Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.808394

52 (2014) 4053–4070
June

Taylor & Francis
Taylor & Francis Group

Development strategies and solar thermal energy utilization for water desalination systems in remote regions: a review

A.E. Kabeel*, Emad M.S. El-Said

Mechanical Power Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt
Tel. +20 40 3453861(62); Fax: +20 40 3453860; email: kabeel6@hotmail.com

Received 16 August 2012; Accepted 30 April 2013

ABSTRACT

This paper reviews the current solar thermal desalination research activities with systems production in the range of 10–150 liter/day for remote or arid regions. A comparative study between different sustainable efforts in such solar thermal desalination systems as well as economics has been done. Throughout the review, the results indicated that most of the reviewed systems are in research stage and have not clear economical feasibility such as the price per cubic meter of water which may stimulates the decision-maker to direct these studies into the actual commercial applications. Also, the review showed that although many developed systems have several novel and valuable features, more efforts are required to further investigate more efficient, economical, and applicable solar thermal energy-driven desalination systems. Small production systems as solar stills and HDH can be used if fresh water demand is low and the land are available at low cost. The economical analyses carried out so far have not been able to provide a strong basis for comparing economic viability of each desalination technology. It is difficult, if not impossible, to assess the economic performance of a particular technology and compare it with others because of the differences of system capacities, locations, system technologies, and water sources.

Keywords: Solar energy; Solar thermal desalination; Remote regions

1. Introduction

The need of water is rising in many parts of the world due to domestic, agricultural, and industrial activities. The standard high-capacity desalination methods such as multi-stage flash (MSF) evaporation and multi-effect evaporation, vapor compression (VC) and reverse osmosis are reliable in the range of some 10,000–330,000 m^3/d fresh water productions are intensive energy techniques [1]. However, the wide-scale implementation of these methods face numerous technological, economical, and political barriers and they are not used in decentralized regions like islands and remote areas with a poor infrastructure due to their permanent need of qualified maintenance and electricity supply.

High-capacity desalination for industries and urban centers has become a marketable technology over the last three decades. At the same time, the marketplace has not inspired similar developments for small capacity desalination technologies for remote and arid areas, particularly, desalination units of solar

*Corresponding author.

driven [2]. Although the application of solar energy for water desalination requires a relatively large capital investment per unit of capacity but in properly designed and constructed systems, a minimum of operating and maintenance costs.

For example, solar stills are used to produce fresh water from brackish water by directly utilizing sunshine to supply the population of remote arid lands of South Algeria with drinkable water from of brackish waters. These stills represent the best technical solution to supply remote villages or settlements in South Algeria with fresh water without depending on high-tech and skills. The production capacity indicates a possible daily production of far more than 15 l/m^2/d. Small, modular high-performance stills with features like the possibility of decentralized use, less maintenance and robust construction can help to reduce fresh water scarcity [3].

Rajasthan, the largest state of the India, faces a grim scenario in relation to water availability resources. Based on the WHO guidelines for drinking-water quality about 56% of the water sources are unpotable. But on other hand, Rajasthan is blessed with ample amount of solar radiation. The arid parts of Rajasthan receive solar radiation about 4.6–7.5 kW h/m^2. Part of this energy may be utilized to meet out drinking water need of remote area dwellers of Rajasthan. Solar distillation and desalination unit is most appropriate for remote area dwellers because it is economical, easy to construct, and maintain. A low-cost high-efficiency solar still with porous evaporating surface is fabricated for distillation purpose of saline water in this state. The solar still is given about 15 l/d fresh water productivity. Water samples are collected from a remote village of state and analyzed to find the quality of drinking water [4].

Solar energy cannot compete favorably with fossil energy particularly under the present international market prices of crude oil. However, in many remote sunny areas of the world where the real cost of fossil energy can be very high, the use of solar energy can be an attractive alternative. A comparison of economics is performed using solar energy to operate small multiple effect seawater distillation systems in remote areas with the conventional method of using fossil fuels. The systems are to be considered for the coastal remote areas which are characterized by very high fuel costs and the unavailability of electricity from the national electrical grid [5].

Most of the high-capacity desalination units using technologies like (MSF) and (RO) facing many restrictions when applied for small family groups and remote or isolated regions, which have neither the infrastructure nor the economic resources to run these plants and which are sufficiently distant from high-capacity production facilities that pipeline distribution is prohibitive. So, the following limitations may be considered:

- Fossil-fuel dependence, these technologies required large amounts of energy in the form of thermal energy or electric power.
- Less applicable for decentralized water production.
- Require large quantities of energy, which normally results in a significant environmental impact if fossil fuels, are used (e.g. CO_2 and SO_2 emissions and thermal pollution of seawater).
- Cause environmental hazards because of the problem of brine disposal.
- The operating cost is high and also very closely linked to the price of energy.
- Require large installation areas and high initial investments.
- The cost of supplying water to such locations by trucks or ships or through pipelines is often quite high.

Several reviews and studies have been published by different authors about solar desalination units and its applications in arid regions [6–16]. Nevertheless, in this paper, we will discuss the features of the strategies, which have developed on desalination systems driven by thermal solar energy. The present review is classified based on main six development strategies such as system's technology, applicability of high-capacity thermal desalination technologies, solar heat collector's enhancement, technologies hybridization, solar heat storage and recovery processes, and sustainability assessment. A comparison between systems productivities and economical benefits will be done.

2. Specific requirements and implementation challenges of solar desalination systems in remote regions

For the successful operation in remote and rural locations of the desalination systems, in particular, the solar thermal energy-powered desalination systems should satisfy a number of specific requirements [17]:

- The capacity of these plants should be in the range of few hundred liters to approximately 10 tons per day and that require no qualified operators.
- They have to work in autonomous or quasi-autonomous mode.
- Recovery should be high and the consumption of water for supplementary needs (cooling and cleaning) should be small.

- They have to work in the minimum of operating and maintenance costs.
- The plant should be environmental friendly.
- The use of chemicals should be avoided and waste production should be small.

In addition to what has been asked of the specific requirements, there are many challenges facing the implementation of solar thermal desalination systems in remote regions must be considered as follow:

(i) The solar thermal energy collectors are not yet commercially realized. It should be noted that at lower operating temperatures, solar collectors have higher collection efficiency, owing to reduced losses, and also, can be designed to use less-expensive materials.
(ii) For low-capacity applications, the cost of water production systems is much higher than for high-capacity systems. For RO systems, which are currently the most economical desalination systems, the cost of water production can go up to 12 US$/$m^3$ for plants of smaller capacity [17].
(iii) Low-capacity units are not appropriate for domestic use because of higher space occupied by the equipment.
(iv) Sociocultural

- User perception of alternative practices and technologies.
- Local water use policy (for saline and product water).
- Traditional rights and beliefs concerning water.
- Community's individual's willingness to pay for the product water.
- Existing rights and obligations among members of a community.

So, in the next sections, we will discuss some of development strategies which may help to perform the requirements and face the implementation challenges of solar thermal desalination systems in remote regions.

3. Development strategies of solar thermal desalination systems

Solar desalination can be a suitable alternative, provided that efficient technologies are developed to utilize the solar energy in a cost-effective way. Solar energy can be used to produce fresh water directly in a solar still or indirectly where the thermal energy from a solar energy system is supplied to a desalination unit. A large number of researchers, institutes, and industries apply serious effort to develop and improve the performance of solar thermal energy-driven desalination units and make it highly desirable and applicable. Advancement's strategies in solar thermal desalination applications for different types of desalination systems reported in the last few years are briefly described and analyzed below, in particular, the traditional solar stills, desalination systems based on multi-effect humidification–dehumidification (MEH) and multi-effect desalination (MED).

3.1. System's technology

Solar desalination processes can be devised in two main types: direct and indirect collection systems. The "direct method" use solar energy to produce distillate directly in the solar collector, whereas in indirect collection systems, two sub-systems are employed (one for solar energy collection and the other one for desalination). The direct solar energy method uses a variety of simple stills, which are appropriate for very small water demands; indirect methods use thermal or electrical energy and can be classified as: distillation methods using solar collectors or membrane methods using solar collectors and/or photovoltaic for power generation. Solar thermal desalination units utilizing indirect collection of solar energy can be classified into the following categories: atmospheric humidification–dehumidification, MSF, multi-effect distillation (MED), VC, and membrane distillation (MD).

Yamaguchi and Sato [18] developed multi-effect solar distillation system by adopting decompressed boiling, as shown in Fig. 1. Various scaled solar stills using decompressed boiling were developed and studied to experimentally solve some problems for simultaneously keeping high performance and low cost, such as distillation vessels and heat exchangers cost and mist contamination into distilled water due to the pumping boiling. It is shown that the best design is the triple-effect still with solar panel of about 8 m^2 which produces of distilled water being 100 kg/d.

Kabeel [19] designed and constructed wick concave type solar still; a concave shaped wick surface increases an evaporation rate because the water surface level is lower than the upper limit of the wick surface as shown in Fig. 2. Results show that average distillate productivity in day time was 4.1 l/m^2 and the maximum instantaneous system efficiency was found to be 45% and the daily efficiency of the still was 30%. The maximum hourly yield was 0.5 l/h per m^2 after solar noon.

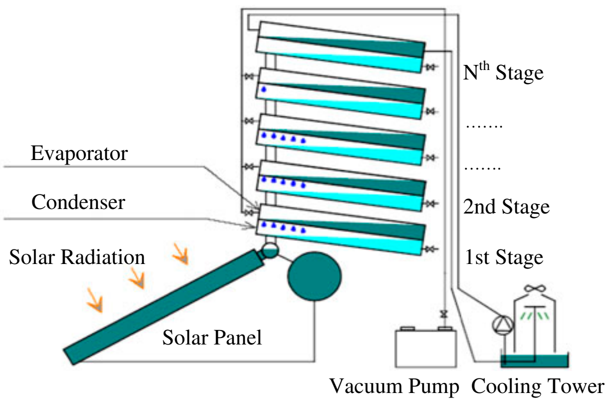

Fig. 1. Outline of newly designed multi-effect still [18].

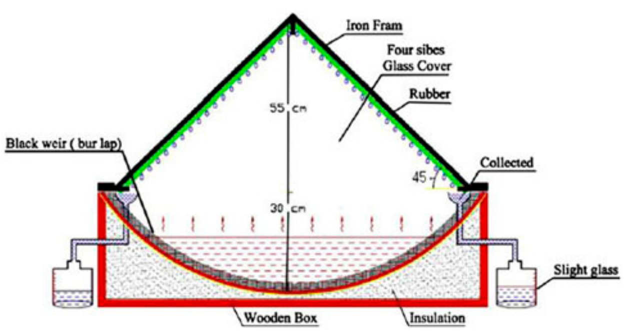

Fig. 2. Schematic diagram of concave wick solar still [19].

Eldalil [20] presented experimentally a new concept of active vibratory solar still as shown in Fig. 3. A flexible packed stretched media are installed in the bottom of the basin to increase the efficiency of the still. A vibratory harmonic effect is applied. The flexible packed media is formed from stretched helical coiled copper wires, and a vibrator (resonator) is installed in the middle of the system structure. The target of using the vibrator was to generate forced vibration to excite the flexible packed media to break the boundary layer and surface tension of the saline water and improve convective heat transfer and also to excite the condensed polycarbonate glass cover to assist the condensed droplets to slide down before it becomes bigger and possibly falls down in the basin. The productivity due to added backed helical wires was found to be 3.41/m² /d, with efficiency of about 35%, and the productivity with vibration is increased to be 5.81/m² /d and the average daily efficiency is about 60%. The nocturnal production ranges are found from 38 to 57%.

El-Zahaby et al. [21] investigated experimentally a new design of a stepped solar desalination system with flashing chamber, as shown in Fig. 4. The main objective of the investigation was to study the performance of stepwise water basin coupled with a spray water system by augmenting desalination productivity through using two air heaters. It is found that the productivity and performance of the system are significantly positive dependent on both inlet sea water temperature and the power consumed. They decrease with the increase in inlet impure water temperature. The maximum system productivity is reached about 71/m^2/d.

Abdel Dayem [22] constructed and tested a system of solar water desalination based on humidification–dehumidification process (Fig. 5). This system can produce about 361/d of purified water where the using of solar energy alone can obtain about 121 on clear days. The economic study was found that one liter of distilled water can cost about 0.2 US$.

Abu Arabi and Reddy [23] observed that lower molecular weight gases such as hydrogen and helium are preferable for higher heat transfer rates while higher molecular weight gases like carbon dioxide are more favorable with respect to mass transfer rates in these processes. So, they studied the performance evaluation for desalination processes through the humidification–dehumidification principle by using different carrier gases through modeling and simulation techniques. The carrier gas is circulated in these systems by natural convection, which is influenced by type of carrier gas employed, degree of saturation of carrier gas and difference in hot/cold or top/bottom temperatures. Different carrier gases besides air were used in the performance evaluation: hydrogen,

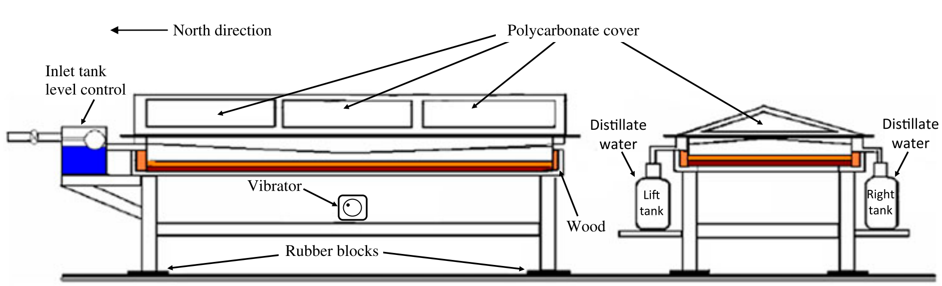

Fig. 3. Active solar still configurations [20].

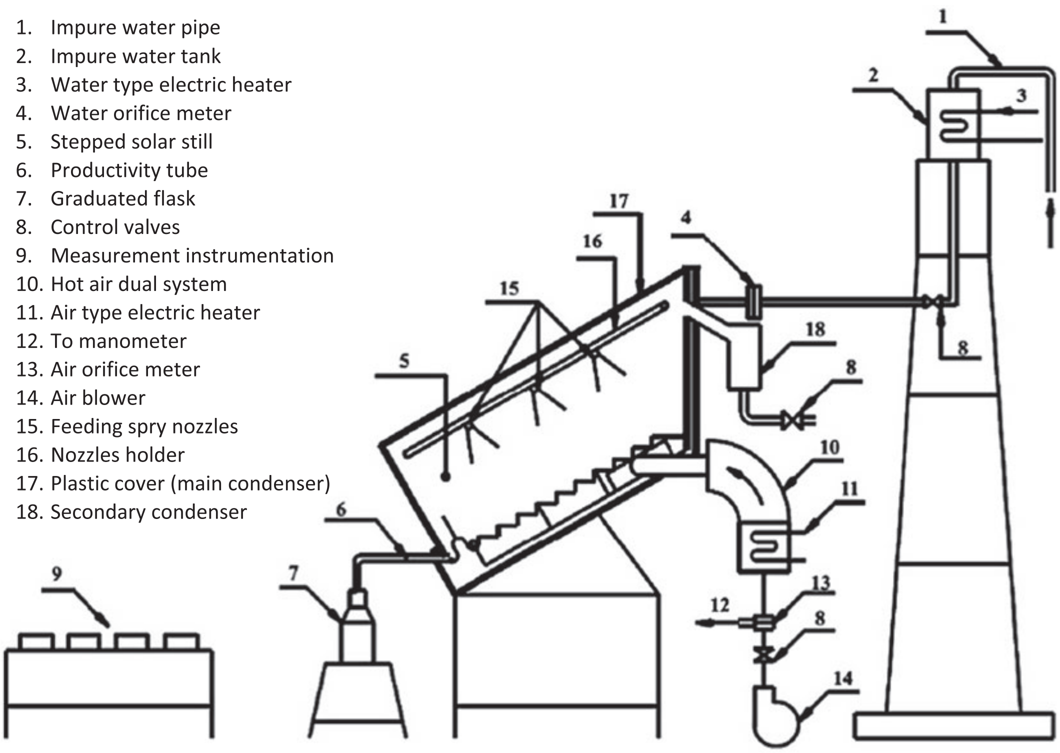

Fig. 4. Schematic diagram of the setup [21].

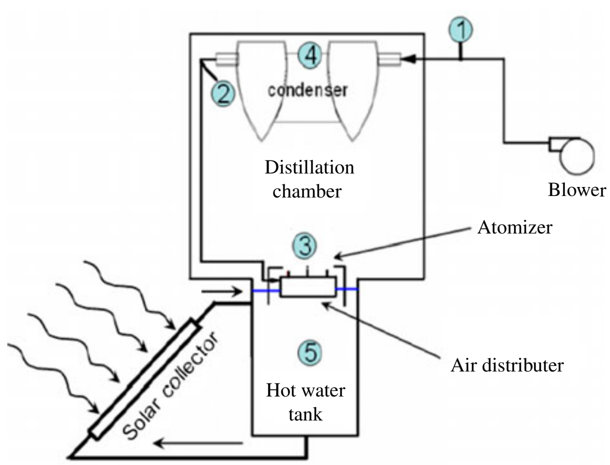

Fig. 5. Schematic diagram of the considered system [22].

helium, neon, nitrogen, oxygen, argon, and carbon dioxide. The results showed that using carbon dioxide as a carrier gas in desalination units based on the humidification–dehumidification principle is more effective to produce desalinated water under the same operating conditions taking into account both the heat and mass fluxes evaluated in them. Furthermore, it helps in reducing the calcium scale formation.

El-Shazly et al. [24] took another way to improve the performance of humidification–dehumidification desalination method by enhancement the mass and heat transfer rates and increase both process production and product quality by using pulsating flow. An experimental investigation was performed in humidification–dehumidification desalination unit consists of the main components (humidifier, dehumidifier, and solar water heater). The results showed that the unit productivity has been increased by increasing the off time, that is, decreasing the frequency of pulsed water flow up to certain levels, a frequency of 20/60 on/off time was found to have the highest productivity of the unit. Increasing the amplitude of water pulsation (water flow per pulse) was found to increase the unit productivity as well.

Rahbar and Esfahani [25] designed and tested experimentally a new type portable thermoelectric solar still (PTSS) as shown in Fig. 6. In the PTSS, a thermoelectric module is used to improve the temperature difference between evaporating and condensing zones. Also, a heat-pipe cooling device is used to cool down the hot side of the thermoelectric cooler. The results showed that ambient temperature and solar radiation have a direct effect on still performance but there is a reduction in water productivity by increasing the wind speed. The results also showed that temperature of thermoelectric device was lower than that of walls which indicated on the higher production of water. Thermoelectric solar still supposed that average

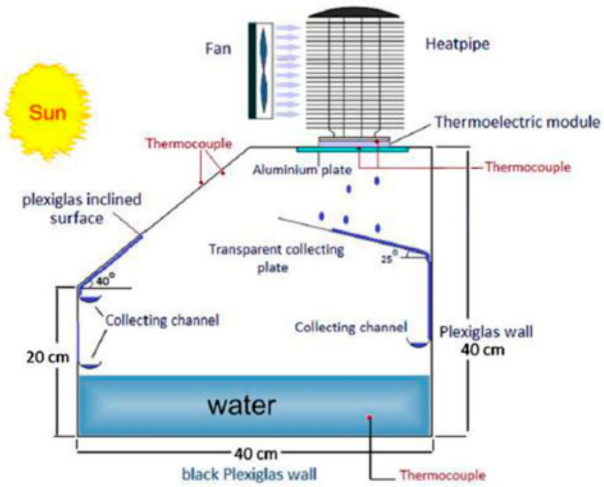

Fig. 6. A schematic diagram of the PTSS [25].

annual yield of fresh water was 180 l/m^2 with cost 0.18 $/l/m^2.

3.2. *Applicability of high-capacity technologies*

In concept, solar energy-based MSF and MED systems are similar to conventional thermal desalination systems. The main difference is that in the former, solar energy collection devices are used. Some proposals use centralized, concentrating solar power at a high receiver temperature to generate electricity and water in a typical large-scale co-production scheme [26].

Saad et al. [27] proposed and designed a new desalination system for converting sea water into fresh water utilizing the waste heat of internal combustion engines (Fig. 7). The desalination process is based on the evaporation of sea water under a very low pressure (vacuum). The low pressure is achieved by using the suction side of a compressor rather than a commonly used vacuum pump. The evaporated water is then condensed to obtain fresh water. The effects of operational variables such as evaporator temperature, condenser temperature, vacuum pressure, and flow rate of both evaporator and condenser on the yield of fresh water are experimentally investigated. It is found that decreasing the vacuum pressure causes a significant increase in the yield of fresh water. It is also found that decreasing the condenser temperature or increasing the evaporator temperature both lead to an increase in the yield of fresh water. Moreover, increasing the condenser flow rate tends to increase the yield of fresh water. The same trend is attained by increasing the evaporator flow rate.

Nafey et al. [28] investigated theoretically and experimentally a small unit for water desalination by solar energy and a flash evaporation process. The system consists of a solar water heater (flat-plate solar collector) working as a brine heater and a vertical flash unit that is attached with a condenser/pre-heater unit (Fig. 8). The average accumulative productivity of

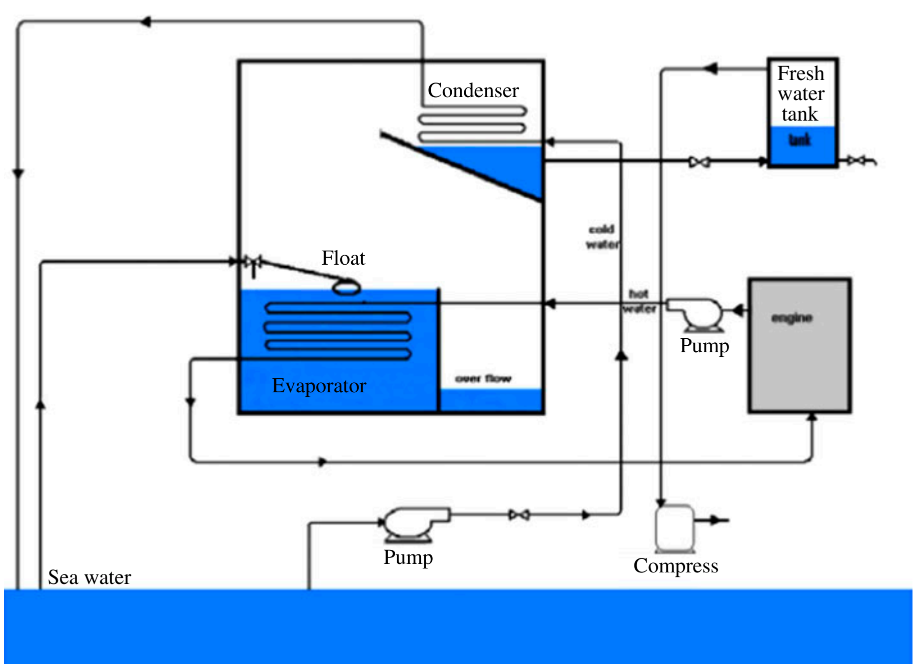

Fig. 7. Schematic diagram of desalination system [27].

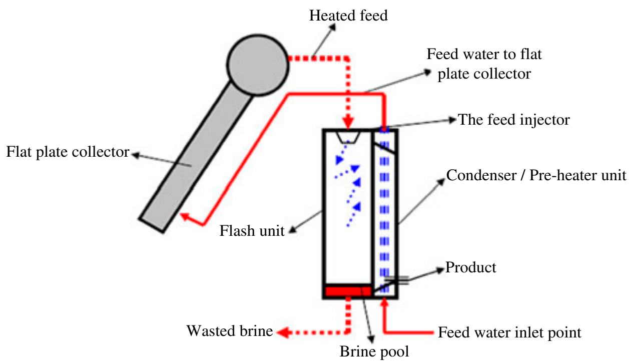

Fig. 8. A schematic diagram of the test rig [28].

the system in November, December, and January ranged between 1.04–1.45 kg/d/m^2. The average summer productivity ranged between 5.44–7 kg/d/m^2 in July and August and 4.2–5 kg/d/m^2 in June.

3.3. Solar heat collectors and concentrators enhancement

The solar collector is a convenient and common heater to be used as heat source for many applications such as domestic water heater and desalination purposes. However, the effectiveness of presently solar collector for low-capacity desalination units is low due to some reasons such as the limiting of the thermal conductivity of this working fluid and inefficiency and cost of solar radiation concentrators.

Several years ago, the nano-fluid has been found to be an attractive heat transport fluids. It has exhibited a significant potential for heat transfer augmentation relative to the conventional pure fluids. It has been expected to be suitable for the solar water heating systems without severe problems in pipes and with little or no penalty in pressure drop [29].

Yousefi et al. [30] investigated experimentally the effect of Al_2O_3/water nano-fluid, as working fluid, on the efficiency of a flat-plate solar collector using test rig as shown in Fig. 9. The weight fraction of nano-particles was 0.2% and 0.4%, and the particles dimension was 15 nm. The mass flow rate of nano-fluid varied from 1 to 31/min. The results showed that, in comparison with water as absorption medium using the nano-fluids as working fluid increase the efficiency. For 0.2 wt.%, the increased efficiency was 28.3%.

Compared to solar water heaters, high-temperature solar air heaters have received relatively little investigation and have resulted in few commercial products. However, in the context of a humidification–dehumidification desalination cycle, air heating offers significant performance gains for the cycle. Heating at a constant temperature and constant heat output is also important

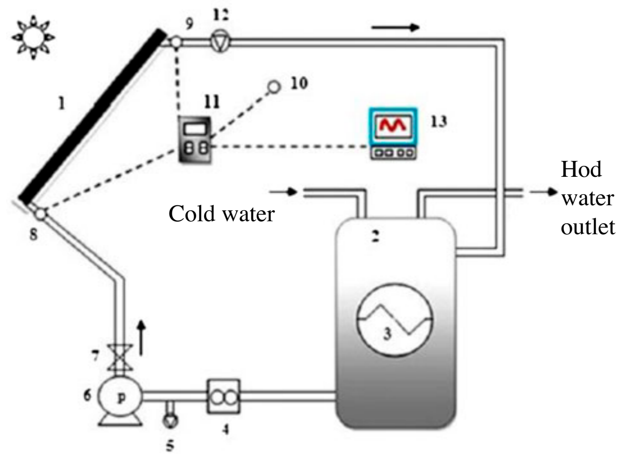

Fig. 9. The schematic of the experiment [30]. (1) Flat-plate solar collector (2) tank (3) heat exchanger (4) rotameter (5) drain (6) pump (7) line valve (8)–(11) thermometer (12) vacuum breaker and (13) computer.

for HDH cycle performance. The use of built in phase change material (PCM) storage is found to produce consistent air outlet temperatures throughout the day or night.

Lu et al. [31] designed an especial open thermosyphon device used in high-temperature evacuated tubular solar collectors as shown in Fig. 10. The indoor experimental research is carried out to investigate the thermal performance of the open thermosyphon using, respectively, the deionized water and water-based CuO nano-fluids as the working fluid. Experiment results show the optimal filling ratio to the evaporator is 60%, and the thermal performance of the open thermosyphon increases generally with the increase in the operating temperature. Substituting water-based CuO nano-fluids for water as the working fluid can significantly enhance the thermal performance of the evaporator and evaporating heat transfer coefficients may increase by about 30% compared with those of deionized water. The CuO nano-particles mass concentration has remarkable influence on the heat transfer coefficient in the evaporation section and the mass concentration of 1.2% corresponds to the optimal heat transfer enhancement.

Abdelkader [32] designed and installed a new multi-effect humidification–dehumidification solar desalination system coupled with solar central receiver (Fig. 11). The system has been out door tested. The heat collection part of the system (central receiver with 28 heliostats around it in three circles) has been designed to provide the hot water to the desalination chamber. The experimental test results showed that, increase in seawater mass flow rate from 0.07 to 0.091/s increases the productivity of the system by

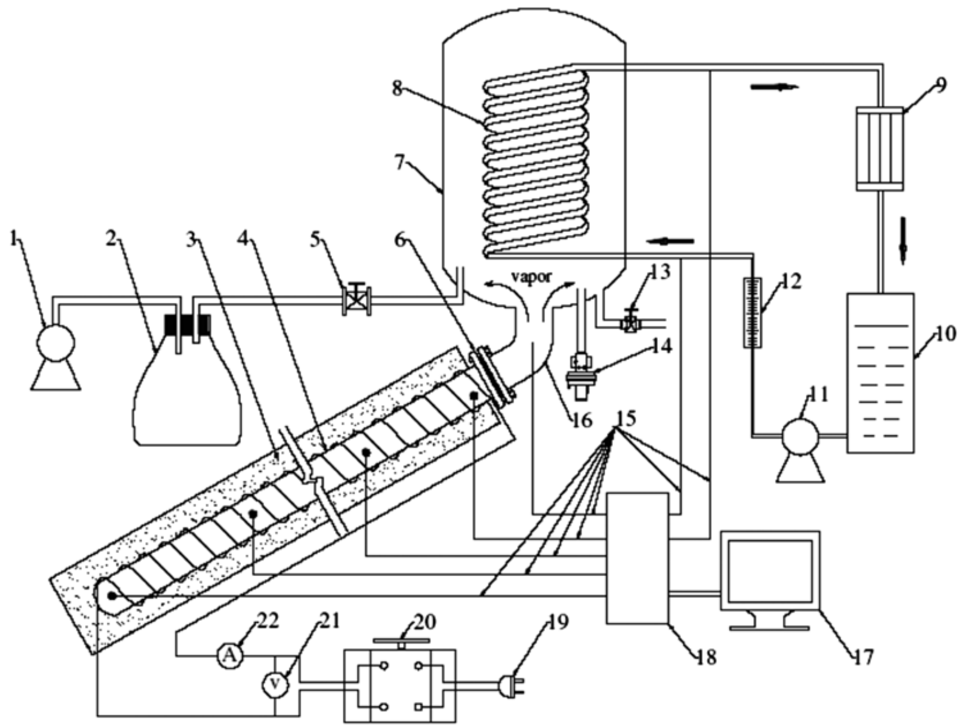

Fig. 10. Schematic of experimental apparatus [31]. (1) Vacuum pump (2) regulators box (3) thermal insulator (4) evaporator tube (5) vacuum valve (6) flange plate (7) condenser box (8) condensing coil (9) heat exchanger (10) water tank (11) pump (12) rotameter (13) water valve (14) relief valve (15) thermocouples (16) elbow tube (17) computer (18) data acquisition system (19) DC power supply (20) transformer (21) voltmeter and (22) ammeter.

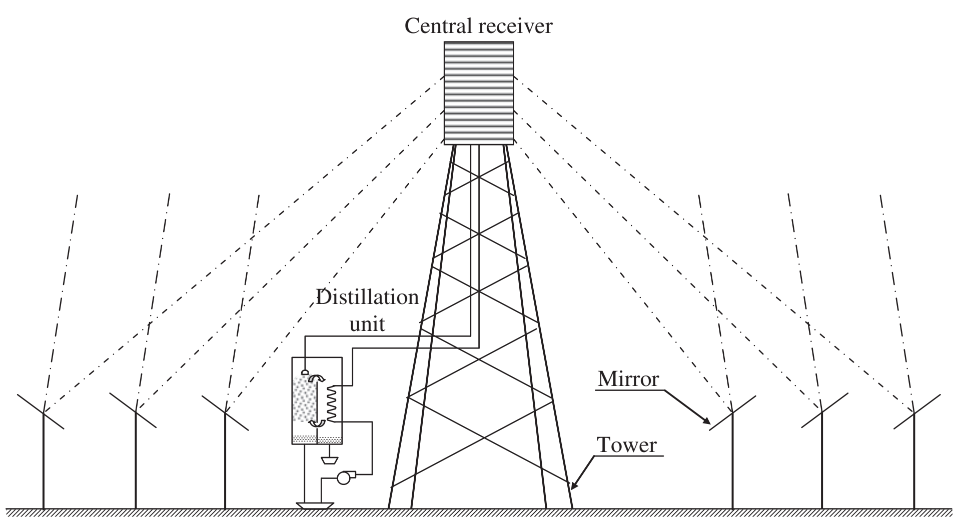

Fig. 11. Schematic diagram of the test rig [32].

10%. Seven flat mirrors are used to concentrate solar radiation on one side of the humidifier tower to heat the humid air. The test results showed that the use of the concentrate solar radiation increases the system productivity by 12%.

Summers et al. [33] implemented numerically and experimentally a PCM layer of 8 cm (paraffin wax) directly below the absorber plate of a solar air heater. It is found that a collector thermal efficiency of 35%. Some benefits may become from this device at the cost of thermal conversion efficiency requiring large collector areas for small heat outputs and have the potential to increase the cost of desalination system. If the cost of such a system can be reduced, then this device has the potential to enhance the solar-driven humidification–dehumidification distillation cycle by eliminating transients and warm up time associated with other system components by maintaining the top temperature of the system at an optimal operating temperature, thereby increasing overall system performance and water production.

Zuo et al. [34] set up a small-scale experimental device for solar chimneys integrated with sea water desalination (abbreviated in integrated system) as shown in Fig. 12. The performance studied based on the practical weather condition. The integrated system can achieve simultaneously the multi-targeted production indeed, such as power and freshwater. The main period of the distilled water output is during the absence of solar irradiance, but the minimum output is during the period of the strong radiance. Compared to the solo solar chimney power generation system, the integrated system would significantly improve the utilization efficiency of the solar energy.

Riffat and Mayere [35] presented experimentally the working principle and thermal performance of a new V-trough solar concentrator as shown in Fig. 13. Compared with the common parabolic trough solar concentrators, the new concentrator has two parabolic troughs which form a V-shape with the focal line at the bottom of the troughs. This is beneficial for the installation and insulation of the receiver, and the shadow on the reflective surface is avoided. The new V-trough collector does not require high precision tracking devices and reflective material. And therefore researchers are expected that the cost of the system could be significantly reduced. The collector is incorporated with an insulated water tank with coil heat exchanger. The water in the tank was heated up to 100˚C and the overall efficiency of the solar collector system reached 38%. The new V-trough solar collector is the most expected in the near future to be a promising technology for small- to medium-scale solar-powered water desalination.

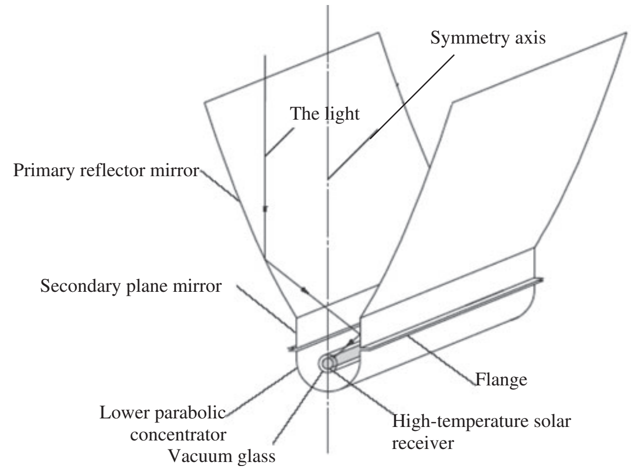

Fig. 13. Schematic of the new v-trough solar collector [35].

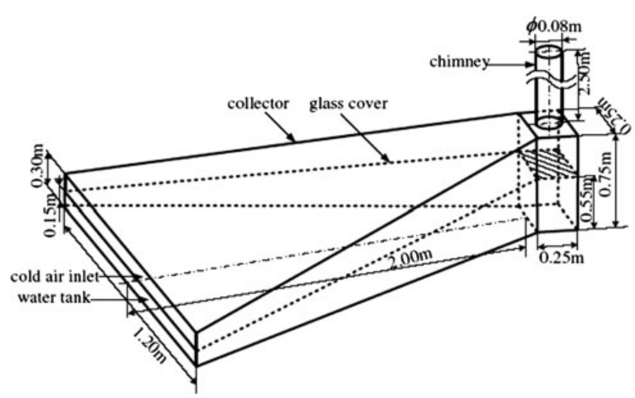

Fig. 12. Dimensions of the integrated system [34].

3.4. Technologies hybridization

In present days, there is a very important subject in the desalination field called "hybrid desalination." Hybrid desalination system is a combination of two or more processes or technologies in order to provide a better cost-effective product, allow a better match between power demand and water requirements and optimum combination of the features of the two processes than either alone can provide. There are two possible options for hybridization system, simple hybridization and integrated hybridization [36].

Hou and Zhang [37] presented a hybrid solar desalination process of the multi-effect humidification–dehumidification and the basin-type unit. Fig. 14 sketches the hybrid solar desalination process. The solar evacuated tube collector is employed in the desalination system, multi-effect humidification–dehumidification desalination (HDH) process is plotted according to pinch technology, and then, the water rejected from multi-effect HDH process is reused to desalinate in a basin-type unit further. The system gained a high-energy recover rate, and the gain output ratio (GOR) of this system was rose by 2–3 at least through reusing the rejected water.

Voropoulos et al. [38] investigated a solar desalination system consisting of a "greenhouse"-type conventional solar still coupled with a solar collector field

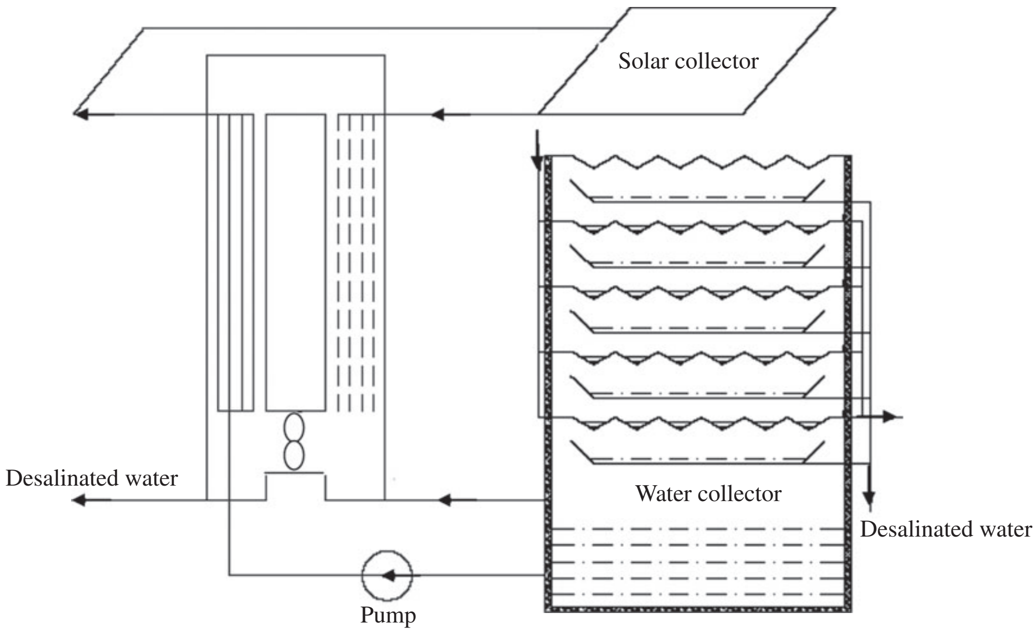

Fig. 14. Hybrid solar desalination process sketch [37].

and hot water storage tank (Fig. 15). It was shown that the model previously developed was capable of estimating long-term distilled water production with deviation not higher than 3% for any considered period. The results showed that draw-off of hot water volume equal to 1/4, 1/2, or 1 tank volume reduces distilled water output by 36, 57, or 75%, respectively. It was found that the output of a conventional solar still can be significantly increased if it is coupled with a solar collector field and hot water storage tank.

Kabeel and El-Said [1] presented a novel hybrid solar desalination system consisting of a humidification–dehumidification unit and single-stage flashing evaporation unit (Fig. 16). The hybrid solar desalination system is studied theoretically for different operating and weather conditions. The results showed that the studied hybrid desalination system gives a significant operational compatibility between the air humidification–dehumidification and flash evaporation desalination processes with daily water production up to 32.56 kg.

3.5. Solar heat storage and recovery

Thermal energy storage can be stored as a change in internal energy of a material as sensible heat, latent heat, and thermochemical or combination of these [39]. For solar desalination process, thermal energy storage has an important function to ensure the availability of energy at night or the next day. It has always been one of the most critical components in solar applications. Solar radiation is a time-dependent energy source with

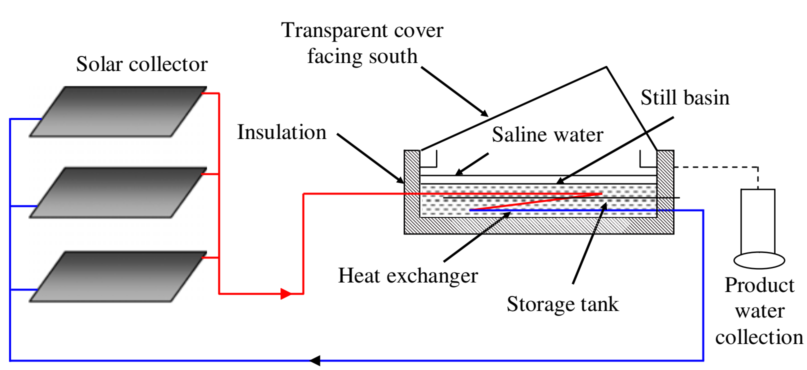

Fig. 15. Schematic diagram of the experimental solar desalination and water heating system [38].

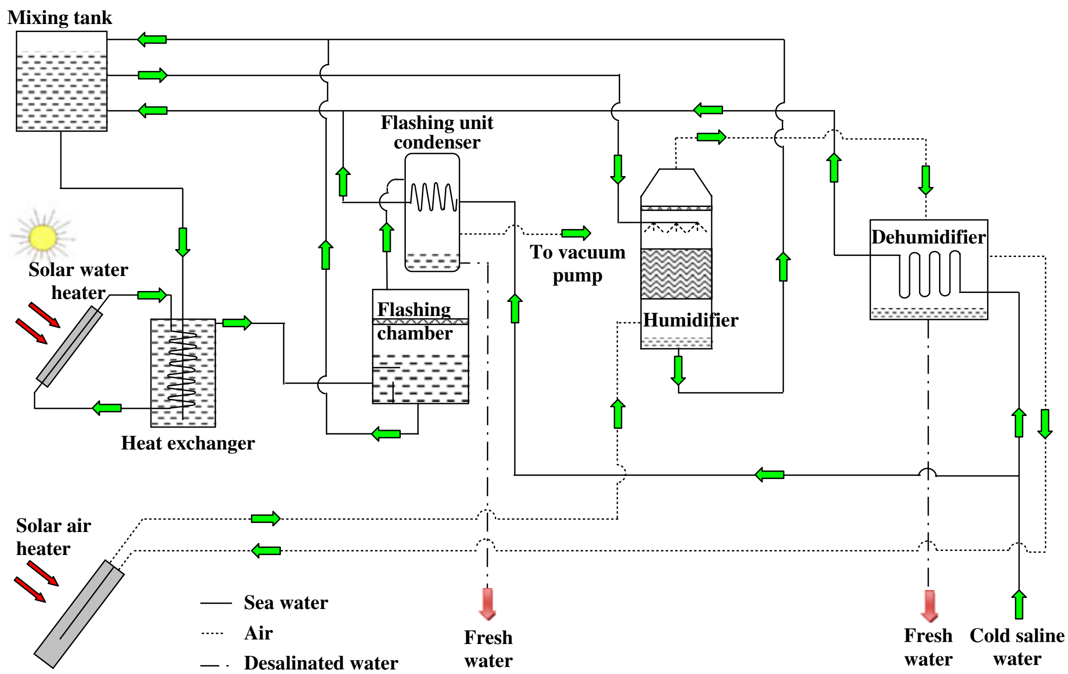

Fig 16. Schematic diagram of (HDH/SSF) system [1].

an intermittent and dynamic character. Thermal energy storage provides a reservoir of energy to adjust the energy needs at all times. It is used as a bridge to cross the gap between the energy source, the sun, and the desalination unit. Many small desalination systems are still built without any energy recovery. Thermal solar systems are different in that its recovery ratios must be high as possible. In practice, it is possible to reduce this greatly by re-using the heat from the condenser to heat new feed water, as is done in large-scale thermal desalination plants: MED, MSF, and VC. Furthermore, it must be stressed that this is heat energy, which is usually much less expensive than electrical or mechanical energy.

Miyatake et al. [40] developed a hybrid latent heat storage and spray flash evaporation desalination system in an attempt to present an energy saving desalination system that stores intermittent thermal energy such as waste heat, solar heat, or heat from the surplus steam of a rower station at night and utilizes the stored energy not only for the generation of process steam form seawater for industries and domestic air conditioning but also for the production of fresh water from the generated steam for industrial and domestic uses on demand (Fig. 17). Experimental results of the transient discharge characteristics of the heat storage column racked with the PCM and the transient spray flash evaporation showed that by using the numerical results of the discharge characteristics and the empirical equation of the efficiency of spray flash evaporation, the amount of generated steam and produced water can be predicted with sufficient accuracy. The

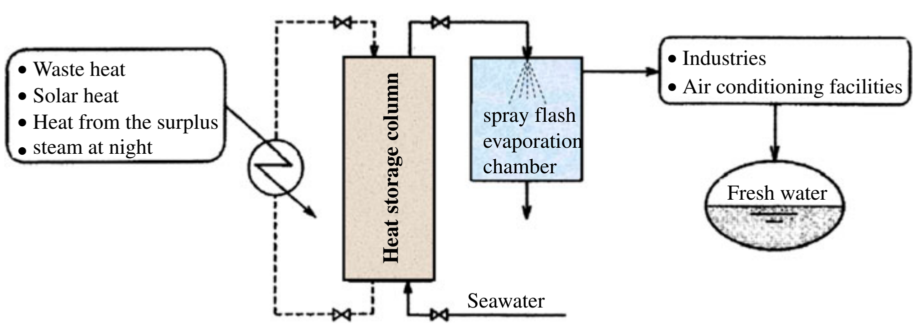

Fig 17. Schematic illustration of hybrid system [40].

utilization of more than 95% of the amount of stored energy for the generation of process steam and the production of fresh water, substantiated experimentally, confirms the high efficiency of the hybrid system.

Gude et al. [41] designed a low-temperature desalination process capable of producing 100 L/d freshwater to utilize solar energy harvested from flat-plate solar collectors as shown in Fig. 18. Since solar insolation is intermittent, a thermal energy storage system was incorporated to run the desalination process round the clock. Results from this theoretical study confirm that thermal energy storage is a useful component of the system for conserving thermal energy to meet the energy demand when direct solar energy resource is not available. Based on an economic analysis on the desalination system with thermal energy storage (interest rate 5%, life time 20 years and plant availability of 90%), the costs for the desalinated water are determined to be 14 $/m^3 for desalination system with thermal energy storage tank system.

A comparative study of solar energy storage systems based on the latent heat and sensible heat technique has been carried out to preserve the solar heated hot water for night duration such as PCMs. For this purpose, D. Vikram et al. [42] studied the feasibility of storing solar energy using PCMs. The system consists of two simultaneously functioning heat-absorbing units. One of them is a solar water heater and the other a heat storage unit consisting of

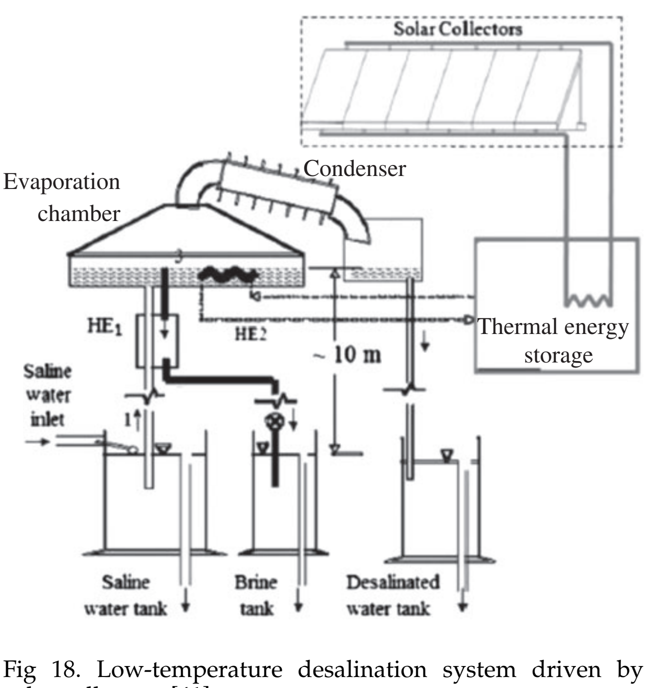

Fig 18. Low-temperature desalination system driven by solar collectors [41].

PCM (paraffin). The water heater functions normally and supplies hot water during the day. The storage unit stores the heat in PCMs during the day supplies hot water during the night. The storage unit utilizes small cylinders, made of aluminum, filled with paraffin wax as the heat storage medium. It also consists of a solar collector to absorb solar heat. At the start of the day, the storage unit is filled with water completely. This water is made to circulate between the heating panel (Solar collector) and the PCMs. The water in the storage unit receives heat form the heating panel and transfers it to the PCM. The PCM undergoes a phase change by absorbing latent heat, excess heat being stored as sensible heat. Using parabolic mirrors accelerates the charging of the tower. The water supply in the night is routed to the storage unit using a suitable control device. The heat is recovered from the unit by passing water at room temp through it. As water is drawn from the storage tower, fresh water enters the unit disturbing the thermal equilibrium, causing flow of heat from PCM to the water.

Ben Bacha et al. [43] investigated the behavior of a distillation module of a desalination unit coupled with hot water storage tank heated by a solar collector field, in order to increase productivity of the desalination unit. The desalination plant consists of a solar unit, which provides the thermal energy, and a desalination module that uses multi-effect humidification to treat the brackish water. The corresponding system scheme presented in Fig. 19 is an illustration of the unit components along with the description of the different modes (daytime and night time/storage mode). The main components of solar unit are flat-plate collector field, conventional insulated heat storage tank, and heat exchanger. The results showed that the main improvement in the solar desalination unit efficiency can be reached by continuous operation. This measure prevents thermal losses during standstill periods and low efficiency periods restarting the system. Twenty-four hour operation can be realized by an extended collector field combined with a hot water storage tank.

Schwarzer et al. [44] presented an experimental laboratory water tests and numerical simulation for a solar thermal desalination unit with a heat recovery system. The two basic system components are as follows: a flat-plate collector and a desalination tower. The desalination tower is made of six stages and a water circulation system through the stages to avoid salt concentration. The numerical results calculated using ambient data showed that the production rate can reach 25 l/m^2/d. Because of the heat recovery process, this unit can reach a higher thermal perfor-

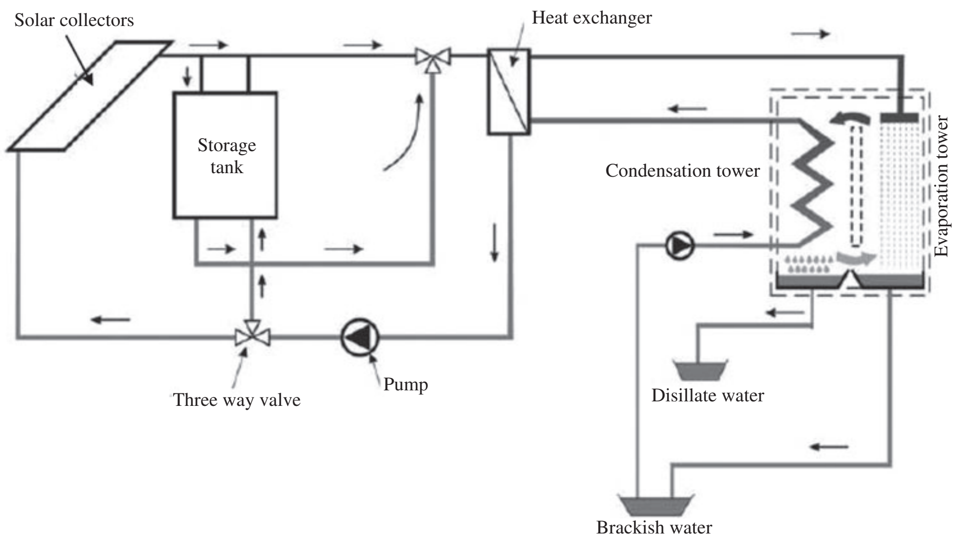

Fig 19. Principle scheme of the desalination unit coupled with solar collectors and storage tank [43].

mance than the conventional still-type solar distiller. Also, there is a continuous water flow through the stages of the unit avoiding salt accumulation. The disadvantage is the higher installation cost when compared to the still-type unit. The water chemical test results for two types of water (polluted seawater and well water) before and after the desalination process indicated the good quality of the water produced.

Schwarzer et al. [45] developed a new solar thermal desalination system with heat recovery as shown schematically in Fig. 20. The system has two components: a desalination tower with multiple stages and one or more solar collectors. The solar collectors are used to absorb solar energy, and a fluid, the desalinated water itself, transports the heat energy to the

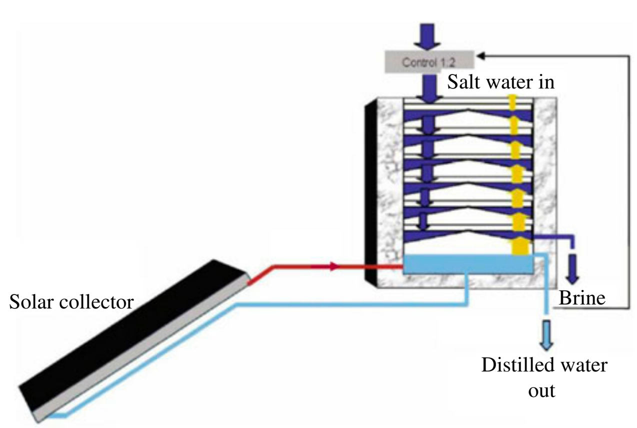

Fig 20. Schematic of the solar desalination system, with heat recovery [45].

tower. The field tests showed some important results: the system produces about 15–18 $l/m^2/d$, which represent a factor of 5–6 times higher than the production of a still-type distiller. The system uses multiple condenser stages and arranged vertically one over the other. Each stage recovers heat of condensation from the vapor produced in the stage directly below. The condensate drains on the tilted condenser surface and moves through flow channels to be collected in a tank. The multiple heat recovery of the evaporation enthalpy leads to a much higher production of desalinated water per m^2 of solar collector, when compared to the still-type distiller. Depending on the number of condenser stages, the production rate can be increased by a factor of 3–4. Depending upon solar radiation, a daily output rate of 10–17 l of drinking water per m^2 of collector area can be reached.

Bouchekima et al. [46] experimentally and theoretically developed desalination system applicable in units of less than 1 m^3/d of flesh water production (Fig. 21). It concerns a new solar thermal desalination system with heat recovery. This type of distiller called the capillary film distiller. It is made up of identical evaporation–condensation cells. The brine to be evaporated is a thin film impregnating a fabric assumed to be very thin and adhering by capillarity forces to the wall of the plate. Its advantage resides in the recovery of latent heat of steam condensed in one stage for water evaporation in the subsequent stage.

Hu et al. [47] studied a new approach for improving the performance of HDH cycle with direct-contact condensation. The proposed condenser utilizes spherically encapsulated PCM elements as a packing med-

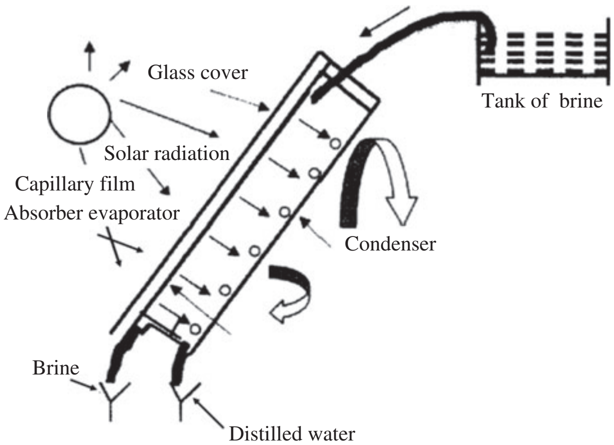

Fig 21. Principle of capillary film distiller [46].

ium while applying forced convection. Fundamental variables and critical parameters affecting the system performance such as the effect of condenser geometrical aspect ratio, packing size, air to water mass flow rate ratio, PCM thermal properties, and the effect of different types of packing media were studied. It can be realized that productivity factor, and NTU are highly influenced by the variation of water to air mass flow rate ratio. The optimum water to air mass flow ratio lays around 1.5.

3.6. Sustainability assessment

The sustainability assessment of a desalination plant should focus on resources, environmental, social and economic considerations of the desalination plant as the following (adapted from [48]):

- Resource indicators: Fuel-amount of fuel per m^3 of desalinated water, kg_{fuel}/m^3. Materials amount of material used in construction of the plant per m^3 of desalinated water, kg_{fuel}/m^3.
- Environmental indicators: Environmental indicators comprise reflection of the environmental pollutants produced by the desalination plant.
- Economic indicator is defined as a unit cost of desalinated water, US$/$m^3$. The cost will include capital cost, operation and maintenance cost, and fuel cost.

Since, to achieve economical and environmental sustainability for desalination, the following challenges must be addressed (adapted from [49]):

(1) Using renewable energy sources, such as solar power, for desalination can contribute greatly to achieving sustainability, reducing the carbon footprint, and transforming the local economy to knowledge-based production with proper R&D incentives and support to small local businesses.
(2) Adopting a decentralized system of smaller desalination plants should be pursued in order to (a) increase the overall availability, (b) reduce transport, leakages, and associated distribution system costs, and (c) ensure water security through multiple unit availability.
(3) Governments should design incentives for local businesses to attract investments in manufacturing locally key components of the desalination plants. This can be achieved by initially assisting local manufacturers produce in accordance with international quality standards and by forcing turnkey contractors to procure locally.
(4) Governments should support local start-ups and investments in knowledge-based sectors of the economy in order to cultivate innovation locally and to attain economic sustainability in strategic industries such as desalination and solar energy.

So, in this section, we will mention several researchers efforts made to achieve sustainability assessments in desalination units.

Fath et al. [50] achieved an autonomous desalination unit not required external electrical power supply by developing a stand-alone system based on MD technology (Fig. 22). The unit is self operating using a PV panel to run the feed pump and solar collectors to heat up the feed water. Condensation energy is recovered in the condenser channel of the membrane to preheat the feed water. The results indicated that the unit produces about 11.2 l/d for every square meter of collector area.

Chen et al. [51] designed, constructed, and field tested a new four-stage distillation unit with triple-effect regeneration based on the mechanism of falling film evaporation condensation as shown in Fig. 23. 1 kW wind turbine power is installed to provide electricity for pumps. The field testing and monitoring of the system had been carried out under the real weather condition for two years. The water production of the system for per unit of solar collector area could reach up to more than 12 $kg/m^2/d$ under the fine weather conditions. Water production of the system was stable in long period and the annual production could reach to 250 tons. The cost of water production is estimated approximately 4.6 $/ton for the 15-year service life.

Ahsan et al. [52] presented a detail comparison of the, fabrication, cost, and water production analysis

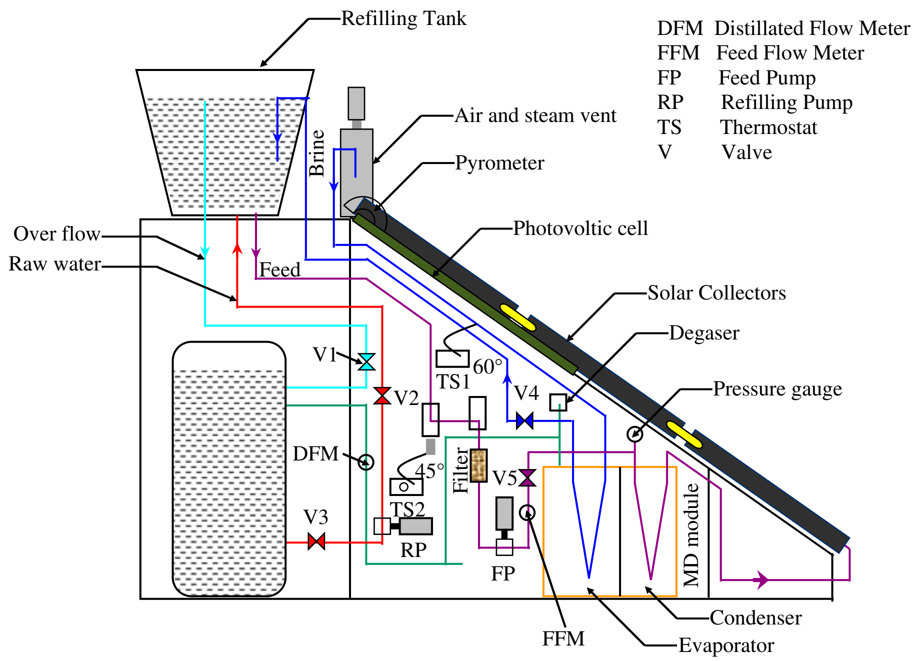

Fig. 22. Flow diagram of MD compact system [50].

between an old tubular solar still (TSS) and improved (new and sustainable) one. The design of new one of TSS is shown in Fig. 24. Since the cover material, a vinyl chloride sheet, of the old TSS was a little bit heavy, expensive and cannot be formed into a desirable size easily; a highly durable polythene film was adopted as the cover of the new TSS. The new TSS is made of cheap and locally acquisitioned light weight materials. Consequently, the weight and cost of the new TSS were noticeably reduced and the durability was distinctly increased. The fabrication cost of a new TSS is as cheap as 2.52 US$, which is about 7% of that of the old TSS. The researchers are expected that the fabrication cost will be reduced by at least one-third in developing countries. The daily water production capacity of the old and new TSSs is almost the same (5 kg/m^2/d). The cost of fresh water production using the new TSS is about 9.56 US$/m^3, which is about 5% of that of the old TSS.

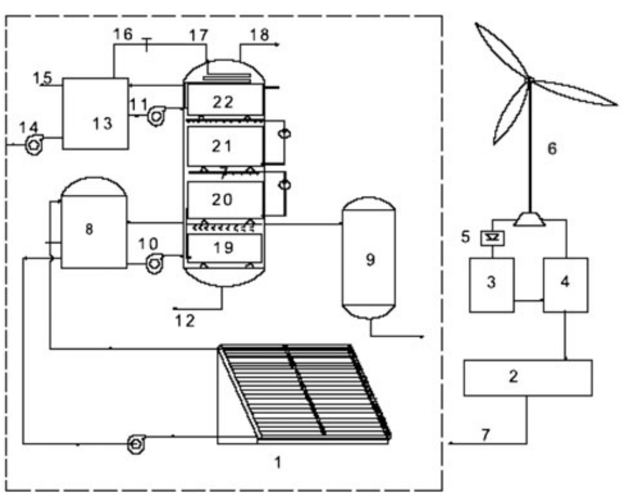

Fig. 23. Practical desalination system driven by nature energy source, [51]. (1) Solar collector (2) control system (3) battery (4) inverters (5) one-way controller (6) wind power installation (7) electricity (8) hot water tank (9) fresh water tank (10) heating water (11) cooling water (12) discharging concentrated seawater (13) seawater tank (14) seawater inlet (15) water overflow (16) flowmeter (17) seawater pipe (18) vacuum pump (19) evaporator (20) first stage evaporator–condenser (21) second-stage evaporator–condenser and (22) Condenser.

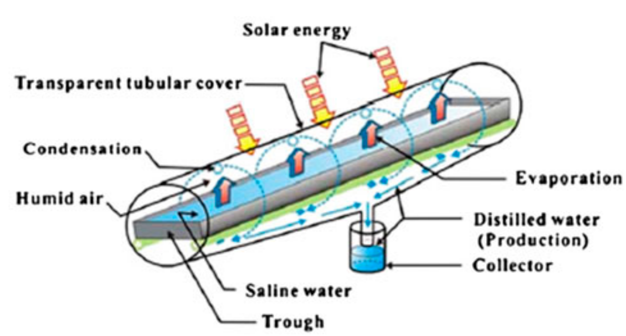

Fig. 24. Potable water production principle in new TSS [52].

Table 1
Water production cost for selective solar thermal desalination systems

Technology	Capacity (m^3/day)	Cost (\$/m^3)	Feed water type	Location	Year	References
MED	100	8.3–9.3	S.W.	UAE	2001	[3]
HDH	0.012	200	Not known	Egypt	2011	[11]
Thermoelectric solar still	6×10^{-5}	21.6	Not known	Iran	2012	[14]
MED	0.96	0.0046	S.W.	China	2012	[51]
TSS	2.45×10^{-4}	9.56	Not known	Japan	2012	[52]
Multi-effect still	10	28.8	B.W.	Germany	2001	[53]
Membrane desalination	0.5	18	B.W.	Jordan	2007	[54]
Membrane desalination	0.1	15	B.W.	Jordan	2007	[54]
Direct contact membrane distillation	Not known	12.	S.W.	UAE	2012	[55]
Air gap membrane distillation	Not known	18.26	S.W.	UAE	2012	[55]
Vacuum membrane distillation	Not known	16.02	S.W.	UAE	2012	[55]
Membrane desalination	0.017	13	B.W.	Tunisia	2005	[56]
Vacuum distillation	0.1	14	S.W.	USA	2012	[41]

Cost analysis of desalination systems usually aims to estimate the cost of a liter or a cubic meter of fresh water and calculates the contribution of each cost item to the total cost. This identifies immediately the most significant cost items and attracts the attention to what should first be examined for possible improvement and cost reduction. In general, cost factors associated with implementing a desalination plant are site specific and depend on several variables. Table 1 presents the list of water production cost for low-capacity solar thermal desalination plants along with a summary of features of these plants.

The economic analyses in Table 1 are carried out to provide a strong basis for comparing economical viability of each desalination technology. The economic performances expressed in terms of cost of water production have been based on different system capacity, locations, system technologies, and water source. These differences make it difficult, if not impossible, to assess the economical performance of a particular technology and compare it with others.

4. Conclusions

This review paper is focused on available solar thermal desalination systems for the use in rural areas based on their technologies, heat source, recovery and storage, optimization, and sustainability has been presented in this study. Solar thermal desalination based on most of presented techniques has not yet to be commercially implemented. Small production systems as solar stills and HDH can be used if fresh water demand is low and the land is available at low cost. To supply the population of remote arid lands with drinkable water, solar distillation of brackish waters is recommended. More attention should be paid to the applicability of high-capacity thermal desalination technologies in small scale needs, especially which have high efficiency such MSF, MED, and VC. The solar water heating applications of nano-fluids have received comparatively little attention in current researches activates. Using of PCM in saline water, desalination applications can improve the efficiency of heat absorption or releasing in distillation towers and solar collectors. It is difficult, if not impossible, to assess the economic performance of a particular technology and compare it with others because the differences system capacity, locations, system technologies, and water source.

Acronyms and abbreviations

BW	—	brackish water
GOR	—	gain output ratio
HDH	—	humidification–dehumidification
MD	—	membrane distillation
MED	—	multi-effect distillation
MEH	—	multi-effect humidification–dehumidification
MSF	—	multi-stage flash
NTU	—	number of transfer units
PCM	—	phase change material
PV	—	photovoltaic
PTSS	—	portable thermoelectric solar still
RO	—	reverse osmosis
SSF	—	single-stage flashing
SW	—	seawater
TSS	—	tubular solar still
WHO	—	World health organization
VC	—	vapor compression

References

[1] A.E. Kabeel, Emad M.S. El-Said, A hybrid solar desalination system of air humidification–dehumidification and water flashing evaporation: Part I. A numerical investigation, in: Proceedings of the 16th International Water Technology Conference, Istanbul, Turkey, 2012.

[2] J. Ayoub, R. Alward, Water requirements and remote arid areas: The need for small-scale desalination, Desalination 107 (1996) 131–147.

[3] B. Bouchekima, A small solar desalination plant for the production of drinking water in remote arid areas of southern Algeria, Desalination 159 (2003) 197–204.

[4] R.K. Khanna, R.S. Rathore, C. Sharma, Solar still an appropriate technology for potable water need of remote villages of desert state of India – Rajasthan, Desalination 220 (2008) 645–653.

[5] A.M. El-Nashar, The economic feasibility of small solar MED seawater desalination plants for remote arid areas, Desalination 134 (2001) 173–186.

[6] R. Saidur, E.T. Elcevvadi, S. Mekhilef, A. Safari, H.A. Mohammed, An overview of different distillation methods for small scale applications, Renew. Sustain. Energy Rev. 15 (2011) 4756–4764.

[7] M. Tauha Ali, H.E.S. Fath, P.R. Armstrong, A comprehensive techno-economical review of indirect solar desalination, Renew. Sustain. Energy Rev. 15 (2011) 4187–4199.

[8] M.A. Eltawil, Z. Zhengming, L. Yuan, A review of renewable energy technologies integrated with desalination systems, Renew. Sustain. Energy Rev. 13 (2009) 2245–2262.

[9] C. Li, Y. Goswami, E. Stefanakos, Solar assisted seawater desalination: A review, Renew. Sustain. Energy Rev. 19 (2013) 136–163.

[10] M.T. Chaibi, An overview of solar desalination for domestic and agriculture water needs in remote arid areas, Desalination 127 (2000) 119–133.

[11] A.M.K. El-Ghonemy, Fresh water production from/by atmospheric air for arid regions, using solar energy: Review, Renew. Sustain. Energy Rev. 16 (2012) 6384–6422.

[12] A.E. Kabeel, S.A. El-Agouz, Review of researches and developments on solar stills, Desalination 276 (2011) 1–12.

[13] K. Sampathkumar, T.V. Arjunan, P. Pitchandi, P. Senthilkumar, Active solar distillation – a detailed review, Renew. Sustain. Energy Rev. 14 (2010) 1503–1526.

[14] S. Parekh, M.M. Farid, J.R. Selman, S. Al-Hallaj, Solar desalination with a humidification–dehumidification technique – a comprehensive technical review, Desalination 160 (2004) 167–186.

[15] H.M. Qiblawey, F. Banat, Solar thermal desalination technologies, Desalination 220 (2008) 633–644.

[16] H.Ş. Aybar, H. Assefi, A review and comparison of solar distillation: Direct and indirect type systems, Desalination 10 (2009) 321–331.

[17] The Middle East Desalination Research Center, The Small Solar MED Desalination Plant, MEDRC Series of R&D Reports, MEDRC Project: 98-AS-024a, Muscat, Sultanate of Oman, 2004.

[18] Y. Yamaguchi, H. Sato, Multi-effect solar distillation system using decompressed boiling, Forum on Desalination using Renewable Energy, 14–15 March, 2003, Saga, Japan, pp. 187–194.

[19] A.E. Kabeel, Performance of solar still with a concave wick evaporation surface, Energy 34 (2009) 1504–1509.

[20] K.M.S. Eldalil, New concept for improving solar still performance by using vibratory harmonic effect experimental prediction, in: Part 1, 13th International Water Technology Conference, 2009, Hurghada, Egypt.

[21] A.M. El-Zahaby, A.E. Kabeel, A.I. Bakry, S.A. El-agouz, O.M. Hawam, Augmentation of solar still performance using flash evaporation, Desalination 257 (2010) 58–65.

[22] A.M. Abdel Dayem, Pioneer solar water desalination system: Experimental testing and numerical simulation, Energy Sci. Technol. 1 (2011) 33–48.

[23] M.K. Abu Arabi, K.V. Reddy, Performance evaluation of desalination processes based on the humidification–dehumidification cycle with different carrier gases, Desalination 156 (2003) 28l–293.

[24] A.H. El-Shazly, A.A. Al-Zahrani, Y.A. Alhamed, S.A. Nosier, Productivity intensification of humidification–dehumidification desalination unit by using pulsed water flow regime, Desalination 293 (2012) 53–60.

[25] N. Rahbar, J.A. Esfahani, Experimental study of a novel portable solar still by utilizing the heat pipe and thermoelectric module, Desalination 284 (2012) 55–61.

[26] F. Trieb, Concentrating solar power for seawater desalination, in: Proceedings of the Fourth Middle East-North Africa Renewable Energy Conference, Damascus, Syria, 2007.

[27] M. Saad, M. Ahmed, V.M. Morcos, Performance analysis of a vacuum desalination system, in: Proceedings of the ASME International Mechanical Engineering Congress & Exposition, Denver, Colorado, USA, 2011.

[28] A.S. Nafey, M.A. Mohamad, S.O. El-Helaby, M.A. Sharaf, Theoretical and experimental study of a small unit for solar desalination using flashing process, Energy Conv. Manage. 48 (2007) 528–538.

[29] W. Daungthongsuk, S. Wongwises, A critical review of convective heat transfer of nano-fluids, Renew. Sustain. Energy Rev. 11 (2007) 797–817.

[30] T. Yousefi, F. Veysi, E. Shojaeizadeh, S. Zinadini, An experimental investigation on the effect of Al_2O_3–H_2O nanofluid on the efficiency of flat-plate solar collectors, Renew. Energy 39 (2012) 293–298.

[31] L. Lu, Z.-H. Liu, H.-S. Xiao, Thermal performance of an open thermosyphon using nanofluids for high-temperature evacuated tubular solar collectors Part 1: Indoor experiment, Solar Energy 85 (2011) 379–387.

[32] M. Abdelkader, Investigation of multi-effect humidification (MEH) –dehumidification solar desalination system coupled with solar central receiver. In: The Second International Conference on Water Resources & Arid, Environment, 2006.

[33] E.K. Summers, M.A. Antar, J.H. Lienhard, Design and optimization of an air heating solar collector with integrated phase change material energy storage for use in humidification–dehumidification desalination, Solar Energy 86 (2012) 3417–3429.

[34] L. Zuo, Y. Yuan, Z. Li, Y. Zheng, Experimental research on solar chimneys integrated with seawater desalination under practical weather condition, Desalination 298 (2012) 22–33.

[35] S. Riffat, A. Mayere, Performance evaluation of v-trough solar concentrator for water desalination applications, Appl. Therm. Eng. 50 (2013) 234–244.

[36] L. Awerbuch, Hybridization and dual purpose plant cost considerations, in: Proceedings of the MEDRC International Conference on Desalination Costing, Cyprus, 2004.

[37] S. Hou, H. Zhang, A hybrid solar desalination process of the multi-effect humidification–dehumidification and basin-type unit, Desalination 220 (2008) 552–557.

[38] K. Voropoulos, E. Mathioulakis, V. Belessiotis, A hybrid solar desalination and water heating system, Desalination 164 (2004) 189–195.

[39] A. Sharma, V.V. Tyagi, C.R. Chen, D. Buddhi, Review on thermal energy storage with phase change materials and applications, Renew. Sustain. Energy Rev. 13 (2009) 318–345.

[40] O. Miyatake, Y. Koito, K. Tagawa, Y. Maruta, Transient characteristics and performance of a novel desalination system based on heat storage and spray flashing, Desalination 137 (2001) 157–166.

[41] V. Gnaneswar Gude, N. Nirmalakhandan, S. Deng, A. Maganti, Low temperature desalination using solar collectors augmented by thermal energy storage, Appl. Energy 91 (2012) 466–474.

[42] D. Vikram, S. Kaushik, V. Prashanth, N. Nallusamy, An improvement in the solar water heating systems using phase change materials, in: Proceedings of the International Conference on Renewable Energy for Developing Countries, 2006.

[43] H. Ben Bacha, T. Dammak, A.A. Ben Abdalah, A.Y. Maalej, H. Ben Dhia, Desalination unit coupled with solar collectors and a storage tank: Modeling and simulation. Desalination 206 (2007) 341–352.

[44] K. Schwarzer, M.E. Vieira, C. Faber, C. Müller, Solar thermal desalination system with heat recovery, Desalination 137 (2001) 23–29.

[45] K. Schwarzer, E.V. Silva, B. Hoffschmidt, T. Schwarzer, A new solar desalination system with heat recovery for decentralised drinking water production, Desalination 248 (2009) 204–211.

[46] B. Bouchekima, B. Cros, R. Ouahes, M. Diboun, Brackish water desalination with heat recovery, Desalination 138 (2001) 147–155.

[47] T. Hu, A.H. Hassabou, M. Spinnler, W. Polifke, Performance analysis and optimization of direct contact condensation in a PCM fixed bed regenerator, Desalination 280 (2011) 232–243.

[48] N.H. Afgan, M. Darwish, M.G. Carvalho, Sustainability assessment of desalination plants for water production, Desalination 124 (1999) 19–31.

[49] A.A. Bushnak, Desalination; Arab Environment Water—Sustainable Management of a Scarce Resource, Report of the Arab forum for Environment and Development, 2010.

[50] H.E.S. Fath, S.M. Elsherbiny, A.A. Hassan, PV and thermally driven small scale, stand alone solar desalination system with very low maintenance needs, in: Proceedings of the 10th International Water Technology Conference, Alexandria, Egypt, 2006, pp. 249–263.

[51] Z. Chen, G. Xie, Z. Chen, H. Zheng, C. Zhuang, Field test of a solar seawater desalination unit with triple-effect falling film regeneration in northern China, Solar Energy 86 (2012) 31–39.

[52] A. Ahsan, M. Imteaz, A. Rahman, B. Yusuf, T. Fukuhara, Design, fabrication and performance analysis of an improved solar still, Desalination 292 (2012) 105–112.

[53] J. Rheinlaender, F. Graeter, Technologies for desalination of typically 10 m^3 of water per day, Desalination 139 (2001) 393–397.

[54] F. Banat, N. Jwaied, Economic evaluation of desalination by small-scale autonomous solar-powered membrane distillation units, Desalination 220 (2008) 566–573.

[55] R.B. Saffarini, E.K. Summers, H.A. Arafat, J.H. Lienhard, Economic evaluation of stand-alone solar powered membrane distillation systems, Desalination 299 (2012) 55–62.

[56] S. Bouguecha, B. Hamrouni, M. Dhahbi, Small scale desalination pilots powered by renewable energy sources: Case studies, Desalination 183 (2005) 151–165.