life cycle and environmental investigation of a system composed of evacuated flat solar collectors and low-temperature geothermal wells.	Life Cycle Exergy	[125]
Sokhansefat et al. (2014)	Comparing FTC with ETC	Presenting a comparison between the performance of evacuated tube collector and a flat plate collector at different conditions.	Modelling and Comparison	[116]
Calise et al. (2015)	Design and simulation of a solar CHP prototype	Studying an ORC-based solar CHP from the technical and economic point of view, and accomplishing a feasibility study to indicate the proper places.	Design and Dynamic simulation	[122]
Wang et al. (2015)	Multi-objective optimization of a CCHP	Maximizing the average useful output and minimizing the total heat transfer area. Different optimal combinations of the parameters were obtained by the single and multi-objective optimization	Mathematical modeling and Optimization	[113]
Wang et al. (2016)	Thermodynamic performance optimization	Comparing the effect of integration of PV panels or a solar heat collector. It was shown that the integration of PVs enhanced the exergy efficiency and integration of a solar heat collector increased the energy efficiency.	Thermodynamic analysis and Optimization	[126]
Freeman et al. (2017)	Combined solar-ORC	Optimizing the performance of a solar CHP system for maximum annual electrical power generation	Optimization and Comparison	[24]

6. Concluding Remarks and Suggestions

This work provides a detailed review of the literature on solar combined heat and power systems to advance our understandings in this area. Reviewing the papers in the field of PVT and CPVT, applied in CHP systems, showed that the majority of published work was on the simulation and modeling aspect, with a focus on the thermal part. Most of the researches in concentrating CHP systems are about parabolic trough collectors due to their high efficiencies, and limited work on economic analysis at the system level was performed, which calls for more systematic study.

Some further studies are recommended as followings:

- More studies are needed for solar hybrid systems with other sources of energy to attain higher levels of temperature and power.

- The performance of CPVTs and compound parabolic collectors, coupled with heat pipes should be investigated further .
- The feasibility and CFD analysis shall be conducted before any experimental and practical actions.
- Exergy, economic and environmental analysis are suggested for the solar CHP and CCHP units.
- More work shall be conducted to investigate the performance of large-scale solar CHPs.
- Large-scale solar CHPs for the power plants located near the industrial zones should be examined to utilize the exhaust heat, and achieve high efficiencies.

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