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A survey of hybrid water desalination systems driven by renewable energy based components

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ABSTRACT

Freshwater availability is a problem faced in many parts of the globe especially in arid and semi-arid areas. It is a consequence of growth in the population, climate change issues, environmental issues, and inappropriate exploitation of groundwater resources. In this regard, freshwater production via desalination represents a potential option to solve this problem. Furthermore, the utilization of renewable energy sources for desalination purposes offers additional benefits. Renewable energy based desalination systems could also be used in urban areas, but they are especially attractive for remote areas where there is a limited or no access to fossil fuels sources or an electrical grid. Many renewable energy technologies can be hybridized for desalination purposes to improve productivity, flexibility, reliability, and economic feasibility. This paper provides a state-of-the art review of hybrid renewable energy based desalination systems and highlights the most significant development and experimental studies that have been carried out. The reviewed hybrid renewable energy desalination systems are classified and reviewed on the basis of the technologies that have been hybridized. The operating principles, advantages and limitations of these systems are described. Finally, some possible hybrid renewable energy desalination configurations are recommended for future investigations.

Keywords: Desalination technologies; Renewable energy; Hybrid systems; System configurations; Fresh water production

1. Introduction

There are several water-stressed regions across the globe such as the Middle-East, North Africa, South-West USA, and Australia. In the future, freshwater availability will become an even larger problem in these regions as a consequence of increase in demand, population growth, and the effects of global climate change. Furthermore, contamination and inappropriate exploitation of groundwater resources have raised concerns about natural water resources in terms of both quality and quantity [1]. Although, the influence of climate change on water availability is uncertain, it may be highly negative. In arid and remote areas, the inaccessibility to fresh water is now considered an alarming issue [2].

Desalination systems have been increasingly employed and developed in recent years to address these water issues. A rapid rise in the utilization of desalination systems has occurred in many parts of the world to meet the increase in the fresh water demands. Improvements in the desalination processes have mainly centered on reducing the costs, increasing the reliability to produce fresh water with higher quality, and reducing the energy requirements. The energy requirements are particularly important because most desalination processes require substantial energy either in the form of electricity or heat. Furthermore, continued utilization of fossil fuels for desalination intensifies the environmental concerns [3,4]. In this regard, for desalination to be a feasible option to solve the fresh water crisis, renewable energy becomes an attractive option to supply its energy requirements.

Utilization of renewable energy for desalination offers notable benefits for climate, health, and economy. For example, it minimizes the air, water and soil contamination

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that typically occurs through the utilization of fossil fuels. Moreover, in contrast to fossil fuels, renewable energy resources are constantly replenished and will never run out. The rapid evolution of renewable energy-based technologies over the past decades makes them more competitive to supply the energy demands for different applications like desalination. In particular, renewable energy sources offer promise in remote areas where there is limited accessibility to either conventional energy sources or grid connected power.

The intermittency of renewable energy sources such as wind and solar represents one limitation of renewable energy use. This problem has motivated researchers to investigate the possible hybridization of renewable technologies for providing continuous power. Hybrid renewable energy systems combine one renewable energy technology with one or more renewable energy systems and/or storage systems. They can be designed and implemented for both stand alone and grid connected applications. It is expected, however, that the applications of hybrid renewable energy systems will be more attractive in remote and isolated areas than grid connected applications. Furthermore, combining two or more renewable energy based technologies can increase the efficiency, flexibility, reliability, and economic viability of the system for desalination [5–7].

The objective of this study is to present a review of hybrid renewable energy-based desalination systems. Hybrid renewable energy-based desalination systems are categorized and reviewed based upon the renewable energy sources and technologies that have been combined. The operating principles, benefits and limitations of these systems are described. Moreover, the possible potential for future developments of the hybrid renewable energy based desalination systems is discussed.

2. Desalination and renewable energy sources

The available desalination technologies are generally classified as: (1) Thermal desalination (also known as phase change process), and (2) Membrane desalination (also known as non-phase change process). In thermal desalination systems, the feed water (seawater, brackish water or other non-pure water) is heated to the boiling point at the operating pressure to generate steam, and then the steam is condensed in the condenser to produce fresh water. There are several types of thermal desalination technologies including multi-stage flash (MSF), multi-effect distillation (MED), mechanical vapor compression (MVC), thermal vapor compression (TVC), membrane distillation (MD), etc. [8,9].

Membrane desalination technologies operate based on the principle of separation of dissolved salts from the feed water using a membrane system between the feed water and the product which is the potable water. This separation process is either accomplished mechanically, chemically or electrically. Reverse osmosis (RO) and electro-dialysis (ED) are major types of membrane technologies [8,9]. The dominant desalination technologies at the current time are RO, MSF, and MED. There are numerous excellent references that review the basics of each desalination technology [2,10−14].

Table 1 presents characteristics of different desalination technologies. It is obvious that thermal desalination technologies are very energy sensitive due to the high thermal energy requirement required to drive the system for fresh water production.

As a result of rapid advances in membrane technology, membrane desalination technologies are increasingly employed. Thermal and membrane desalination technologies require thermal/electrical energy to produce fresh water. Renewable energy sources have recently gained much attention to provide the energy requirements of the desalination unit although they still represent a small share of the total.

Solar, wind, geothermal, and biomass are renewable energy sources that are utilized for desalination processes. Renewable energy based desalination technologies fall mainly into two main groups. In the first group, the desalination process is driven by heat generated using renewable energy technologies, while in the second group the desalination process is driven by electricity generated by renewable energy technologies [1]. Solar stills are the most employed and studied types of using renewable energy sources for desalination process for which the energy from the sun is directly used to produce fresh water [1]. Also, as will be reviewed here, a number of research efforts and experiments have been conducted in various parts of the world to develop different combinations of renewable energy driving desalination systems.

Renewable energy sources represent significant options to supply the required energy of autonomous desalination systems, particularly in arid, semi-arid, and remote areas where conventional energy sources are not easily accessible. Arid and semi-arid remote regions lack not only the fresh water but also grid connected power. Despite the benefits of

Table 1
Characteristics of different desalination technologies [15]

Characteristics	MED	MSF	TVC	MVC	SWRO[a]	BWRO[a]	ED
Typical capacity (m^3/d)	5,000–15,000	50,000–70,000	10,000–30,000	100–3,000	Up to 128,000	Up to 98,000	2–145,000
Electrical energy requirement (kWh/m^3)	2–2.5	2.5–5	1.6–1.8	7–12	4–6	1.5–2.5	2.6–5.5
Thermal energy requirement (MJ/m^3)	145–230	190–282	227	n/a	n/a	n/a	n/a
Fresh water quality (ppm)	≈10	≈10	≈10	≈10	400–500	200–500	150–500

[a] SW is Seawater; BW is Brackish Water.

using renewable energy systems to power the desalination technologies, the share of renewable energy based desalination systems is still very limited compared with the total installed capacity. The main reasons are lack of availability of all renewable energy sources in the water stress regions, economic issues, and technological barriers.

Although there are several suitable combinations of renewable energy driven desalination systems that can be used in practice, some of these combinations may not be feasible in specific situations. In this regard, more appropriate technology combinations should be identified and studied by considering different local parameters such as geographical conditions and topography of the location, capacity, and type of available of renewable energy, cost, plant size, and the salinity of feed water [16]. For example, photovoltaic (PV) panels might be considered more suitable for small scale applications in the sunny regions while for larger application wind turbines might be more appealing because they occupy less land. For example, islands with favorable wind regimes and limited flat areas are typically selected for wind energy applications [16]. In general, thermal renewable energy technologies are typically combined with thermal based desalination processes, and electromechanical renewable technologies are used to power the desalination processes that require mechanical or electrical energy.

The most widely studied and employed renewable energy driven desalination systems related to the scope of this study are summarized next.

2.1. Solar energy based desalination

The utilization of solar energy is one of the most appealing applications of renewable energy for a desalination process. A thermal solar desalination unit normally includes two major parts: a collector device, and a distiller. Solar thermal desalination processes are divided into two groups: (1) direct systems which thermal desalination process occurs in only one device such as solar stills, and (2) indirect process that include two subsystems of solar collecting devices such as different types of solar collectors or solar ponds and a desalination component [16].

2.1.1. Solar still

A solar still is a simple device that directly utilizes the solar energy to distillate the water. A container with black paint coated surface and an inclined glass cover are the main components of solar stills. Solar stills operate based on a simple basic such that solar radiation passes through a glass cover, and it is absorbed by the black surface that is in contact with salty water. Then the evaporated water by the heat condenses along the inclined glass cover, and it is collected at the bottom through a groove. Simplicity, high reliability, and low operations and maintenance costs are the main advantages of solar stills. However, the productivity of solar stills is low (around 3–4 L/m^2/d for a well-designed solar still) [17]. Over the past years, several modifications have been made to improve the efficiency of the solar stills, and several configurations have been designed to couple the solar stills with flat plate collector, evacuated tube collector, solar ponds, and mirrors [18,19].

2.1.2. Solar pond

A solar pond can be considered as a large thermal solar collector with integrated hot water storage. It typically includes three layers of saline water with different levels of salt concentration: (1) top layer or upper convective zone (UCZ), (2) intermediate layer or non-convective zone (NCZ), and (3) storage layer or lower convective zone (LCZ). In the first layer, the surface is either seawater or fresh water depending on the site location. The purpose of this layer is to protect the lower layer from the impacts of the environment such as wind. The second layer is a salt gradient layer in which the salinity level increases with the depth of the layer. This layer represents transparent insulation. The thickness of the intermediate layer is a function of the selected operating temperature of the heat source. It may typically vary between 60 and 120 cm. In the third zone, depending on the thickness of the layer, thermal energy can be collected and stored up to temperatures of 80°C–90°C. The stored energy in this zone can be extracted similar to a conventional thermal storage system [20].

Low cost, inherent storage capacity and ability to use reject brine are some advantages of solar ponds. Also, the surface water in the solar ponds can be utilized as cooling water due to its lower temperature throughout the summer. However, a solar pond has some disadvantages. It requires sunny conditions for operations and a large surface area. Furthermore, environmental concerns such as soil contamination from pond brine leakage present some problems faced by solar ponds [21].

2.1.3. Other solar thermal power driven desalination systems

In general, other solar thermal desalination systems consist of two separate devices; the solar thermal collector and a conventional distiller (desalination plant). The solar collector can be a flat plate collector, evacuated tube collector, or a concentrating solar power (CSP) system, and it can be coupled with any of the thermal desalination process types that are based on evaporation and condensation principles [22]. CSP plants operate based on the advantage of providing high temperature energy. Thus, CSPs provide a viable option for both membrane and thermal desalination technologies. CSP plants are typically large enough to be an appropriate source of power for medium to large scale desalination plants. The choice of CSP-RO or CSP-MED processes can be attractive depending on the feed water salinity level [23].

Solar humidification-dehumidification is another widely employed solar thermal desalination technique. This technique offers some advantages such as simplicity, flexibility in capacity, moderate capital, and operating costs. Humidification-dehumidification systems operate based on the principle that air is mixed with high quantities of vapor, and also the fact that magnitude of vapor carried by the air increases with temperature. When the flowing air comes in contact with the saline water, a specific amount of vapor is extracted by air which provides a cooling effect. The distillated water is recovered when the humid air comes in contact with a cooling surface. The condensation generally occurs in another exchanger where the latent heat of condensation preheats the saline water. Thus, an external heat source is required for compensating the resulting heat loss. More details and descriptions regarding the humidification-dehumidification process have been reviewed in [24,25].

2.1.4. Photovoltaic driven desalination

PVs can be coupled directly to RO or ED desalination technologies. A PV-RO system includes a PV source to supply the electricity to the desalination unit via a DC/AC converter and a RO membrane desalination system. Due to the improved efficiency of both PV and RO systems, a combined PV-RO system offers a promising renewable energy based desalination systems for the future [23].

ED is a technology that operates based on the principle of migration of the salt ions from the dilute solution side to the concentrated solution via ion-exchange membranes using the employed electric potential difference. PV systems can be used to supply the energy for the ED process. The advantage of a PV-ED system over a PV-RO unit is that the former doesn't need an inverter, as ED can operate with direct current. ED technologies are currently not economically feasible for seawater desalination applications due to the high salinity of seawater, high cost of electrodes, and ion exchange membranes as well as the relatively short life time of electrodes. Consequently, most investigations have focused on the application of PV-ED for brackish waters [19,21].

2.2. Wind energy based desalination

Wind energy is the second most broadly utilized renewable energy for desalination process, after solar energy. Wind energy driven desalination can be an appealing option to desalinate sea water, particularly in coastal regions that have a high wind energy resource. Wind turbines produce electrical and mechanical energy that can be used to drive desalination systems such as RO, ED, and MVC [26–31]. In the case of MVC, the mechanical power of the wind turbine can be utilized directly for vapor compression without conversion to electricity [1,8,16]. Similar to PV and CSP systems, the intermittence nature of wind energy represents a disadvantage of wind driven desalination systems. In fact, the major issue regarding the utilization of wind energy for desalination is its high variability in terms of both geographical and temporal parameters. In this context, since the available wind energy that can be harnessed by wind turbines depends on the site wind resource, the selection of a proper location for development of wind energy based desalinations is an important task needed to ensure economic feasibility [32].

2.3. Geothermal energy based desalination systems

The first geothermal energy driven desalination plant was constructed in the U.S. in 1972, followed by ones in France, Tunisia, and Greece [33]. Although geothermal energy sources are not as common as solar and wind energy driven systems, they currently represent a mature technology that can be used to provide a reliable and effective source of power for desalination processes at a competitive cost. One of the main advantages of geothermal energy, compared with other renewable energy sources such solar and wind energy, is continuously available over a 24-h daily cycle and can be predicted; thus, there is no requirement for energy storage systems [16]. Also, geothermal energy can be utilized for both thermal and membrane desalination systems since it can provide both heat and electricity.

High pressure geothermal sources can be used to directly supply the power required for mechanically driven desalination processes and high temperature geothermal sources can be utilized to provide the required energy for electrically driven desalination systems like RO and ED [34–37]. In fact, direct utilization of high temperature geothermal sources for thermal desalination systems is considered by some researchers as a most appealing option [33].

Another viable choice is a thermal distillation technique using direct heating from geothermal energy sources. A review on the different aspects of geothermal energy driven desalination systems is available in [38].

2.4. Ocean power

Ocean power can be utilized for desalination in three forms: wave energy, ocean thermal energy conversion (OTEC), and tidal energy. Wave and tidal power desalination technologies are still under investigation and are in the prototype stage. Wave power driven desalination is a potential option for seawater desalination since both ocean energy and sea water are abundantly available at the same location [17]. Wave and tidal energy can be utilized to power RO and vapor compression systems. All previously constructed prototypes wave driven desalination units have used RO. The RO systems are operated either using electricity produced by the wave energy system or directly utilizing the pressurized sea water by the movements of the waves [4]. A wave-MVC plant has been also proposed, but a prototype system has not been constructed. Current proposed wave driven desalination systems are relatively large scale with a capacity of 500–5,000 m^3/d [4]. Many studies have been carried out to use wave power for desalination [39–45], however, this type of application is still under development.

Ocean thermal energy conversion is based on the use of the temperature difference between the surface and deep sea layers [46]. Because ocean thermal energy is a low grade thermal energy source, it may be a good option for coupling with desalination plants [47,48]. Japan, India, and Mexico most recently have carried out research on OTEC based desalination systems [4].

Leijon and Boström [49] reviewed the potential of ocean and wave energy driven desalination systems. They outlined RO, ED, and MVC as suitable technologies for integration to different wave energy conversion systems. They classified different wave driven desalination systems and identified the most common designs.

3. Hybrid renewable energy systems for desalination

The intermittency of renewable energy sources such as solar and wind leads to a lack of persistent power that can be harnessed from these sources. One solution to this problem is the idea of integrating two sources (i.e., hybrid systems) to ensure that power can be available continuously. That is, as previously noted, hybrid renewable energy systems are generally defined as systems that integrate one renewable energy technology with one or more either conventional or renewable energy systems and/or storage systems that can be designed to operate for both stand alone and grid connected applications.

Hybrid renewable energy technologies can potentially provide more efficient and a higher quality reliable power [50]. Hybrid renewable energy technologies can address the drawbacks of each technology from different aspects such as efficiency, reliability, flexibility, and economics. In general, applications of hybrid renewable energy technologies are more appealing in remote and isolated areas rather than grid connected applications. Due to various existing renewable energy sources and enabling technologies, and there are numerous possible configurations for hybridizing renewable energy technologies. For example, numerous hybrid renewable energy sources have been investigated and proposed in the literature such as, solar-wind [51–54], solar-biomass [55–58], solar-geothermal [59–61], solar-hydro [62,63], wind-biomass [64,65], wind-tidal [66,67], and hydro-biomass [68,69].

Hybridizing the renewable energy technologies for desalination purposes has several advantages, particularly for remote areas. In this context, a storage system is an important element that requires careful consideration. Also, it is possible to produce large quantities of purified water and store it for later utilization when the energy supply drops. Current literature indicates that a number of efforts have been carried out to combine two or more different renewable energy systems for desalination purpose. In the following, examples of such systems are categorized and reviewed.

3.1. Solar-wind

The motivation behind utilizing hybrid solar/wind systems for desalination is that there are many locations for which solar and wind time profiles can complement each other. As a result, hybrid solar-wind systems can be utilized for desalination.

Zejli et al. [70] proposed a hybrid PV-Wind desalination unit to produce domestic water for meeting the hourly demands of 20–40 households in three different locations in Morocco. Their proposed system included a PV module, a wind turbine, a MVC desalination unit, and an energy storage system. In this system, the generated power of PV panels and the wind turbine could be used to supply the needs of the MVC unit. They designed the system in a way that the surplus energy from PV and wind turbine could be directed to the energy storage system or/and to the external electricity network. In addition, an optimization model was developed for all the sub-systems to minimize the received electricity from the network and maximize the production of fresh water. Based on their optimization results, the authors concluded that the cost of fresh water production using the proposed hybrid PV-wind-MVC plant was comparable with the traditional costs of fresh water in Morocco for MVC plants with a capacity higher than 120 m^3/d. They also found that the storage system could supply a substantial part of the required electricity by the MVC plant in cases of a deficit in energy; thus limiting the power exchange with the electrical network.

Yılmaz and Söylemez [71] designed a feed forward MED seawater desalination system, with a capacity of 1000 l/d, driven by a hybrid solar and wind energy system. They developed a design simulator program to study the feasibility of the proposed system in 18 locations of Turkey. The system consists of a feed forward MED, a flat plate solar collector and a wind turbine. The energy from the solar collector provided the required heating steam for the MED unit. A wind turbine was also used to produce the total required electricity for the operation of the system (mostly pumps). During the time that the desalination unit was not operating, the generated energy from the wind turbines was stored in the energy storage system. Fig. 1, shows the sub-system of the solar collector and MED desalination in their system. The authors concluded that the proposed hybrid solar and wind desalination system could be utilized suitably without any external thermal and electrical energy.

Tzen et al. [72] designed and developed a small-scale hybrid PV/Wind driven RO desalination system to provide the fresh water for a remote area in Greece. The hybrid system included a 3.96 kW PV, a 900 W wind turbine, a seawater RO unit with 130 l/h capacity, a battery, and two inverters. They stated that the designed autonomous system could operate around 5 h in winter and 8 h in summer meaning that the RO unit is driven only a few hours per day for fresh water production. The fresh water product was transferred to the water storage tank. For this project, they reported an estimated cost of fresh water of approximately 23 Euro/m^3. The main reasons for this higher cost were given by the authors as the small size of the system, high costs of the PV panels, wind turbines, and RO units at that time. Figs. 2(a)–(c) illustrate a schematic view of PV/RO, wind/RO, and hybrid PV/wind-RO systems, respectively [73].

Bourouni et al. [74] designed and optimized several single and hybrid PV and wind driven RO desalination systems for a rural area in southern Tunisia with a maximum fresh water capacity of 15 m^3/d. They evaluated five configurations: (1) PV/RO, (2) PV/ batteries/RO, (3) wind/RO, (4) wind/batteries/RO, and (5) hybrid PV/wind/ batteries/ RO. According to their analysis, the configuration of wind/ batteries/RO was determined to be the most economical option. The authors concluded, however, that since they assumed the nature of wind energy to be random, the hybrid system consisting of PV, wind turbines, and batteries was promising and should be investigated further.

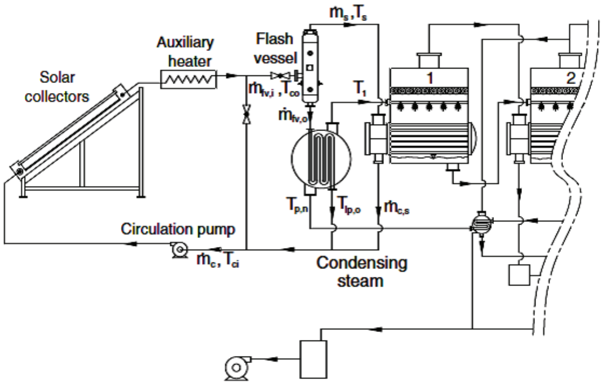

Fig. 1. Sub-system of solar collector and MED desalination in a hybrid system [71].

Koutroulis and Kolokotsa [75] developed a method to simulate RO desalination systems driven by PV, wind turbines, and hybrid PV/Wind turbines. In their systems, batteries with different nominal capacities were considered to store the generated energy and water storage tank to store the fresh water. Their primary aim was to optimize the size and cost of the systems. They considered a single residential household and a community consisting of 15 houses to study the effect of size of the desalination system. They showed that the total cost of the systems for each household in the community's desalination system was significantly lower than similar systems designed for a single household. Moreover, a substantial part of the system's capital cost (between 15% and 35%.) was due to the cost of batteries. Furthermore, the authors concluded that the hybrid PV/Wind driven RO system was more economical compared with the single PV or wind driven RO system.

Setiawan et al. [76] designed and evaluated the performance of a mini-grid hybrid system used to power a RO unit in a remote area in the Maldives in terms of technical, economic, and environmental issues. They evaluated three options: PV/diesel, wind/diesel, and PV/wind/diesel, and then compared them with a standalone diesel generator system. Their system was equipped with battery storage, and a fresh water storage tank with storage capacity of two days. In their proposed system, the RO unit was designed to produce 5 m^3/d fresh water. Their results indicated that although the single diesel unit had the lowest initial capital cost, the whole system had the highest net present cost when a single diesel unit was used. They concluded that the hybrid PV/wind/diesel powering the RO unit was the more suitable option based on all technical, economic, and environmental aspects.

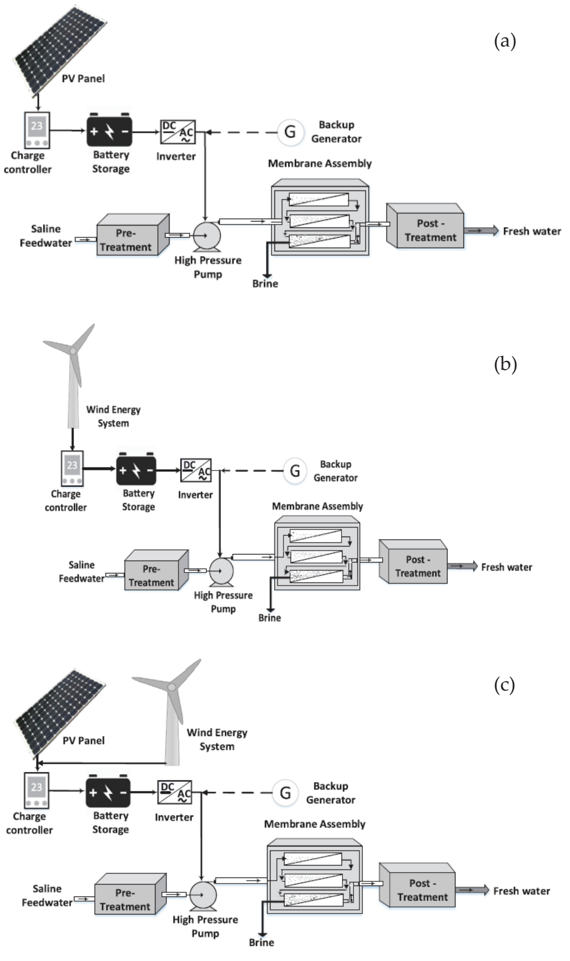

Fig. 2. A schematic view of (a) PV-RO, (b) wind-RO, and (c) hybrid PV/wind-RO systems (adopted from [73]).

Khalifa [77] examined the possibility of supplying the power required for a RO desalination unit using three systems of diesel, wind turbine and PV, and combinations of these systems such as wind/diesel, PV/diesel, PV/wind, and PV/wind/diesel equipped with battery storage systems. The systems were designed to provide the fresh water for a small remote area in Iraq with a total capacity of 50 m^3/d. He concluded that the lowest cost of fresh water was obtained for either the diesel generator or the hybrid PV/wind/diesel. Also, reducing the size of the diesel generator increased the cost of fresh water.

Mokheimer et al. [78] optimized a hybrid PV/wind turbine driven RO desalination system with 5 m^3/d capacity for operation in a remote area of Saudi Arabia. They evaluated the performance of the system for a constant RO load of 1 kW for two operational cases of 12 and 24 h/d. They also determined the optimal number of PVs, wind turbines, and batteries for both cases. Their results showed that levelized cost of energy for the first case (a load demand of 1 kW for 12 h/d) was lower than the second case. The authors concluded that the optimal design of the hybrid PV/wind driven RO system was the main factor that reduced the cost of the produced water.

Weiner et al. [79] presented the design and experimental results for a small-scale hybrid PV/wind driven RO desalination system for brackish water with a design capacity of 3–9 m^3/d, established in a small remote area in the Negev Desert in Israel. The system consisted of PV arrays, Inverter, RO unit, batteries, wind turbine, and a diesel generator. They designed a control system to determine if the PV and wind turbine could satisfy the required energy or if back-up energy from diesel generator was required.

Smaoui et al. [80] designed a stand-alone hybrid PV/wind/hydrogen system powering RO desalination to be operated in the Kerkennah islands in the south of Tunisia. Fig. 3, shows a schematic of their hybrid system. They developed

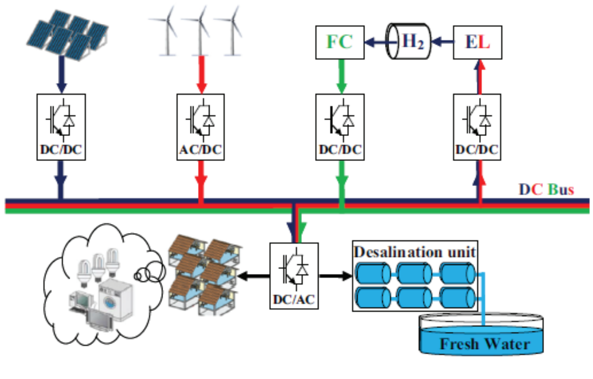

Fig. 3. Schematic of a stand-alone hybrid PV/Wind/Hydrogen driven RO desalination system [80].

a new algorithm to optimize the system configuration in terms of technical and economic considerations. Using this algorithm, they optimized different parameters including the rated power of wind turbine, the rated power of fuel cell and electrolyzer, number of PVs, capacity of hydrogen tank, and size of the RO unit. The final system included PV, a wind turbine, a fuel cell coupled to an electrolyzer, converters DC/DC and an inverter, a RO desalination unit, and a fresh water tank fed by the RO unit. Excess power was utilized for operating the electrolyzer and generating hydrogen. In case of an electricity shortage, the stored hydrogen was converted into electricity via the fuel cell.

Kershrnan et al. [81] developed a hybrid PV/wind driven RO system with a total capacity of 300 m^3/d and a fresh water storage tank of 300 m^3 to provide the drinking water to a village on Libya's coast. They compared the hybrid system with three systems: PV/RO, Wind turbine/RO and grid connected RO. The primary objective of their work was to reduce the annual non-renewable energy consumption to around 40% and to reduce environmental emissions. They concluded that the highest environmental benefit was achieved by a hybrid PV/Wind/RO system. The best case in terms of economic was the Wind/RO system - with a water cost of around 30% higher than the grid connected RO system.

Mohamed and Papadakis [82] carried out a techno-economic analysis to simulate and size a hybrid PV-wind system for driving a RO unit in a village in Greece. They found that utilizing a pressure exchanger as energy recovery device in the RO unit reduced the energy requirement of the RO system, size of the hybrid PV/wind system, and subsequently the water production cost. Also, the cost of water production by hybrid PV/wind/RO was less expensive than a PV/RO system due to the high cost of PVs at the time. Another finding was that storage of fresh water was more cost effective than storage of electrical energy.

Hossam-Eldin et al. [83] evaluated the utilization of a hybrid PV/wind turbine system for powering a RO desalination unit in a remote location in Egypt. Their system included a diesel generator, battery and inverter as a back-up and storage system. They noted it was not simple to select the most appropriate system design, and that it required careful consideration such as optimizing the hybrid system which is also contingent upon the design site and specific system design. They also concluded that in order to reduce the cost of electricity generation by a hybrid PV/Wind system, the amount of excess energy generated by the system should be minimized. Furthermore, for locations in Egypt, the Hybrid PV/wind/RO system was more suitable for medium-scale than small-scale applications.

Cherif and Belhadj [84] evaluated a hybrid PV-wind system without a storage system used to power a RO unit for producing fresh water from brackish water in southern Tunisia. Their system included: 400 m^2 of PV, a 10-kW wind turbine, a DC bus, and converters. They conducted both steady state and dynamic analyses, and pointed out that the hybrid system can drive the RO unit throughout the year. A schematic of a system using a hybrid PV/wind/RO system is shown in Fig. 4.

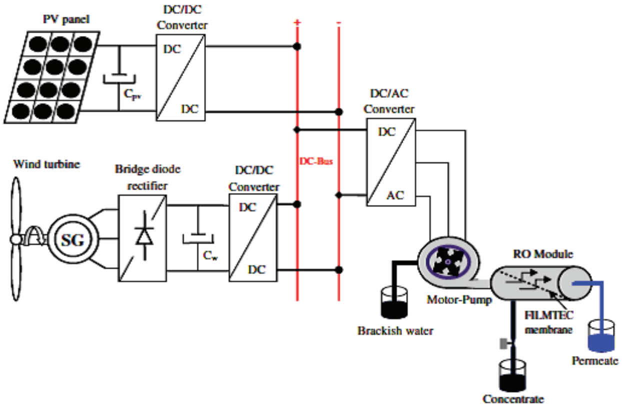

Fig. 4. Schematic of a hybrid PV/wind/RO system evaluated in [84].

Caldera et al. [85] estimated the potential of seawater RO (SWRO) driven by hybrid PV/wind/battery systems for supplying the global fresh water demands in 2030. Their estimations showed that the required SWRO capacity to supply global fresh water demand in 2030 is around 2,374 million m^3/d. Their results showed that, depends on availability of solar and wind energy resources as well as transportation costs of fresh water, the fresh water production cost is estimated between 0.59 and 2.81 €/m^3. Peng et al. [86] designed a hybrid PV-wind system coupled with a battery tank for fresh water production using a RO unit with a fresh water production capacity of 10 m^3/d. They used 19 single and hybrid algorithms for optimizing the hybrid PV-wind system. Their results showed that using hybrid PV-wind reduces the system costs and increases the system reliability. Also, using hybrid optimization techniques gives a higher performance than single optimization techniques for designing the system. In a recent study, Soni et al. [87] proposed a wastewater treatment system driven by a hybrid solar/wind system for a single household in India. In the proposed hybrid system, the wastewater is pumped from ground to roof of the house using a wind energy driven piston pump and it becomes drinkable using a solar energy based distillation system. The distillation system consists of a flat plate solar collector, a heat exchanger, and a type of solar still as an evaporation condensation unit. Their results showed that the proposed hybrid solar/wind energy driven system can produce around 0.025–0.045 m^3/dof purified water as long as wind speed of 1–5 m/s is available.

A detailed technical and economic review on different aspects of PV-RO, wind-RO, and hybrid PV-wind-RO systems has been provided by Khan et al. [73].

To summarize this section, Table 2 presents a summary of important features of the previously described hybrid solar-wind desalination systems. Note that a unit conversion was done to convert all fresh water production capacities to m^3/d.

3.2. Solar-solar

In many studies, two or more solar energy systems have been combined for desalination process with several specific purposes such as enhancing efficiency and productivity. In the following section, representative studies are reviewed and categorized based on the different hybrid technologies.

Table 2
Summary of important features of referenced hybrid solar-wind desalination systems

Authors	Hybrid systems	Capacity	Storage	Remarks
Zejli et al. [70]	PV/wind-MVC	To meet the demands of 20–40 households, but they evaluated different capacities ranging from 20 to 1,000 m^3/d	Yes (battery storage)	The produced power by PV and wind turbine was directly utilized to supply the MVC unit and the surplus energy was directed to the energy storage system or/and to the external electricity network.
Yılmaz and Söylemez [71]	Flat plate solar collector/wind-MED	The capacity of 1 m^3/d	Yes (battery storage)	The collected energy by the solar collector provided the required energy for the MED unit. A wind turbine was used to produce the total required electricity for the operation of the system (mainly pumps). During the non-operational hours, the generated energy from the wind turbine was stored.
Soni et al. [87]	Flat plate solar collector/wind-solar still	The capacity of between 0.025 and 0.045 m^3/d	No	The wastewater is pumped from ground to roof of the house using a wind-energy driven piston pump and it becomes drinkable using a solar energy based distillation system which consists of a flat plate solar collector, a heat exchanger, and a type of solar still as an evaporation condensation unit.
Tzen et al. [72], Bourouni et al. [74], Koutroulis and Kolokotsa [75], Setiawan et al. [76], Khalifa, [77], Mokheimer et al. [78], Weiner et al. [79], Kershrnana et al. [81], Mohamed and Papadakis [82], Hossam-Eldin et al. [83], Cherif and Belhadj [84], Peng et al. [86]	PV/wind-RO	Different designed capacities ranging between 0.52 and 1.34 m^3/d reported in [76] and between 150 and 300 m^3/d reported in [83]	Yes (battery storage)	Power generated by PV and wind turbines supplied the RO unit. In these studies, water storage tank was also employed to store the fresh water for later days and offer autonomy. Mohamed and Papadakis [82] pointed out that storage of fresh water was more cost effective than storage of electrical energy. The majority of these studies concluded that hybrid systems are more suitable than single systems.
Smaoui et al. [80]	PV/wind/hydrogen system/RO	Variable depends on the demands in different seasons. Also, to feed 14,400 inhabitants in winter. The average capacity of 193.6 m^3/h which is equivalent to 4,646 m^3/d.	Yes (hydrogen production)	The designed system was comprised of PV, a wind turbine, a fuel cell coupled to an electrolyzer. and RO desalination unit. The PV panels and the wind turbines supplied the power, and the excess power was used for operating the electrolyzer and generating hydrogen. The stored hydrogen could be converted into electricity via a fuel cell. Also, a fresh water tank was considered for a few days of autonomy.

3.2.1. Photovoltaic (PV/T)-solar still

Hasnain and Alajlan [88] proposed a system combining PV-RO brackish water desalination with a solar still system for a site in Saudi Arabia. In their system, single effect solar stills with a capacity of 5.8 m^3/d and effective evaporating surface area of 1,449 m^2 were coupled to an existing PV-RO plant. The PV-RO unit included a smaller PV field for water pumping from well and a larger PV field for powering the RO unit as well as a battery storage unit. The PV/RO unit was capable of converting only 30% of the brackish water and the remaining was rejected as concentrated brine. The solar stills were combined with the PV-RO system to produce 5.8 m^3/d drinking water using 10 m^3 rejected brine from a PV/RO unit. A fresh water storage tank was also provided to store the drinking water for later consumption. The authors pointed out this combination of PV-RO system with solar stills could provide a completely solar based power desalination system for any location and any brackish water salinity. They concluded that the efficiency of solar stills could be improved by 10%–15% provided that rejected brine from PV/RO unit was preheated by passing through solar pond before entering the solar stills.

Kumar and Tiwari [89], under the climate conditions of New Delhi, India, combined a PV/T (PV-thermal flat plate collector) with a solar still, and tested the performance experimentally compared with a single passive solar still. Fig. 5, shows this system where the water was re-circulated through the collector using a DC pump. In this design, only 23% of the generated electricity was required to power the DC pump; thus, the remaining electricity could be utilized for other applications or the PV size could be reduced. Their results showed that, for the same sized solar still, the productivity of the hybrid PV/T solar still system was about 3.2 and 5.5 times higher than the single solar still during the summer and winter, respectively.

In another study, Kumar and Tiwari [90] evaluated the life cycle cost analysis of a hybrid PV/T active solar still and single passive solar still for operation in New Delhi, India. After varying a series of design parameters, the authors concluded that although the hybrid PV/T solar still had much higher purified water productivity, the cost of distillated water from the single solar still was lower. The authors also pointed out that the primary reason for a higher cost of the hybrid system was the high cost of the PV module at that time.

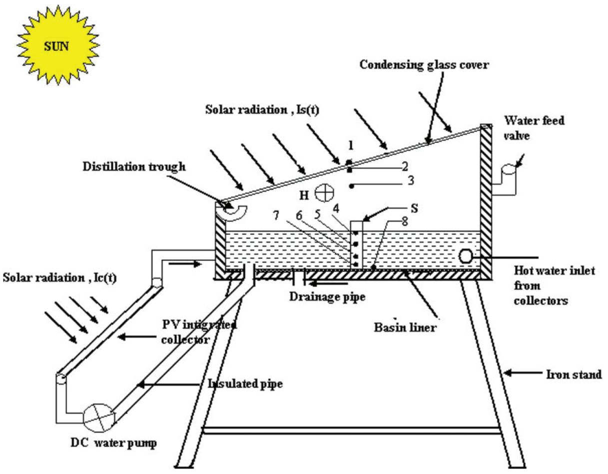

Fig. 5. Schematic of a hybrid PV/T active solar still system [89].

Saeedi et al. [91] carried out an investigation to optimize the performance of a hybrid PV/T solar still. Their study included a review of the influence of many design and ambient parameters on the efficiency of the hybrid system. For example, they determined the optimum number of PV/T collectors and mass flow to achieve the maximum efficiency for the system.

Gaur and Tiwari [92], using an energy and exergy analysis, optimized the number of solar thermal collectors for a hybrid PV/T system integrated and connected in series with the basin of a solar still. They found that the optimal number of collectors increased with the increase of the water mass in the basin while the energy and exergy efficiency decreased with an increase of water mass. Kumar et al. [93] designed an integrated PV/T with solar still system via experimental tests (Fig. 6). They incorporated a nickel-chromium spiral wire heater powered by PV in the proposed hybrid system to enhance the performance. In this system, PV module was cooled by the saline water leading to improve in the PV efficiency and fresh water production. Their results showed that the daily fresh water production of the proposed hybrid PV/T solar still system is around six times more than the conventional passive solar still.

Pounraj et al. [94] designed a hybrid PV/T solar still system that incorporated a PV powered Peltier system enhancing fresh water production during both evaporation and condensation processes. Fig. 7 shows a schematic view of the proposed hybrid system by Pounraj et al. [94]. They demonstrated that, using the proposed hybrid system, the fresh water production capacity increases up to 6.5 higher than a conventional solar still.

A brief review on hybrid PV/T solar still systems and configurations has been provided by Manokar et al. [95].

3.2.2. Solar still-solar collector

Sathyamurthy et al. [96] provided a review paper on some different aspects of integrated solar still with solar collector systems. Eltawil and Omara [97] carried out experimental studies in Egypt to examine the effect of different modifications strategies on the performance of a conventional small solar still with a productivity of 3–4 l/m^2. The authors examined the following system improvement possibilities:

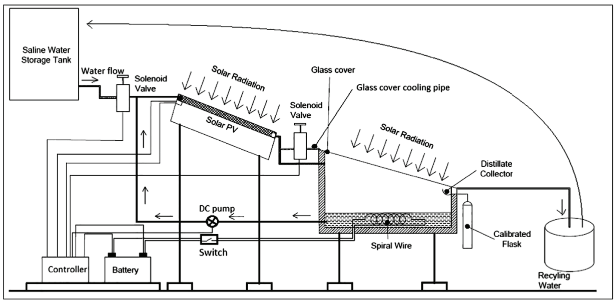

Fig. 6. Schematic of a hybrid PV/T solar still system that incorporated a nickel-chromium spiral wire heater [93].

(1) connecting a suction blower to the solar still in order to withdraw the water vapor and transfer it to an external condenser, (2) combining a solar water collector with the solar still to increase the temperature of the feedwater by either circulating the water under natural or forced mode conditions or spraying the water, (3) coupling a solar air collector to the solar still to increase the evaporation rate, and (4) different combinations of the above three strategies. In their design, a PV was used to provide the required power for driving the suction blower, water pump, and air blower. They compared the performance of their hybrid solar still with a conventional solar still. A schematic of the hybrid experimental set up designed in this study is shown in Fig. 8. The authors concluded that improvements in productivity between 51% and 148% were achievable via the modification strategies. The highest enhancement in the productivity was achieved by combining the solar water collector, solar air collector, and condenser to the developed solar still. The authors, however, generally advised against coupling the solar air collector to the solar still because although it improved the productivity, it resulted in decreased efficiency as well as increasing the cost and complexity.

Voropoulos et al. [98] analyzed the performance of a combined solar still with a solar water collector equipped with a hot water storage tank. In this hybrid system designed to provide the distillate water and hot water simultaneously, the hot water from the solar water collector was used to heat the saline water. The authors showed that the combined system had a substantially higher performance in terms of producing the distillated water compared with the single solar still (since the solar collector increased the temperature of the saline water in the basin). They also pointed out that withdrawal of hot water from the storage tank reduced the productivity of the system in terms of the output fresh water.

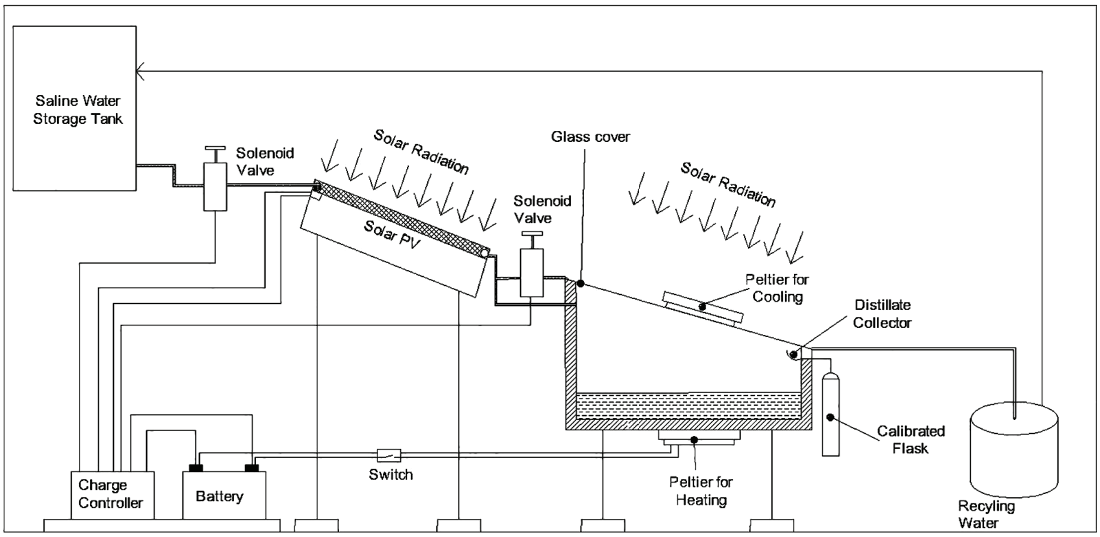

Fig. 7. Schematic of a hybrid PV/T solar still system that used a Peltier system [94].

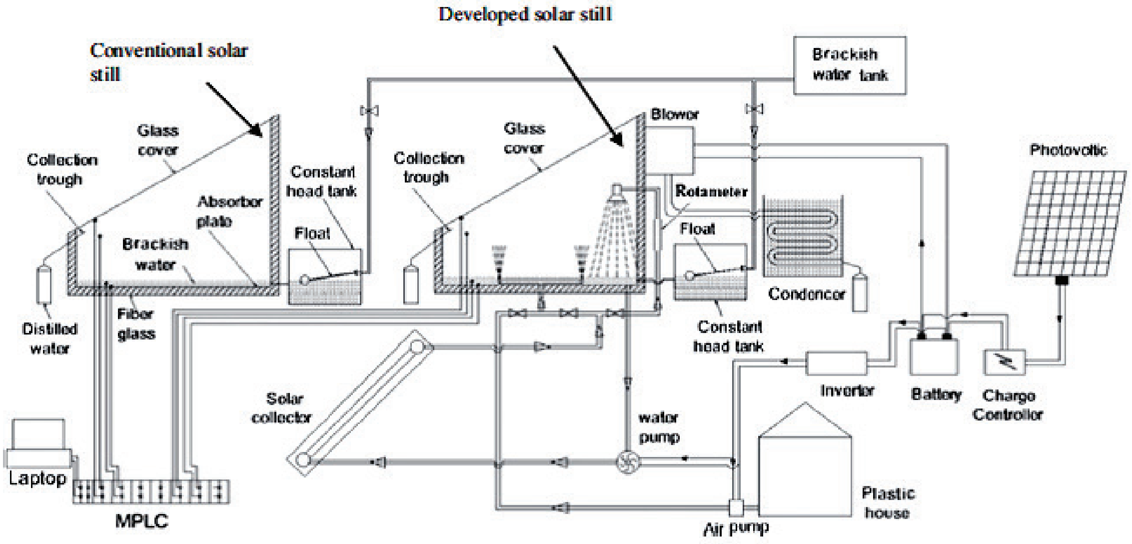

Fig. 8. Schematic of hybrid solar still developed by Eltawil and Omara [97].

Omara et al. [99] carried out experiments to develop a small-scale hybrid desalination consisting of an evacuated solar water heater and conventional/wick solar stills. They combined the evacuated solar water heater with a conventional solar still and two wick solar stills (single layer and double layers) to evaluate the production of distillate water. The authors examined the productivity of the new design compared with a conventional still. Fig. 9, shows a schematic view of their system. During night time, the feed water to the solar still was preheated by an evacuated tube solar collector through using a hot water storage insulated tank. They concluded that preheating the feed water at night increased the productivity significantly and kept solar driven productivity almost constant. Furthermore, they also noted that wick solar stills had a higher productivity than a conventional solar still.

Badran et al. [100] combined a basin type solar still with a flat plate finned type solar water collector. In their design, the hot water provided by solar water heater was used to feed the solar still instead of the typical storage tank. They also considered different types of operations such as: combined solar still-water collector for 24 h operation, single solar still for operation only throughout the sunlight hours, and single solar still for a 24 h operation. The authors showed that coupling the solar water collector to the solar still increased the productivity by 231% when tap water was used as a feed and by 52% when salt water was utilized.

Badran and Al-Tahaineh [101] carried out an experimental study, under the climate conditions of Amman in Jordan, to examine the influence of combining a flat plate solar water heater with a small solar still equipped with interior mirrors. They found that coupling the solar water heater with solar still increased the water temperature in the solar still and subsequently increased the productivity of the solar still compared with a single solar still.

Sampathkumar and Senthilkumar [102] designed and constructed a hybrid solar still with an evacuated tube solar water heater to produce both fresh water and domestic hot water in Tamil Nadu, India. They also added a storage tank at the outlet of solar collector for continuous production of fresh water during the night time. Their hybrid system is shown in Fig. 10. The authors demonstrated that combining the evacuated tube solar water heater with a solar still significantly enhances the pure water productivity.

Feilizadeh et al. [103] developed a combined basin type multi-stage solar still with a flat plate solar water collector. Their system included a multi stage still combined with one,

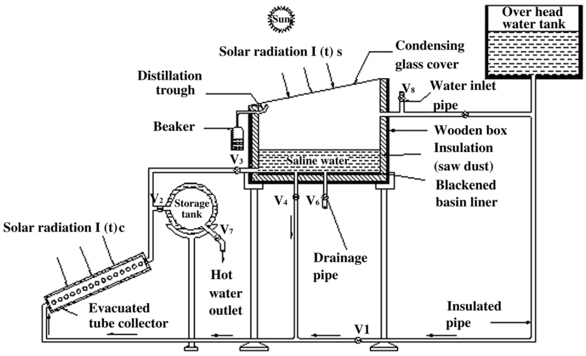

Fig. 10. Combined solar still with evacuated tube solar water heater equipped with storage tank [102].

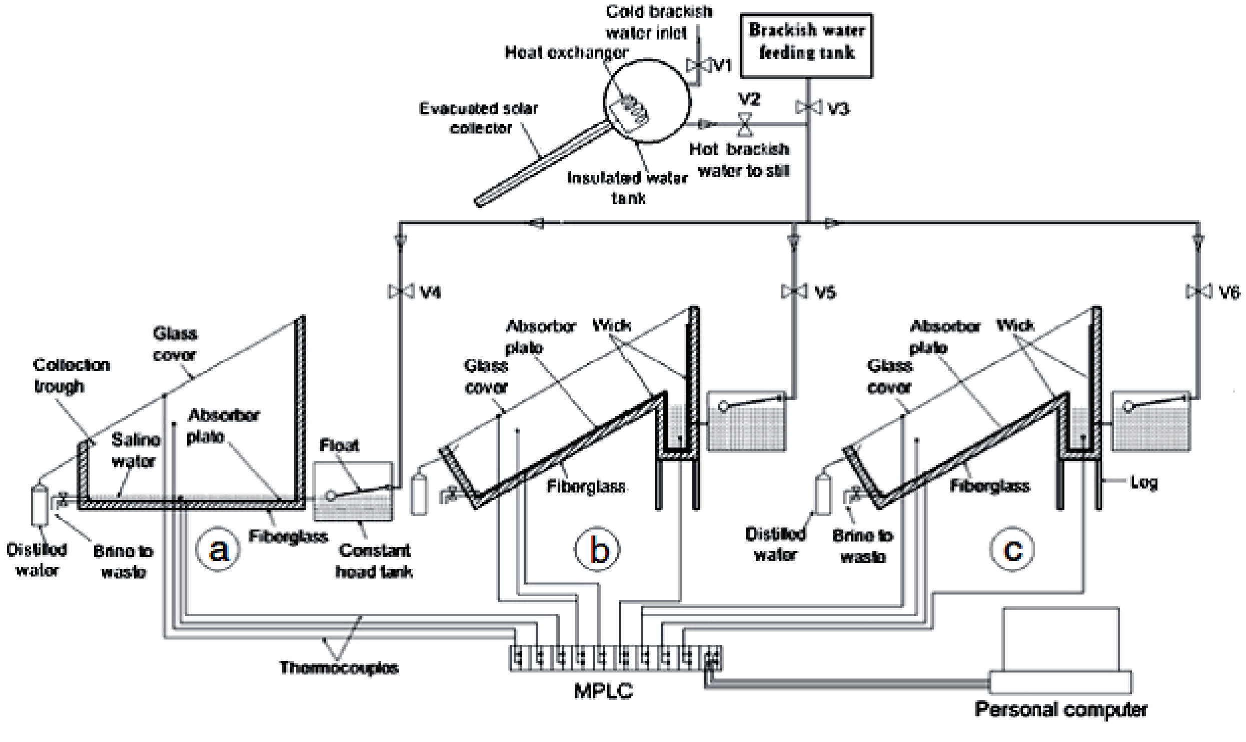

Fig. 9. Schematic of combined solar stills with evacuated tube solar water heater [99]. (a) Conventional still, (b) Double layers wick still, and (c) Single layer wick still.

two or three solar collectors. When more collectors were used, the costs, brine temperature and distillate production increased. They concluded that increasing the number of collector from one to two substantially increases the productivity whereas addition of the third collector was not that productive.

Singh et al. [104] evaluated the thermal performance of a hybrid system consisting of a solar still and an evacuated tube solar water collector. The evacuated tube collector was operated in a free convection mode. The authors concluded that combination of evacuated tube solar collector with solar still increased both water temperature and productivity. They also noted that increasing the water depth in the solar still decreased the productivity. Furthermore, they developed the best combination of these two systems based on the number of tubes of the collector and water depth in the still.

Kumar et al. [105] appraised the performance of a combined solar still with an evacuated tube solar water collector operating in a forced mode as a modification to their previous study [83]. The authors pointed out when the evacuated collector operates in the forced mode, it can remove the heat from the tube and prevent some effects like internal recirculation and stagnation of cold water in reservoir. They demonstrated that for the same size and design parameters, the system has a higher productivity under the forced mode condition than the natural mode.

Voropoulos et al. [106] designed a combined system consisting of a greenhouse type single effect solar still, a flat plat solar water heater, and a storage tank. They reported that combining the hot water tank with the solar still provided double the productivity because of continuous heating from the storage tank. Also, the increases in the productivity were higher at night than the day time due to higher temperature differences between water and the cover.

Thakur and Ali [107] proposed a hybrid experimental configuration by coupling a double sloped solar still with a flat plate solar water collector equipped with a storage tank for both hot water and fresh water productions. In this system, the hot water in the storage could be used for a desalination process at night. The results from this study also showed that the productivity of the coupled system was higher than a single solar still.

As noted by Tanaka, et al. [108], multiple-effect solar stills have the highest productivity among all types of solar stills. In these devices, solar energy is recycled many times. A multiple effect diffusion-type solar still is comprised of parallel partitions in contact with saline-soaked wicks with narrow gaps between the partitions. The first partition absorbs the solar energy either directly or indirectly. The absorbed energy penetrates the first partition plate, and water vapor evaporates from the saline-soaked wick of the first partition, and then diffuses across the gap and condenses on the surface of the second partition. The latent heat of condensation leads to more evaporation from the second partition. Thus, this latent heat is recycled to improve the productivity of the entire solar still.

Tanaka and Nakatake [109] and Tanaka et al. [110] developed and tested a combined multiple-effect diffusion solar still with a heat pipe type solar collector. Their multiple-effect diffusion solar stills included vertical and parallel partitions with thin air gaps between them. These partitions have contact with saline-soaked wicks that receive the saline water constantly. In this combined design, the absorbed solar energy by the solar collector is transferred as latent heat to the solar still. In [109], the authors found that the productivity of this combined design was higher than the vertical multiple effect diffusion solar still combined with basin type solar still. It was found that the productivity increases with increasing the number of partitions; however, this also led to a higher capital cost. A parametric study conducted in [108] showed that the productivity of the multi-effect diffusion-type solar still coupled with heat-pipe solar collector was influenced by several parameters such as number of partitions, temperature of the water entering the wicks, the ratio of solar collector area to partition area, thickness of the diffusion gaps between partitions and the flow rate of saline water entering the wicks.

Based on the work of Chong et al. [111], Fig. 11, shows a typical multiple-effect diffusion unit (MDU) illustrating the distillation process inside of the unit. As seen, the seawater is fed from the top side and the pure water and affluent are collected separately from the bottom side.

Chong et al. [111] developed a multiple-effect diffusion solar still with a new design of a MDU. Their design consisted of a MDU, a vacuum-tube solar collector, and a heat recovery exchanger. In this design, the MDU is heated by the solar energy provided by the vacuum-tube type solar collector with energy transferred by the thermosyphon heat pipe. Also, the energy of the hot brine and distilled water was recovered by a heat recovery exchanger for preheating the seawater feed. Fig. 12 shows the multiple-effect diffusion solar still designed for this study. To decrease the level of energy loss, this MDU was made in two parts symmetric to the heat source (i.e. condenser of the heat pipe) as shown in Fig. 13. The authors demonstrated that for the case of using a flat plate solar collector it was not possible to obtain higher collector temperature; thus, the productivity of the system was lower. In their design, however, the vacuum tube solar collector was able to provide a much higher temperature gradient in the MDU, and consequently enhanced productivity.

Huang, et al. [112] proposed a multiple-effect diffusion solar still in which the MDU unit had a spiraled shape.

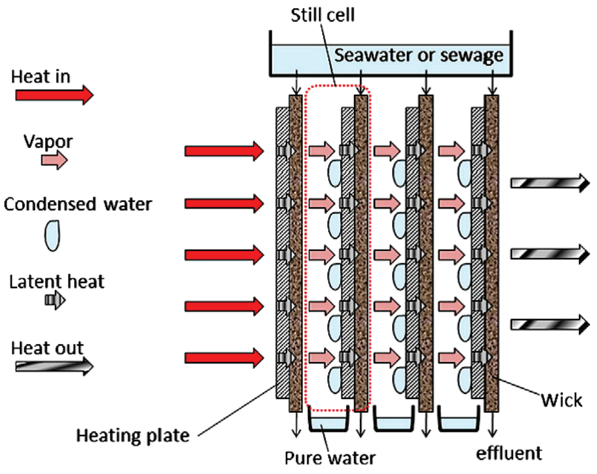

Fig. 11. A multiple-effect diffusion unit (MDU) illustrating the distillation process [111].

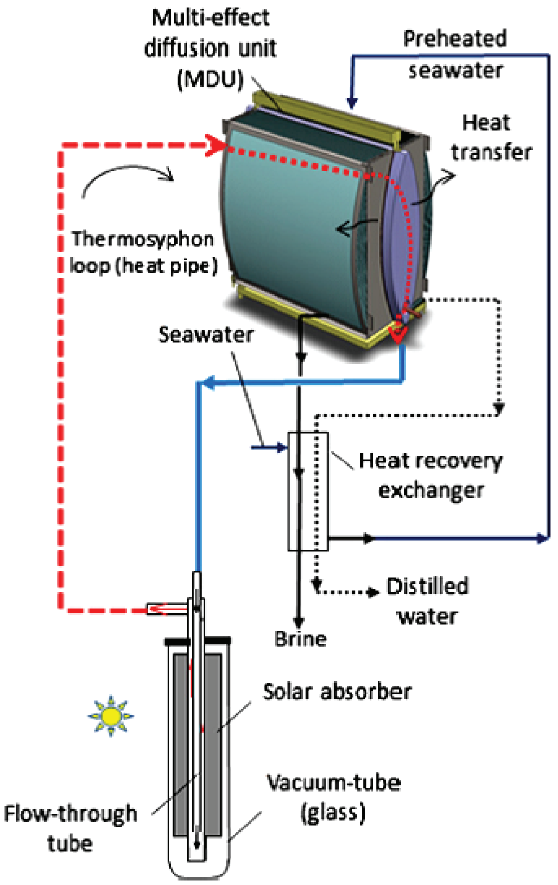

Fig. 12. Multiple-effect diffusion solar still (MEDS) consisting of a vacuum tube solar collector and a heat pipe [111].

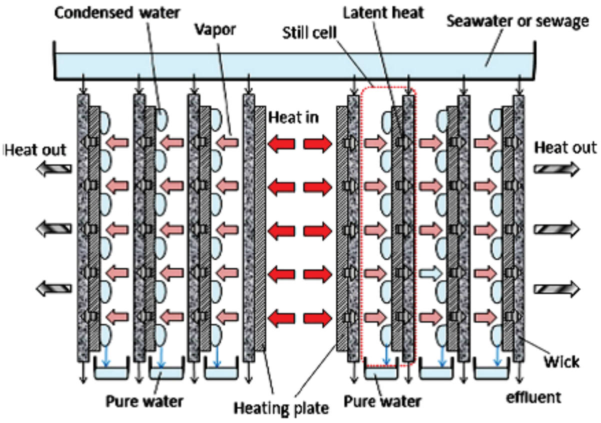

Fig. 13. A symmetric multiple-effect diffusion unit (MDU) [111].

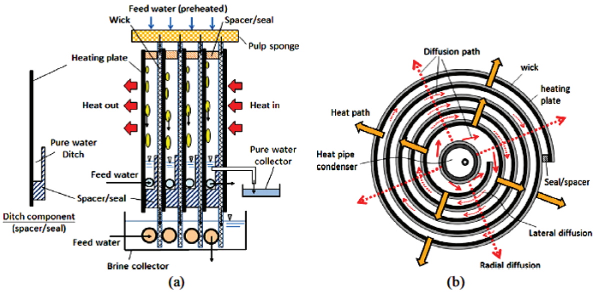

Fig. 14. Two views of a spiral shaped MDU [112].

In this design, the still cell gap is a single spiraled continuous cell from the first heating section (from solar source) to the last heat sink section (to ambient). In addition to the vapor diffusion in the direction perpendicular to the plate, vapor can also flow freely and laterally down to the end of the still cell to enhance the mass transfer. This improves the thermal and mass transfer processes with high temperature solar radiation input. Fig. 14, illustrates the design of the spiral MDU unit proposed in this study. Similar to the previously illustrated design [111], the MDU is combined with a vacuum-tube solar collector. Also, a thermosyphon heat pipe was utilized to transfer the solar energy to the MDU. Fig. 15, illustrates two different views of a spiral shaped MDU. Results of this study showed that this design provided a higher productivity compared with the previous design presented in [111]. This improvement was primarily achieved due to the improved diffusion process in the spiral design cell.

3.2.3. Solar pond-solar still

Much work has been conducted to improve the performance of solar stills by integrating them with mini solar ponds [113–118]. In solar stills, the inlet water temperature is the major operational parameter that is directly linked to the performance of the solar stills. For this combination, the solar pond is utilized to pre-heat the saline water entering the solar still. As discussed next, many experimental configurations have been implemented.

El-Sebaii et al. [114,117] designed an experimental set-up combining single-basin solar still integrated with a shallow solar pond (see Fig. 16). The authors performed experiments to examine the influence of the addition of a shallow solar pond to a solar still under the climate conditions in Tanta, Egypt. They developed a mathematical model of the system and compared the analytical and experimental results. It was found that both fresh water productivity and efficiency of the solar still improve when it was combined with a shallow solar pond.

Velmurugan et al. [115], in an experimental investigation performed in Tamil Nadu, India, combined a mini solar pond with a basin solar still and a stepped solar still for the purpose of desalinating industrial effluents. Fig. 17, shows the combined system. In this design, the single basin and stepped solar stills were combined independently with a solar pond. In the basin type solar still, fins were attached to the basin plate and in the stepped solar stills, basin plates were used as trays with two different depths and the fins were attached to the trays. Addition of fins increased the heat transfer surface area, and as a result decreased the required time for heating the saline water. To improve the productivity, sand, pebbles, and sponges were also utilized as storage in both solar stills. It was found that preheating the solar stills by the mini solar pond enhanced the productivity in both solar stills. Also, the use of sand, pebbles, and sponges improved the productivity of the solar stills.

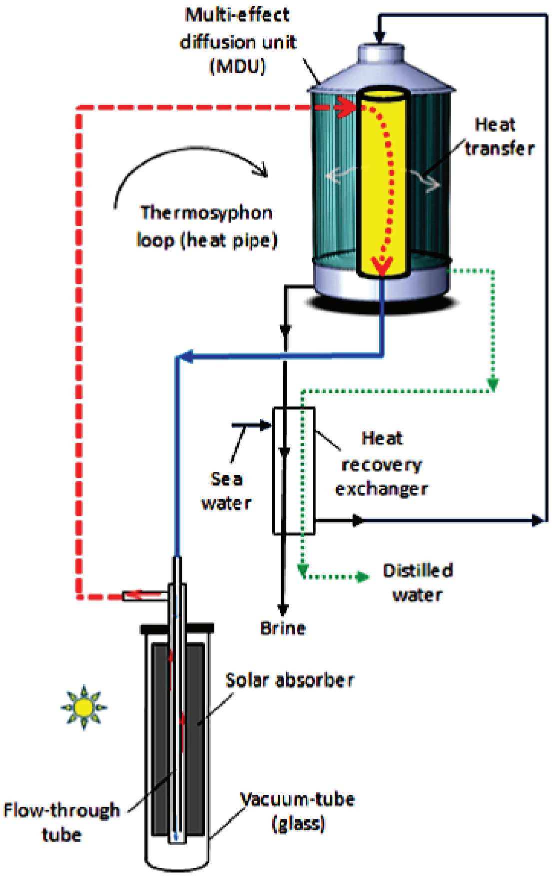

Fig. 15. Schematic of a multiple-effect diffusion solar still with spiral MDU [112].

In another study, Velmurugan et al. [116] carried out two different experiments by combining solar stills with a mini solar pond in series. In the first experiment, a stepped solar still, a single basin solar still and a mini solar pond were connected in series while in the second experiment, a wick type solar still was connected in series with a stepped solar still and a mini solar pond. These two designs of combined solar stills with mini solar pond are illustrated in Figs. 18(a) and (b). For this study, the solar stills were also equipped with fin,

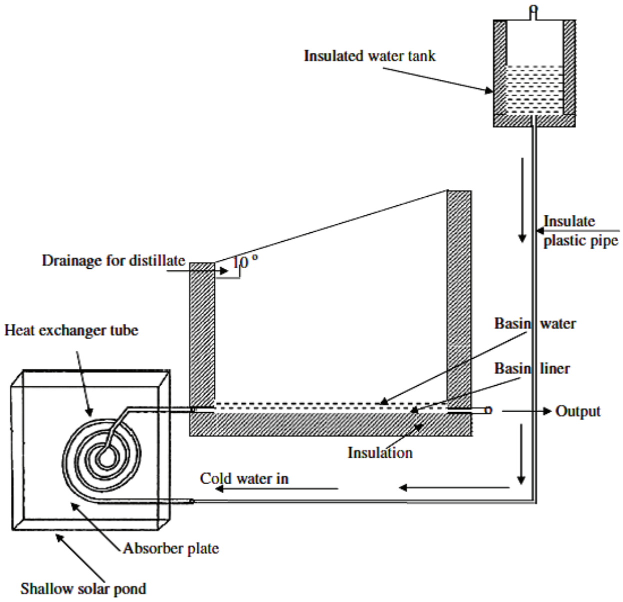

Fig. 16. A single-basin solar still combined with a shallow solar pond [114].

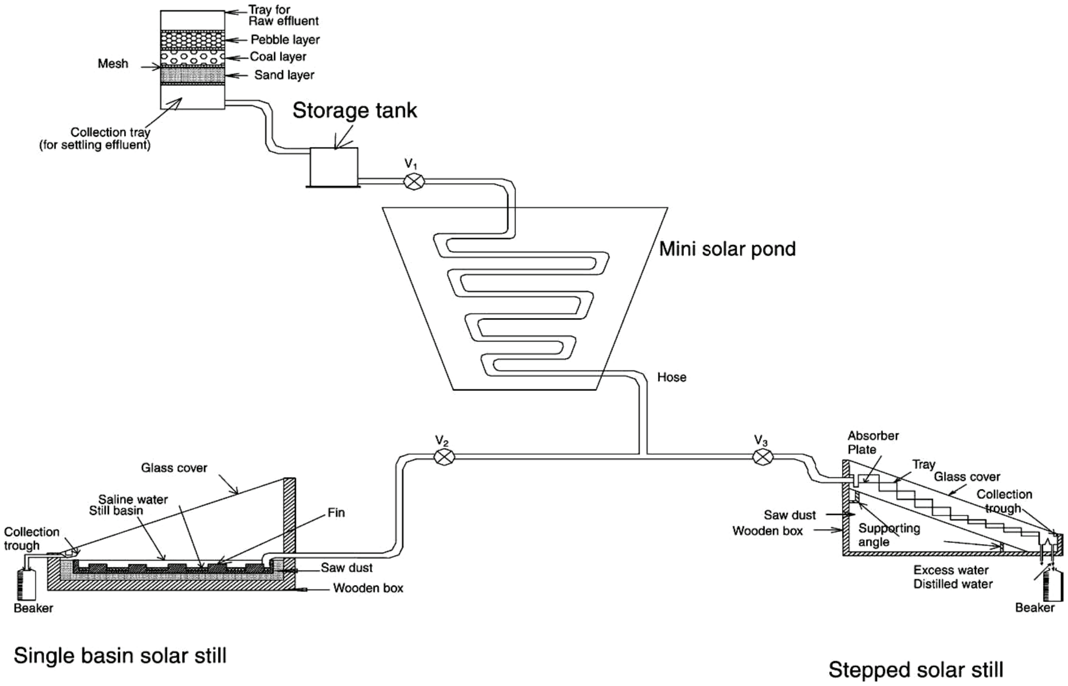

Fig. 17. Schematic of a combined solar still and a solar pond [115].

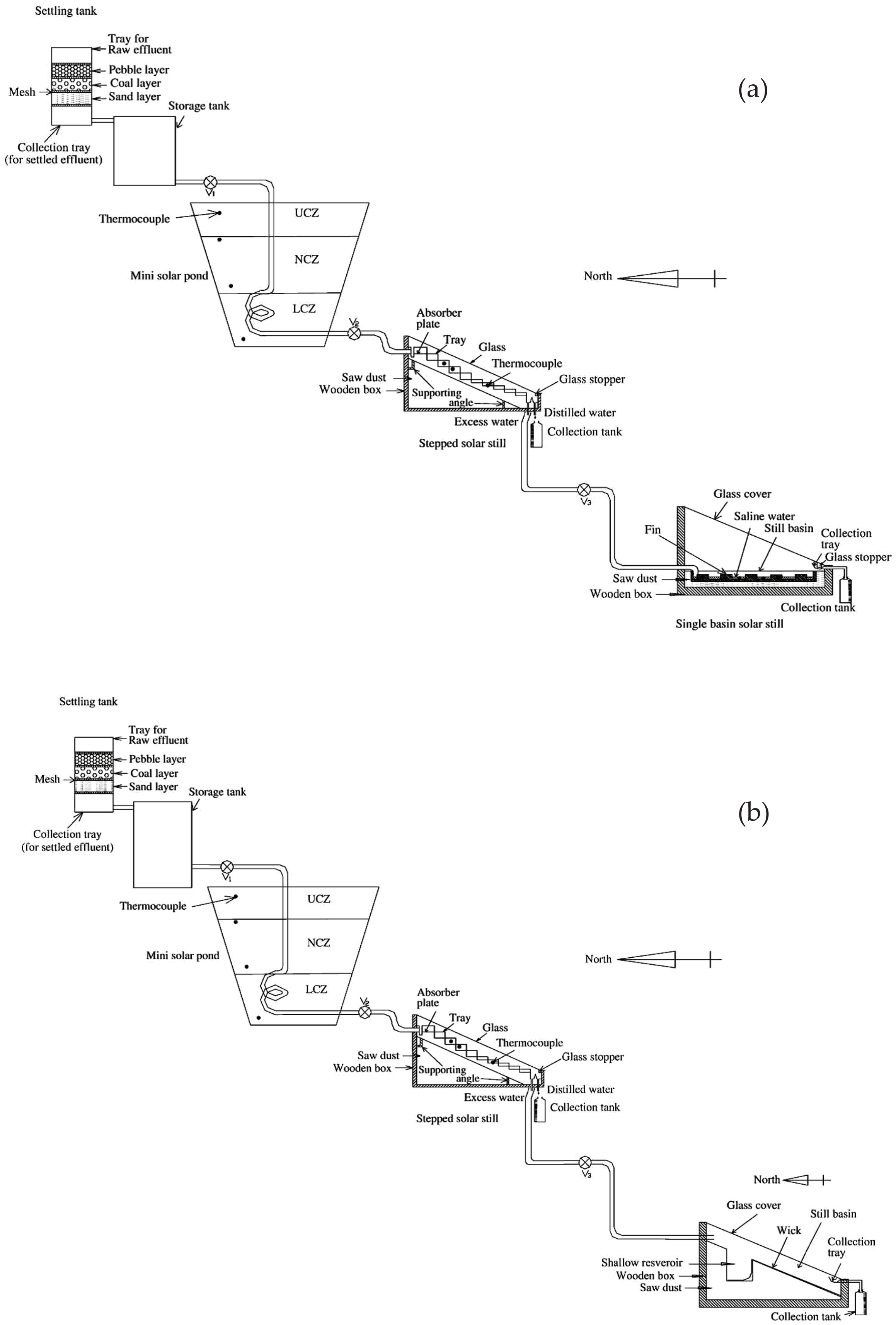

Fig. 18. Two designs of combined solar stills with mini solar pond in series [116].

baffle, pebbles, and sponges to increase the productivity. The fin, baffle, and pebbles served as both energy collector and energy storage devices. Thus, they could supply the thermal energy requirement even after sunset as the energy is released gradually.

Appadurai and Velmurugan [118] carried out experiments by coupling a fin type solar still with a fin type mini solar pond. They compared this design with the combination of fin type mini solar pond and a typical solar still. The findings of this study demonstrated that, due to the increased heat transfer area of the system, higher productivity can be obtained by combining the fin type mini solar pond with fin type solar still.

3.2.4. Solar water collector-solar air collector

According to a number of researchers, solar humidification-dehumidification desalination is among the most efficient solar desalination processes. For example, Fig. 19, shows a schematic of a typical solar humidification-dehumidification system using solar air and water heaters [19]. In [119], the authors reviewed different types of solar humidification-dehumidification systems.

There are many studies in the literature that used a combination of solar water heater and solar air heater to heat the water and air in the humidification-dehumidification process. For example, in a number of recent papers [120–125], researchers designed and evaluated the experimental performance of solar humidification–dehumidification water desalination systems. These designs were generally comprised of a flat plate solar air heater, a flat plate solar water heater, a humidifier, an evaporation tower, and a condensation tower. In a typical system, the saline water is preheated in the condensation tower using the condensation latent heat. The preheated water is then heated in the solar water heater and flows into the humidifier unit and the evaporation tower. Afterwards, the saturated moist air is transferred to the condensation tower where it comes in contact with a condenser surface that has a lower temperature than air dew point temperature. Finally, the pure water is collected underneath of the condensation tower. Also, the brine collected underneath of humidifier and evaporation tower is either combined with the feed flow or rejected when the salinity is high.

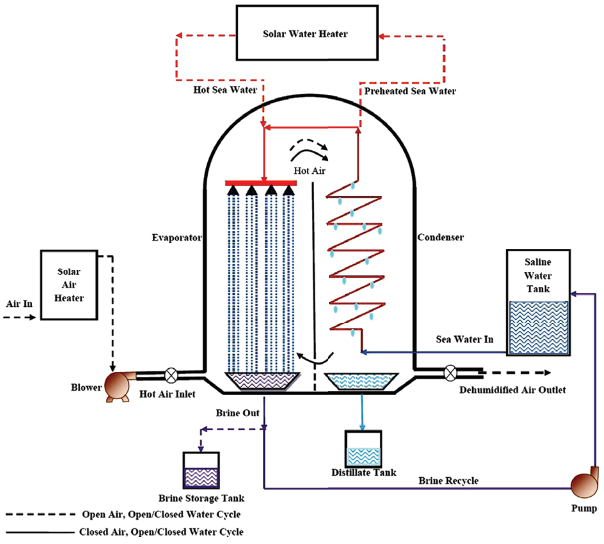

Fig. 19. A typical solar humidification dehumidification system using solar air and water heaters (adopted from [19].

Kabeel et al. [126] evaluated the technical and economic performance of a hybrid solar desalination system consisting of a solar humidification–dehumidification unit and single-stage flash evaporation. The humidification–dehumidification unit of this design used a humidification tower and dehumidifier as well as the solar water and air heaters. The single-stage flashing unit consisted of a flashing chamber and a condenser. They evaluated four configurations including two hybrid configurations with and without solar air heaters (see Fig. 20) and two stand-alone configurations for which the humidification–dehumidification and single-stage flashing units were separated. It was shown that the system configuration had a notable influence on the performance. They concluded that the hybrid configuration using solar air heater was the more suitable economic option while the stand-alone configuration obtained a higher performance.

Yıldırım and Solmus [127] evaluated a solar humidification dehumidification system operating using solar air and water heaters with the primary components of a flat plate solar water heater, a flat plate double pass solar air heater, a humidifier, a dehumidifier, and a storage tank. They concluded that water heating is of main significance on the production of fresh water while air heating does not bring remarkable enhancement on the productivity. Furthermore, an increase in the mass flow rate of air and feed water increases the water production; however, mass flow rate of air should be optimized because increase in its amount higher than a specific value can lead to a decrease in the water production.

3.2.5. Solar collector-photovoltaic

Many studies have been carried out to develop hybrid solar thermal collector-PV systems to provide the thermal and electrical energy requirements of thermal desalination system with MD desalination [128–137]. The primary reason of integrating thermal solar collector with PV panels is to make the system self-contained and autonomous; thus suitable for off grid applications in remote areas. Some of the most important studies are highlighted next.

Membrane distillation (MD) is an innovative and promising desalination based on a separation technique that combines thermal distillation with membrane process. Thermal energy is utilized for phase changing of liquid water into vapor while the membrane is only permeable to the vapor phase, and thus separates the pure distillate from the retained solution [128]. The thermal energy requirements of MD desalination can be provided by low-grade waste heat and renewable energy sources such as solar and geothermal energy. MD desalination has not become commercially available for large scale desalination purposes; nevertheless, many researchers have worked on the development and evaluation of MD desalination, particularly using renewable energy sources. In MD desalination, a microporous membrane serves as a physical support that separate a warm solution from a cooler chamber containing a gas or a liquid or a gas. The vapor pressure difference through the membrane is

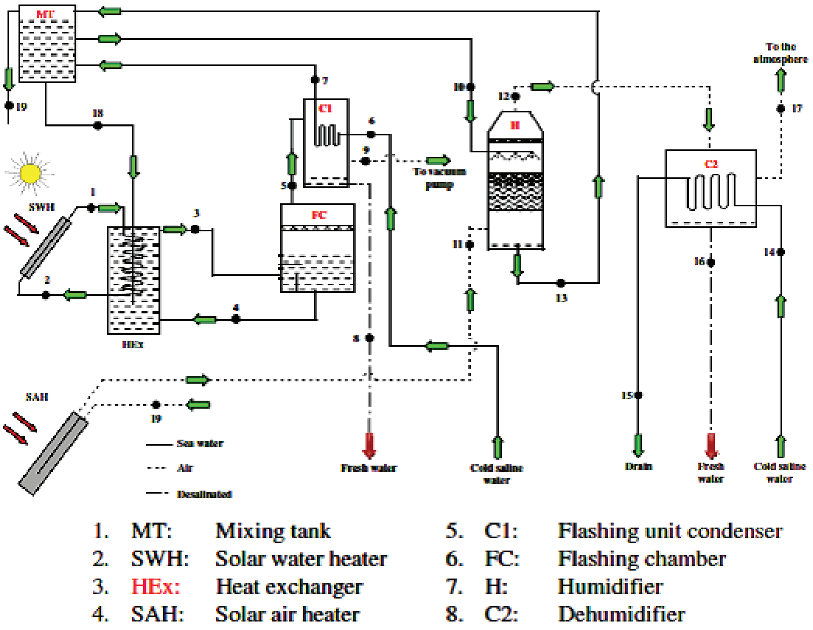

Fig. 20. Hybrid solar humidification–dehumidification unit and a single-stage flashing evaporator [126].

the driving force in MD which can be applied by different methods such as direct contact, air gap, sweeping gas, and vacuum MD. Among all types of MD, vacuum MD (VMD) provides the highest flux and better performance. In VMD, a pump is utilized to provide a vacuum in the permeate membrane side. The vapor is withdrawn by applying a vacuum on the permeate side. The pressure on the permeate side is smaller than the saturation pressure of evaporating species and condensation occurs outside of the membrane module. One main advantage of VMD is that energy lost due to conduction is negligible.

Thomas [129] reported a solar-powered membrane distillation system (40 l/h) installed in Tokyo, Japan, in 1994. The system operated using solar water heater collectors to provide thermal heating for a MD process, and PV panels provided the required electricity for pumping. In the experimental system, the automatic controls start up the desalination system when there is adequate solar radiation to power the solar collectors and PVs.

Banat et al. [130] a small-scale autonomous solar powered MD plant was designed under the SMADES, project and tested in Irbid, Jordan. In the experimental system, flat plate solar water collectors and a PV panels were hybridized to supply the entire thermal and electrical energy of the plant such that the plant could operate autonomously to produce 120 l/d of fresh water. The MD desalination unit included a spiral-wound air-gap MD module with an internal heat recovery function. A schematic of this plant is illustrated in Fig. 21.

Koschikowski et al. [133] proposed two solar powered MD systems based on different design approaches. The first one, “compact” system is for small fresh water production between 100 and 500 l/day, and the second one, “two loops” is for larger production. The system was driven by a combination of solar collector and a PV sized to require no external energy. The compact system was designed such that cold feed water was pumped by a PV-pump to the condenser and after

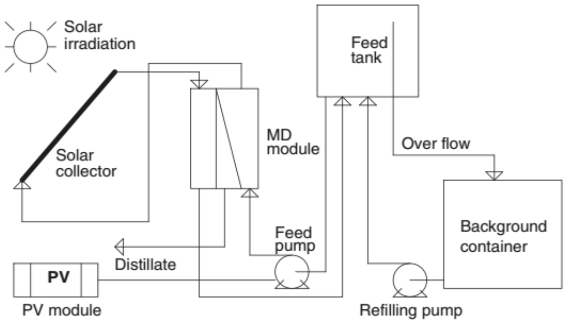

Fig. 21. Schematic of a solar powered MD plant [131].

pre-heating in the condenser outlet entered the solar thermal collector. The feed temperature was increased by 5–10 K and was re-circulated to the evaporator. The “two loop” design was more economical because of its daily productivity (higher than 1000 l/day). The “two loop” design had four key components: (1) A thermal storage tank was employed to increase the operation time of the system and fresh water production and subsequently decrease the costs, (2) The system had two loops: a solar collector loop and desalination loop. The desalination loop was separated from the collector loop by a corrosion resistant heat exchanger, (3) The system had five MD modules that worked in parallel in the desalination loop, (4) It had a control unit that controlled the system’s operation. When the solar radiation level was lower, the desalination unit operated directly using the energy from the solar collectors. In case of higher solar radiation level, the surplus energy was stored in the tank for night and cloudy sky time. Consequently, the operation conditions could be adjusted optimally for the MD module.

Saffarini et al. [134] conducted an economic analysis of solar driven MD desalination for three different types of MD systems: direct contact (DCMD), air gap (AGMD), and vacuum (VMD). The solar driven unit consisted of a flat plate solar water heater to provide thermal heating, and PV panels to power the required electricity for pumping. Their economic evaluation results showed that DCMD was the most economical option in spite of high conductive losses from the feed to the permeate side. Furthermore, the cost of the solar water heater was more than 70% of the total system costs; thus, when waste free energy was available it could be used alternatively to reduce the costs. For the case of using a solar collector, the multi-stage solar driven MD should be employed to make the process more effective. The authors also carried out a parametric study for the AGMD system, and found that cost of fresh water production depended upon: (1) effective membrane length, (2) air gap width, (3) feed channel depth, and (4) solar collector efficiency.

Chafidz et al. [136] developed a solar-driven desalination system that utilized the MD process to generate fresh water in arid remote areas of Saudi Arabia. Their solar energy system was a hybrid system that integrated an evacuated tube solar water heater with a PV module and included thermal and battery energy storage to provide an autonomous system for desalination. The main components of the system were a solar thermal system, a solar-PV system, and a vacuum multi-effect MD (V-MEMD). Also, the authors integrated a heat pump to the system to enhance the performance of the system. The heat pump was added to simultaneously preheat the feed water and cool down the cooling water. The system was designed to be portable so that it could be utilized for emergency situations. A block diagram of the developed hybrid solar powered desalination system is presented in Fig. 22. Based on the conducted experiments, the highest fresh water production of 15.39 l/h was achieved.

Beitelmal and Fabris [137] designed an autonomous solar powered desalination system for small scale off-grid application. Their system contained two parabolic trough solar collectors, PV panels, regenerative heat exchanger, boiler, condenser, tracking system, and pumps. In this system, the thermal energy for desalination of brackish water was provided by parabolic trough collectors, and the PV panels equipped with battery storage system were used to supply the power of pumps, tracking systems and solenoid valves. Duratherm 450, thermally stable oil with a boiling point of 232°C was selected as heat transfer fluid for the parabolic trough collectors. The system operated such that the thermal energy absorbed by the heat transfer fluid could be transferred via a heat exchanger to the salty water inside the boiler. The produced water vapor from the boiling process was sent by a vapor pump with variable speed circulation to the condenser in which the water vapor was condensed and finally was collected into a clean water container. Fig. 23, shows a schematic layout of the hybrid solar trough collector-PV thermal system.

A summary of important features of some selected combined solar-solar desalination systems is presented in Table 3. Note that a unit conversion was done to convert all fresh water production capacities to m^3/day.

3.3. Solar-geothermal

Solar energy systems providing energy can only operate efficiently during the day time, and the energy production is reduced when the sky condition becomes cloudy or season changes. This drives the application of thermal energy storage systems to collect the solar energy during sunny hours, and store it for later applications. In this regard, combining the geothermal energy source with solar energy could be a promising option to overcome the difficulties related to utilization and design of thermal storage, the intermittency of the solar energy, and reliability problems.

Missimer et al. [138] proposed a combined solar-geothermal energy system for a desalination process using an adsorption desalination (AD) technique with a capacity of 10,000 m^3/d. AD is a thermally driven desalination technology that can utilize waste heat, solar, and geothermal heat sources. The AD cycle process consists of: (1) evaporation–adsorption, and (2) desorption–condensation. A review of AD technology is given by Beitelmal and Fabris [137].

In a Missimer et al.'s design [138], a combined solar and geothermal energy source was utilized to provide the latent

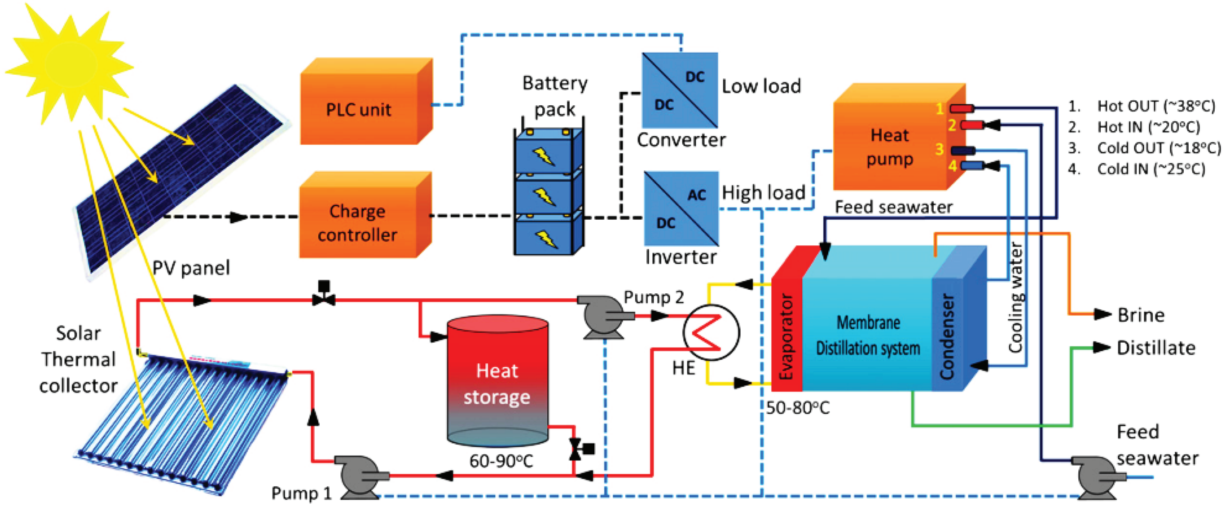

Fig. 22. Block diagram of a hybrid solar powered desalination system [136].

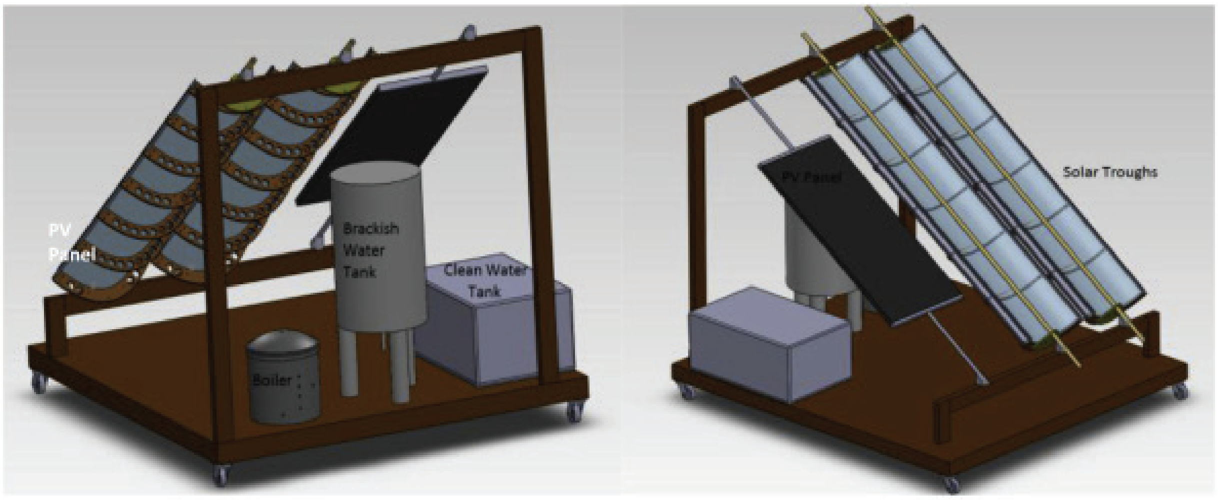

Fig. 23. Schematic layout of a hybrid solar trough collector-PV system [137].

Table 3
Summary of important features of selected combined solar-solar desalination systems.

Authors	Hybrid systems	Capacity	Storage	Remarks
Hasnain and Alajlan [88]	Solar stills-PV/RO	5.8 m^3/d by solar stills using 10 m^3/d rejected brine from PV/RO	Yes (battery storage)	Single effect solar stills with effective evaporating surface area of 1,449 m^2 were coupled to an existing PV-RO plant to produce drinking water from rejected brine of PV/RO unit. Water storage tank was also considered to store the fresh water for later consumption.
Kumar and Tiwari [89]	Solar stills- PV/T	Variable in different days ranging from 0.0025 to 0.0035 m^3/d	No	Solar collector was used to preheat the water in solar still and enhance the productivity. A part of generated electricity by PV was used to power the DC pump to re-circulate the water in solar collector. The extra power by PV could be used for other purposes.
Eltawil and Omara [97]	Solar stills-Solar air heater-Solar water heater-PV	The capacity of 0.0015–0.002 m^3/d	No	Several modifications were examined: (1) connecting a suction blower to the solar still to withdraw the water vapor and transfer it to the external condenser, (2) a solar water collector to the solar still to increase the temperature of the feedwater, (3) a solar air collector to the solar still for increasing the evaporation rate, and (4) different combinations of the above three strategies. PV was also used to provide the power of suction blower, water pump and air blower.
Voropoulos et al. [98]	Solar still-flat solar water collector	The average capacity of around 0.008 m^3/d	Yes (hot water thermal storage tank)	The system was designed to provide the drinking water and hot water simultaneously. Hot water from solar water collector was used to heat the saline water in solar still.
Omara et al. [99]	Solar still-evacuated solar water heater	The average capacity of around 0.006 m^3/d	No	An evacuated solar water heater was integrated to a conventional solar still and two wick solar stills (single layer and double layers) to preheat the feed water to the solar stills during night time and the cloudy sky during the daytime, and provide the continues production of distillate water.

(*Continued*)

Table 3 (*Continued*)

Authors	Hybrid systems	Capacity	Storage	Remarks
Badran et al. [100]	Solar still-finned type solar water heater	The average capacity of around 0.004 m^3/d	No	A flat plate finned type solar water collector was combined with a basin type solar still to enhance the productivity. In this design, the hot water provided by solar water heater was used to feed the solar still instead of the typical storage tank.
Badran and Al-Tahaineh [101]	Solar still equipped with interior mirrors-flat plate solar water heater	The average capacity of around 0.003 m^3/d	No	A flat plate solar water heater was coupled with a small solar still equipped with interior mirrors to increase the water temperature in the solar still and subsequently increase the productivity.
Sampath-kumar and Senthilkumar [102]	Solar still-evacuated tube solar water heater	The average capacity of around 0.007 m^3/d	Yes (hot water thermal storage tank)	An evacuated tube solar water heater was hybridized with solar still to produce both fresh water and domestic hot water. A hot water storage tank at the outlet of solar collector was used for continuous production of fresh water during the night time.
Feilizadeh et al. [103]	Multi-stage solar still-flat plate solar water heater	For different collector over basin area (CBA) ratios, the average capacity of between 0.008 and 0.015 m^3/d was obtained for Summer and average capacity of between 0.005 and 0.013 m^3/d was obtained for Winter	No	A multi stage still was combined with one, two or three solar water collectors so that solar collectors could pre-heat the water in the solar still, and provide the required energy for the evaporation in solar still. Increasing the number of collector from one to two substantially increases the productivity while addition of the third collector doesn't bring notable change in productivity.
Voropoulos et al. [106]	Greenhouse type single effect solar still-flat plat solar water heater	For different levels of solar radiation, the capacity was between 0.032 and 0.039 m^3/d	Yes (hot water thermal storage tank)	A greenhouse type single effect solar still was combined with a flat plat solar water heater to provide both hot water and fresh water. Addition of water tank with the solar still provided two times higher productivity because of the continuous heating from the storage tank.
Tanaka and Nakatake [109]	Vertical multiple-effect diffusion solar still-heat pipe solar collector	The average capacity of between 0.038 and 0.044 m^3/d was obtained	No	A vertical multiple-effect diffusion solar still was combined with a heat pipe solar collector. The absorbed solar energy by the solar collector was transferred as latent heat to the solar still. This design could provide higher productivity than combined vertical multiple effect diffusion solar still with basin type solar still.
Chong et al. [111]	Multiple-effect diffusion solar still-vacuum-tube solar collector-thermosyphon heat pipe	The highest capacity of 0.028 m^3/d	No	Multiple-effect diffusion solar still was coupled with a vacuum-tube solar collector and a heat recovery exchanger. In this design, multiple-effect diffusion unit was heated by the solar energy provided by the vacuum-tube solar collector, and transferred via the thermosyphon heat pipe. Also, the heat of hot brine and distilled water was recovered by the heat recovery exchanger for preheating the seawater feed.

(*Continued*)

Table 3 (*Continued*)

Authors	Hybrid systems	Capacity	Storage	Remarks
Huang et al. [112]	Multiple-effect diffusion solar still- vacuum-tube solar collector-thermo-syphon heat pipe	The highest capacity of 0.041 m^3/d	No	Similar to design of [101] but the multiple-effect diffusion unit had a spiraled shape. This design provided a higher productivity compared with the design of [101] due to the improved diffusion process in the spiral design cell that improves the water evaporation and condensation processes particularly at higher level of solar radiation.
El-Sebaii et al. [114]	Single basin solar still-shallow solar pond	The average capacity of between 0.0019 m^3/d in February and 0.0066 m^3/d in July	No	A single-basin solar still was integrated with a shallow solar pond to enhance the productivity and efficiency, by preheating the water in solar still.
Velmurugan et al. [115]	Basin solar still-mini solar pond and stepped solar still-mini solar pond	The average capacity of over 0.003 m^3/d for single basin solar still with fin, pebbles and storage	Yes (sand, pebbles and sponges as storage)	A basin solar still and a stepped solar still were coupled independently with a mini solar pond to preheat the water in solar stills and enhance the productivity. Fins were attached to solar stills to improve the productivity. Also, sand, pebbles, and sponges were utilized as storage in both solar stills.
Velmurugan et al. [116]	Stepped solar still-single basin solar still- mini solar pond and wick type solar still-stepped solar still- mini solar pond	The capacity of around 0.006 m^3/d for the first design and the capacity of around 0.005 m^3/d for the second design.	Yes (pebbles and sponges as storage)	Two different designs proposed. In first design, a stepped solar still, a single basin solar still and a mini solar pond were connected in series while in the second design, a wick type solar still was connected in series with a stepped solar still and a mini solar pond. The solar stills were equipped with fins and baffles as energy collector surface as well as pebbles and sponges as energy storage devices.
Kabeel and El-Said [126]	Solar water heater-Solar air heater	The fresh water production capacity of between 0.077 and 0.096 m^3/d was obtained for different configurations	No	The solar water and air heaters were used in this design for heating the water and air in the solar humidification–dehumidification process. Four configurations were evaluated including two hybrid configurations with and without solar air heaters and two stand-alone configurations.
Banat et al. [130]	Flat plate solar water heater-PV	The capacity of 0.120 m^3/d	No	Flat plate solar water collectors and a PV panels were coupled to supply the entire thermal and electrical energy of the MD desalination unit included a spiral-wound air-gap MD module with internal heat recovery function.
Saffarini et al. [134]	Flat plate solar water heater-PV	It was not specified by authors as the main goal was economic evaluation.	No	The solar driven unit consisted of flat plate solar water heater to provide thermal heating for DCMD, AGMD, and VMD, and PV panels to power the required electricity for pumping in the system. DCMD was identified as the most economical option to be powered by hybrid solar water heater-PV system.

(*Continued*)

Table 3 (*Continued*)

Authors	Hybrid systems	Capacity	Storage	Remarks
Chafidz et al. [136]	Evacuated tube solar water heater-PV	For the best tests, the average capacity of between around 0.068 and 0.1 m^3/d	Yes (both thermal and battery energy storages	The designed solar energy system integrated evacuated tube solar water heater with PV module equipped with thermal energy and battery energy storages to provide autonomous system for Vacuum Multi-Effect Membrane Distillation (V-MEMD). A heat pump was also integrated to the system to boost the performance. The system was designed portable to provide fresh water for emergency situations.
Beitelmal and Fabris [137]	Parabolic trough solar collectors- PV	It was not given by authors	Yes (battery storage system)	A combined Parabolic trough solar collectors- PV solar energy system was developed to distillate the brackish water. Desalination unit operates using the thermal energy provided by parabolic trough solar collectors to the salty water inside a boiler. Then the produced water vapor was sent to the condenser in which the water vapor was condensed and finally was collected into a clean water container.

heat requirements of the AD unit located on the coastline of the Red Sea. For this application, the solar collectors were designed to provide energy around 90°C in day time which provided the possibility to produce the highest fresh water requirement by the AD unit until early evening. Then the geothermal heating source could be used to supply the heat demands at night time for a period of around 12 h. The authors pointed out that in addition, the geothermal energy could be utilized as an independent heat source and also in combination with thermal energy storage and solar water collectors to prohibit any energy losses when the storage is charged. The capacity of the desalination plant, the type of the desired system (including a single geothermal or combined solar-geothermal system), and the thermal features of the utilized geothermal reservoir are among the most important parameters for designing the required geothermal wells.

A brief review on hybrid solar-geothermal driven desalination systems has been provided by Yousefi et al. [139].

3.4. Solar/wind-ocean

The application of wave and tidal energy is attractive for desalination process in coastal regions where both energy and seawater are accessible. Thus, some attempts have been made to hybridize the solar or wind energies with wave and tidal energy to supply the energy requirement for desalination process.

Zhao and Liu [140] proposed a multi effect solar desalination system that used solar and tidal energy for desalination process. Multi effect solar distillation, that operates mainly based on waste heat or solar energy, is a technology with high thermal efficiency due to reuse of the latent heat of vapor. It is a thermally driven desalination technology, however, the vacuum pumps and water pumps in the system require electrical energy for seawater supply and drainage. For this design, the authors suggested the direct utilization of tidal energy for supplying the required power of vacuum extraction, water supply and drainage instead of electrically driven pumps. Their system consisted of a solar collector, an evaporator, an evaporator–condenser, a condenser, a tidal energy storage system, and a vacuum extraction system that was driven by tidal energy. To study the efficiency of this system, the authors evaluated a two effects desalination system. They pointed out that the system was capable of operating in regions with a tidal range larger than 2m, and that it could potentially have higher performance with appropriate system modification.

Nikitakos and Stefanakou [141] analyzed a combined wind and wave power project to power a RO desalination plant with an 8 kW up to 25 kW capacity on an island of Greece. Their system consisted of a system combining a wind turbine situated on a floating platform with a wave power conversion device near to the floating platform with the desalination unit installed on the floating platform. The analysis carried out for this study concentrated on minimizing the wave movements, enhancing the operation conditions for the wind turbine and wave device and resisting against the extreme weather conditions. The authors also reviewed the most important design issues concerning the wind turbine, wave device, and desalination plant.

4. Challenges and the potential of hybrid renewable energy desalination systems

Fig. 24 shows fresh water production capacities by different hybrid renewable energy driven desalination systems reviewed in this paper. Note that the data presented in Fig. 24, is based on data given in Tables 2 and 3 and Section 3.3 for the hybrid solar-geothermal driven AD system. This figure shows that the hybrid systems that incorporated solar still, solar air heater, solar water heater or solar humidification-dehumidification have very small production capacities. Larger capacities are realized for hybrid PV/Wind and hybrid solar-geothermal driven desalination systems.

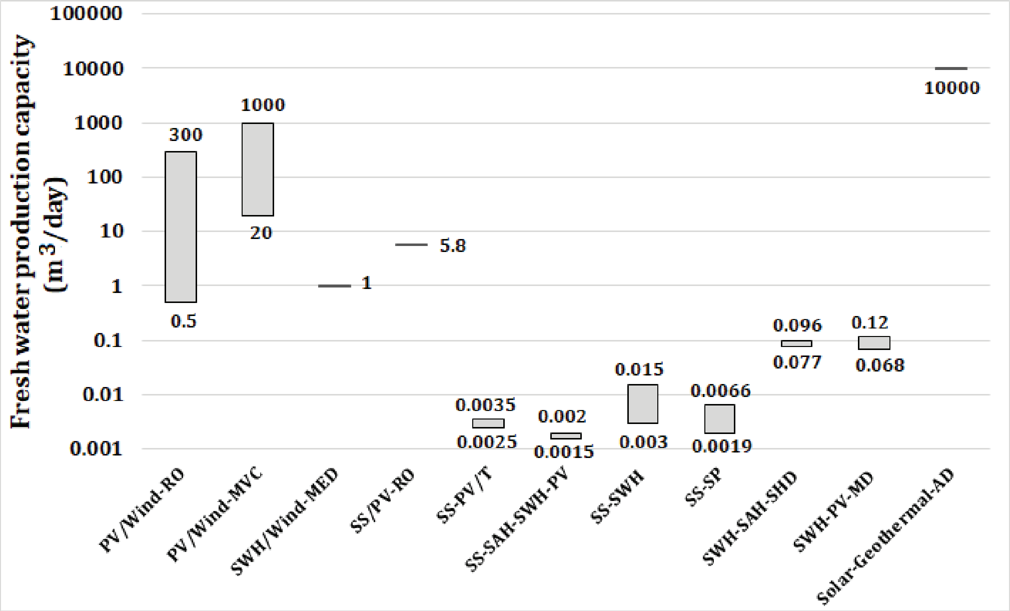

Fig. 24. A summary of fresh water production capacity by different reviewed hybrid renewable energy driven desalination systems (SWH: solar water heater, SS: solar still, SAH: solar air heater, SP: solar pond, SWH: solar humidification-dehumidification).

This review paper has pointed that there are two major design challenges that the implementation of hybrid renewable energy desalination faces: economics, and energy storage. In addition, the potential hybrid system choices are numerous and one must address the question of selecting a potential system configuration. These subjects will be addressed in this section.

4.1. Economic considerations

The economic evaluation of a hybrid renewable energy driven desalination systems is an important factor that determine the viability of the proposed configuration for fresh water production for a particular site. An economic analysis is normally carried out to calculate the capital cost of each component and the total systems as well as the production cost of the fresh water. Both factors provide information on what modifications can be made to the system in order to reduce economic costs. Furthermore, the costs associated for development of these systems are highly site specific and are dependent on the types of renewable energy systems that are combined for desalination process. The cost of water production using hybrid renewable energy driven desalination systems depends upon (1) capital costs that include cost of land and site preparation as well as cost of equipment and installation of hybrid renewable energy systems and desalination unit, and (2) operation and maintenance costs that include the cost of energy, maintenance and replacement cost. The fact that major applications of these systems are in the remote and isolated areas makes the costs more variables and locations dependent that highlights the importance of a thorough economic evaluation.

Some of the main economic variables for the development of hybrid renewable energy driven desalination systems are: (1) Quality and characteristics of renewable energy resources, (2) Site characteristics that impact the cost of water production such as availability and conditions of the required lands, the proximity of plant location to water source and concentrate discharge point as well as cost of pumping and pipe installation, (3) The capacity and design of the plant which determines the design and size of sub-units. Although, larger capacities require higher initial capital investment compared with smaller capacities, the cost for purified water for larger plants can be lower, (4) The quality of the feedwater; with a lower salt concentration (brackish water) requires less energy input as compared with feedwater with higher concentration (sea water), and (5) Transportation and erection of the renewable energy systems and desalination equipment and commissioning the project.

In general, at the present time, the cost of fresh water production using renewable energy sources is still higher than producing fresh water by conventional desalination systems. Hybridizing different renewable energy systems may either increase or decrease the cost of fresh water production compared with a single renewable energy driven desalination, depending on the specific site characteristics, types of renewable energy systems that are combined, capacity of the plant, etc. Nevertheless, for a remote application where there is no access to conventional energy sources and grid connected power, fresh water production using hybrid renewable energy systems could be cost competitive.

The economic evaluations conducted in the reviewed papers have not produced a solid base to compare the economic feasibility of hybrid renewable energy desalination technologies. They have been carried out for different locations and based upon different system capacities, energy source and used components for the technologies and source of water (seawater or brackish water with different level of salinity). Due to these differences, at the present time, it is not properly possible to appraise the economic performance of a specific hybrid technology, and provide a comparison with other hybrid technologies.

4.2. Energy storage

As noted previously, there are several options for energy storage in hybrid renewable energy desalination systems. That is, the available storage systems for hybrid renewable desalination systems can be classified into two main groups: thermal or electrical energy storage.

RO and ED are the major desalination technologies that operate primarily on electrical energy sources. The electrical energy required for these technologies can be provided by PVs, wind turbines, and wave or tidal energy conversion systems. As the produced energy by these technologies is intermittent, however, electrical energy storage systems should be employed to supply continuous power for desalination processes. By hybridizing these technologies for desalination purpose the generated energy from each technology can complement another one, thus there is a significant need to consider a proper storage system for such applications [14].

For solar stills, one of the simplest and most traditional desalination systems, increasing the depth of saline water is a convenient way to improve the thermal storage capacity. When this occurs, it increases the heat storage capacity resulting in continuous evaporation throughout cloudy hours and night time. Furthermore, there are several thermal storage materials that are normally used to enhance the productivity. These materials include sand, pebbles and sponges, quartzite rock, red brick, cement concrete, washed stones, and iron scraps.

Solar ponds represent a thermal desalination device that can collect and also store solar energy for later applications. In solar ponds, the bottom layer is the storage zone which has the maximum thickness with high concentration of salt uniformly distributed. The thickness of storage zone influences the magnitude of temperature variations in response to solar radiation [142]. The stored solar thermal energy in the lower zone of solar pond can provide continuous hear for other desalination devices such as hybrid solar pond-solar still desalination system.

Thermal energy storage systems are also used to store the produced heat in different types of solar collectors and concentrated solar power (CSP). This provides the possibility for reducing the mismatch between the demands and the energy that can be supplied by the sun [143]. Sensible heat and latent heat are two major and appealing types of thermal energy systems that are in advanced stage of development and utilization for solar collector applications. However, thermo-chemical storage systems, which are still in laboratory level, have shown to find promising applications in the future [144,145]. Sensible heat storage medium such as synthetic oil and molten salt are currently used in large-scale application of combined CSP-desalination systems. Such thermal energy storage systems should be designed depends on the size, type, and design of combined CSP-desalination system [144].

In summary, there are several factors that should be considered for sizing the thermal energy storage: (1) type of desalination technology, (2) availability and duration of the energy source, (3) heat capacity of the storage material, and (4) required storage duration. Optimizing the size of thermal energy storages is important in order to achieve a higher cost effective system. Oversizing increases the capital, operation and maintenance costs and it may result in energy waste [14].

4.3. Potential configuration for hybrid systems

Identifying a suitable hybrid renewable energy desalination system is contingent upon several factors such as potential and availability of renewable energy sources at particular location, size and capacity of desalination plant, feed water salinity, remoteness, economic consideration, etc. Some hybrid renewable energy desalination combinations are more suitable and applicable for large scale fresh water production while there are many other configurations that are more proper for small scale fresh water production. Hybrid PV/wind desalinations systems seem more applicable to meet larger scales fresh water demands while the hybrid systems that incorporated solar still, solar air heater, solar water heater or solar humidification-dehumidification are more suitable for small fresh water production capacities.

In order to design and implement hybrid renewable energy desalination systems several design steps should be carried out. The first task is to propose a list of possible hybridizations and configurations that can improve the performance in terms of productivity, reliability, and continuous water production, compared with a single renewable energy desalination system. The next step is to conduct a thorough design analysis of each possible hybrid system and configuration to identify the capacity, power (thermal or electrical) requirements, structure and size of renewable energy technologies and desalination units, and their operational features. The last step focuses on the economic and financial assessment of the selected hybrid renewable energy desalination system.

Optimizing hybrid renewable energy desalination in terms of a match of the output power of hybrid renewable energy system with the required energy for desalination process as well as the size of the systems and cost of fresh water production is one of the most challenging factors faced in the future development of such systems. In order to address the intermittent nature of renewable energy sources of solar, wind and ocean, one should consider combining one source with another one when their input profiles can complement each other. The use of different types of energy storage systems is another possibility that require careful consideration. Furthermore, combining intermittent renewable energy sources with non-intermittent renewable energy source, e.g., geothermal, is another option that should be addressed.

Hybrid solar-solar energy desalination systems are the most widely used hybrid renewable energy desalination systems because solar energy is abundantly available in most regions with lack of fresh water. Hybrid solar-wind and in particular hybrid PV/wind desalination has been widely used because of the complementary nature of solar and wind energy sources in many areas. However, depending on the previously mentioned factors the utilizations of other hybrid renewable energy desalination such solar-ocean, wind-ocean can be attractive.

From a feasibility view point, the following potential hybrid systems are suggested for future studies:

(1) Adsorption desalination (AD) is an appealing thermally driven method because of the possibility of generating two useful products: potable water, and a cooling effect, with only one thermal energy source. The energy generated by hybrid solar and geothermal energy sources can be utilized

as an input heat source for thermal desalination. Solar energy is available during the day, according to the specific climate conditions in a given site, while geothermal energy does not present variations by season. The available heat in CSP power plants (either exhaust gas in a Brayton power cycle or extraction or condensation steam in a Rankine power cycle) is an attractive source for thermal desalinization like AD. When a CSP plant is combined with a geothermal source, it could increase the performance and reliability of a system by continuous production of fresh water. Previous studies discussed that applications of hybrid solar-geothermal plants have been discussed in previous studies [146–149]. In this context, combination of parabolic trough collector (PTC) with geothermal sources represents a mature technology driving the AD. Thus, due to the co-generation capability of AD technology, this hybrid CSP-geothermal-AD system can provide three useful outputs of electricity, fresh water and cooling from small to large scales. Consequently, it is of particular significance to continue work on this topic by evaluating and optimizing the design and operational parameters as well as the economic factors.

(2) Vacuum membrane distillation (VMD) is another attractive alternative desalination that has attracted many investigators. VMD is considered as a hybrid desalination technology that combines the membrane and evaporative processes. VMD represents a desalination process that can use the low-grade waste heat from renewable energy sources such as solar and geothermal. Similar to AD technology, one major benefit of VMD process is that its performance is not significantly influenced by the high salinity of feed water. However, the energy requirement of VMD technology is high, and more than 98% of that is in the form of thermal energy. Therefore, a hybrid CSP-geothermal system can be designed to provide the thermal energy of the VMD. This can be accomplished as a co-generation plant by generating both electricity and fresh water.

5. Summary and conclusions

The utilization of renewable energy for desalination processes has been considered as a practical and technically feasible option to settle the stressing energy and fresh water issues. Despite the work of worldwide researchers, the share of renewable energy driven desalination is still very minimal. Hybridizing renewable energy systems for desalination provides the possibility for renewable energy systems to complement each other, and enhance the overall systems in terms of efficiency, reliability, flexibility, and economics.

Hybrid renewable energy systems can be used to drive the desalination process for several different reasons:

(1) To provide all thermal and electrical energy requirements of desalination technologies, and make the system autonomous,
(2) To improve the performance and productivity of the fresh water production by desalination technologies compared with a single energy source desalination system,
(3) To enhance the reliability and flexibility of the desalination unit for fresh water production and provide continuous production of fresh water as renewable energy sources such as solar, wind, and wave are intermittent.

As reviewed in this paper, several configurations of hybrid renewable energy based desalination have been suggested, designed, evaluated, and implemented. These hybrid systems were classified based on the used renewable energy sources and technologies as:

(1) Solar-wind desalination systems including hybrid PV/wind-RO systems, PV/wind-MVC, solar collector/wind-MED, and PV/wind/hydrogen-RO.
(2) Solar-solar desalination systems including solar stills-PV/RO, solar stills-PV/T, solar stills-solar air heater, solar water heater-PV, solar still-flat plate solar water heater, solar still-evacuated solar water heater, vertical multiple-effect diffusion solar still-heat pipe solar collector, single solar still-solar pond, solar water heater-solar air heater, solar water heater-PV, evacuated tube solar water heater-PV and parabolic trough solar collectors- PV.
(3) Solar-geothermal systems
(4) Solar or wind-ocean energy system consisting solar water heater-tidal and wind-wave.

Generally, it is not possible to determine and introduce the most appropriate hybrid renewable energy desalination system. In fact, determining the proper hybrid renewable energy desalination is dependent on several factors such as potential and availability of renewable energy sources at particular location, size and capacity of desalination plant, feed water salinity, remoteness, economic consideration, etc. Some hybrid renewable energy desalination combinations are more suitable and applicable for large scale while others are more appropriate for small scale fresh water production. This could be determined taking into account the aforementioned factors. Nevertheless, among reviewed systems, application of hybrid PV/wind desalinations systems seems more promising as solar and wind energy resources can complement each other increasing the availability and reliability of the system. Also, the system can be scaled up to meet larger scales fresh water demands. Further reduction in capital costs of PV modules and wind turbines would make such hybrid systems more attractive.

To further improve and promote the utilization of hybrid renewable energy desalination systems, we suggested two potential hybrid systems for future studies which were the combination of solar and geothermal energy sources with AD and VMD desalination technologies. These combinations are worth to be investigated in the future for the locations with accessibility of both solar and geothermal energy.

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