JSER

Journal of Solar Energy Research (JSER)

Journal homepage: www.jser.ut.ac.ir

A Review of Solar Energy Driven HDH and Solar Still Desalination Technologies

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ARTICLE INFO

Received: 19 Aug 2017
Received in revised form: 31 Aug 2017
Accepted: 2 May 2017
Available online: 5 Oct 2017

Keywords:
solar energy, solar distillation systems, solar still, solar HDH

A B S T R A C T

World-wide water scarcity, especially in the developing world, indicates a pressing need to develop inexpensive, decentralized small-scale desalination technologies which use renewable resources of energy. Major desalination processes consume a large amount of energy derived from oil and natural gas as heat and electricity, while emitting harmful CO2. Solar desalination has emerged as a promising renewable energy-powered technology for producing fresh water. One of the innovative methods for decentralized low-scale purification of water is the humidification dehumidification (HDH) desalination technology. Combining the principle of humidification-dehumidification with solar desalination results in an increase in the overall efficiency of the desalination plant. Solar still is an ideal source of fresh water for both domestic and agricultural aspects. It is one of the most important viable applications of solar energy.
In this review the operated desalination of solar stills and HDH units; their operating principle; advantage and disadvantage has been extensively reviewed.

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1. Introduction

More than two-thirds of the earth's surface is covered with water. Most of the available water is either present as seawater or icebergs in the Polar Regions. More than 97% of the earth's water is salty; rest around 2.6% is fresh water. Less than 1% fresh water is within human reach. As the available fresh water is fixed on earth and its demand is increasing day by day due to increasing population and rapid advancement of industry, there is an essential and earnest need to get fresh water from the saline/brackish water present on or inside the earth. Fresh water from saline/ brackish water can be obtained using different water treatment processes.

Water consumption in the world is used for irrigation (70%), industrial purposes (20%) and domestic use (10%) for drinking and cleaning. The installed capacity of water desalination systems by the beginning of millennium was about 22 million m3/day and has increased to 71.7 million m3/day in ten years which requires roughly 650 million tons of oil annually if only the oil is to be used for heating salt water [1].

Conventional desalination plants operated by fossil fuel has also contributed to greenhouse gas (GHG) emissions. This has forced researchers to look for alternate way of powering desalination units by renewable energy [2].

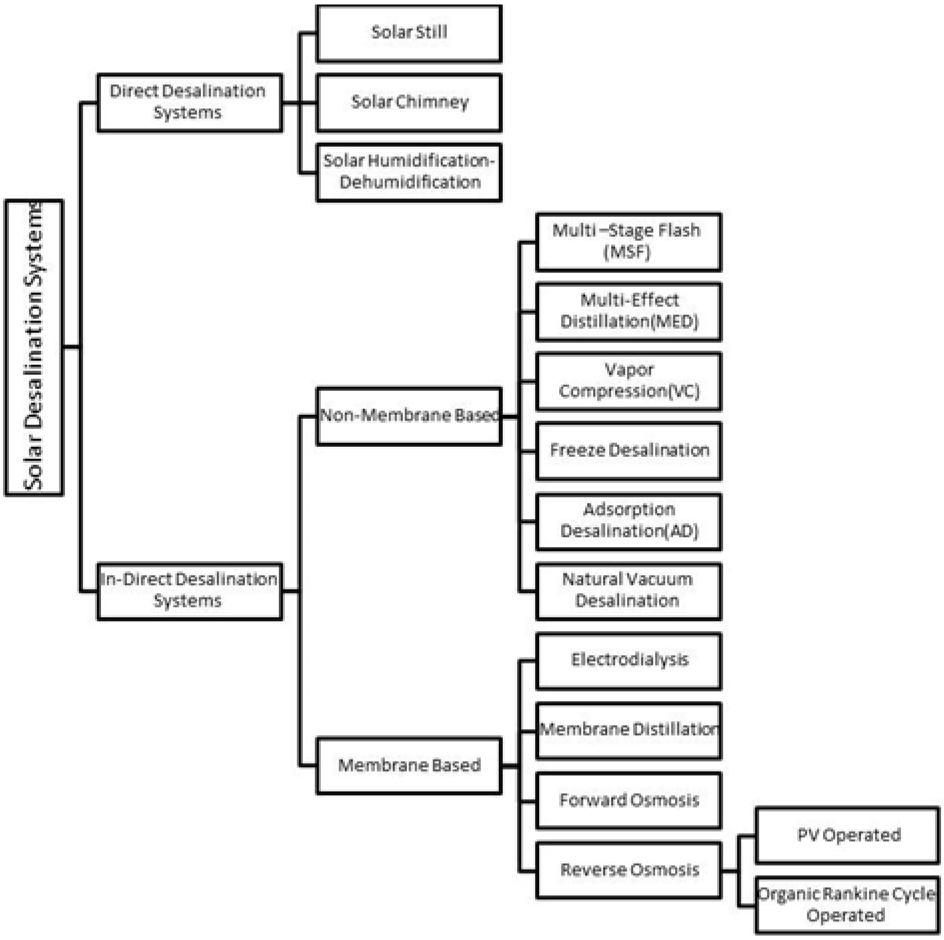

Figure 1. Classification of solar desalination systems

Renewable energy commonly considered for desalination are solar, wind and geothermal and among these solar energy occupies nearly 57% of renewable energy based desalination market [3]. Fossil fuel rich countries like Middle East and Arab Nations have turned their attention towards solar energy with the aim to provide desalinated water in an sustainable way [9]. Renewable energy based desalination units are highly suitable for arid, semiarid and remote regions where no other mode of power supply is possible [10]. Most of the desalination systems require thermal and/or electrical input that can be provided by solar energy and hence much focus has been given to solar based systems. The solar thermal collectors are very well developed [11] and now attention has been paid towards solar PV cells to reduce its cost and increase its efficiency there by considerable reduction in water production cost could be achieved. The classification of solar desalination systems is shown in Figure 1.

There are two types of solar desalination with two ways of using solar energy as directly or indirectly. Solar energy, collected from solar radiation, can be used directly to heat salty water in order to produce fresh water which is low cost and practical especially for small scale applications. They have low operation temperature and vapor pressure which make their production output less than their indirect counterparts.

Two main types of direct desalination technique are HDH method and solar stills. In this paper the operated desalination of solar stills and HDH units; their operating principle; pros and cons has been extensively reviewed.

2. Desalination Technologies

2.1. Conventional desalination technologies

Desalination of seawater or brackish water is generally performed by either of two main processes: by evaporation or by use of a semi-permeable membrane to separate fresh water from a concentrate. In the phase-change or thermal processes, the distillation of seawater is achieved by utilizing a heat source. The heat source may be obtained from a conventional fossil fuel, nuclear energy or from a non-conventional source like solar energy or geothermal energy. In the membrane processes, electricity is used either for driving high-pressure pumps or for establishing electric fields to separate the ions.

The most important commercial desalination processes [2] based on thermal energy are multi-stage flash (MSF) distillation, multiple effect distillation (MED) and vapor compression (VC), in which compression may be accomplished thermally (TVC) or mechanically (MVC). The MSF and MED processes consist of many serial stages at successively decreasing temperature and pressure. The MSF process is based on the generation of vapor from seawater or brine due to a sudden pressure reduction (flashing) when seawater enters an evacuated chamber. The process is repeated stage-by-stage at successively decreasing pressures.

Condensation of vapor is accomplished by regenerative heating of the feed water. This process requires an external steam supply, normally at a temperature around 100°C. The maximum operating temperature is limited by scale formation, and thus the thermodynamic performance of the process is also limited. For the MED system, water vapor is generated by heating the seawater at a given pressure in each of a series of cascading chambers. The steam generated in one stage, or ‘‘effect,’’ is used to heat the brine in the next stage, which is at a lower pressure. The thermal performance of these systems is proportional to the number of stages, with capital cost limiting the number of stages to be used. In TVC and MVC systems, after vapor is generated from the saline solution, it is thermally or mechanically compressed and then condensed to generate potable water.

The second important class of industrial desalination processes uses membrane technologies. These are principally reverse osmosis (RO) and electro dialysis (ED). The former requires power to drive a pump that increases the pressure of the feed water to the desired value. The required pressure depends on the salt concentration of the feed. The pumps are normally electrically driven [3]. The ED process also requires electricity to produce migration of ions through suitable ion-exchange membranes [4]. Both RO and ED are useful for brackish water desalination; however, RO is also competitive with MSF distillation processes for large-scale seawater desalination.

The MSF process represents more than 90% of the thermal desalination processes, while RO process represents more than 80% of membrane processes for water production. MSF plants typically have capacities ranging from 100,000 to almost 1,000,000 m3/day [5]. The largest RO plant currently in operation is the Ashkelon plant, at 330,000 m3/day [6].

Other approaches to desalination include processes like the ion exchange process, liquid–liquid extraction, and the gas hydrate process. Most of these approaches are not generally used unless when there is a requirement to produce high purity (total dissolved solids <10 ppm) water for specialized applications.

Another interesting process which has garnered much attention recently is the forward osmosis process [7]. In this process, a carrier solution is used to create a higher osmotic pressure than that of seawater. As a result the water in seawater flows through the membrane to the carrier solution by osmosis. This water is then separated from the diluted carrier solution to produce pure water and a concentrated solution which is sent back to the osmosis cell. This technology is yet to be proven commercially.

2.1.1. Limitations of conventional technologies

Conventional processes like MSF and RO require large amounts of energy in the form of thermal energy (for MSF) or electric power (for RO). Most desalination plants using these technologies are fossil-fuel driven. This results in a large carbon footprint for the desalination plant, and sensitivity to the price and availability of oil. To avoid these issues, desalination technologies based on renewable energy are highly desirable.

Solar energy is the most abundantly available energy resource on earth. Solar desalination systems are classified into two main categories: direct and indirect systems. As their name implies, direct systems use solar energy to produce distillate directly using the solar collector, whereas in indirect systems, two sub-systems are employed (one for solar power generation and one for desalination). Various solar desalination plants in pilot and commercial stages of development were reviewed by [8].

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 coproduction scheme [9].

These solar 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.

Moreover, owing to their fossil-fuel dependence, conventional desalination techniques are less applicable for decentralized water production. Decentralized water production is important for

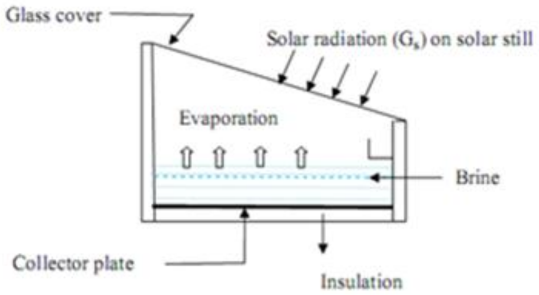

Figure 2. The schematic view of a single effect single slope basin type conventional passive solar still

regions which have neither the infrastructure nor the economic resources to run MSF or RO plants and which are sufficiently distant from large-scale production facilities that pipeline distribution is prohibitive. Many such regions are found in the developing world in regions of high incidence of solar radiation. The importance of decentralizing water supply was reviewed in detail by [10].

For small-scale applications (from 5 to 100 m3/day water production), the cost of water production systems is much higher than for large-scale systems. For RO systems, which are currently the most economical desalination systems, the cost of water production can go up to US$ 3/m3 [11] for plants of smaller capacity. Also, RO plants require expert labor for operation and maintenance purposes. This a clear disadvantage for small-scale applications in less developed areas, particularly when compared to the HDH system.

2.2. Solar still

Solar stills can easily provide enough water for family drinking and cooking needs. Solar stills the oldest device used for treating saline or impure water to provide drinking water to small, isolated communities. In Remote and arid locations where the conventional energy sources are costly and scarce, the demand for fresh water can be met by using solar stills. In locations where there is plenty of solar energy and where sources of brackish water are available, supplies of small amounts of fresh water can be produced at reasonable cost by solar stills. The first known use of stills dates back to 1551 when it was used by Arab alchemists. Other scientists and naturalists used stills over the coming centuries [1]. The first "conventional" solar still plant was built in 1872 by a Swedish engineer Charles Wilson in the mining community of Las Salinas in what is now northern Chile [2]. The basic principles of solar water distillation are simple, yet effective, as distillation replicates the way nature purifies water. The most conveniently used solar distillation system consist of simple passive solar stills shown in Figure 2. The sun's energy heats water to the point of evaporation. As the water evaporates, water vapor rises and condenses on the glass surface for collection. This process removes impurities such as salts and heavy metals, as well as destroys microbiological organisms. The end result is water cleaner than the purest rain water. But water is usually contaminated with chemical impurities and harmful organisms. The distilled water from the present solar stills does not acquire the “flat” taste of commercially distilled water since the water is not boiled (which lowers pH) because of the natural evaporation which is the rainwater process. Therefore, it is recommended to add small amounts of minerals or salts to the distilled water, since the minerals found in water may be healthy. Lost minerals can also be replaced by trickling the distilled water through a bed of marble chips [1]. Solar still can be easily fabricated using locally available materials and are easy to operate and maintain [3]. The productivity of fresh water by solar distillation depends drastically on the intensity of solar radiation and the sunshine time interval during the day [1]. Some researchers indicated that some parameters such as water mass [4], black dye [5], wind speed, insulation thickness [6] and installing booster mirrors [7] have an effect on the output of the solar stills.

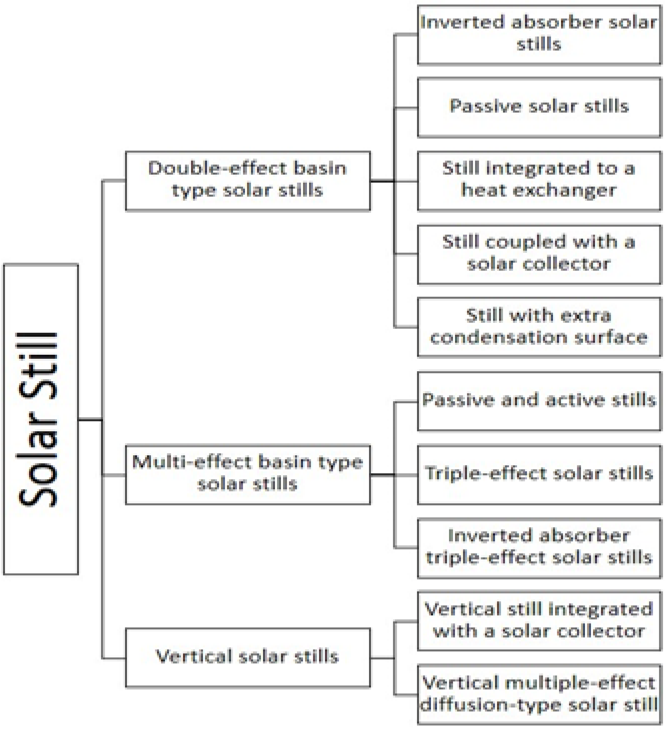

Figure 3. Classification of solar stills

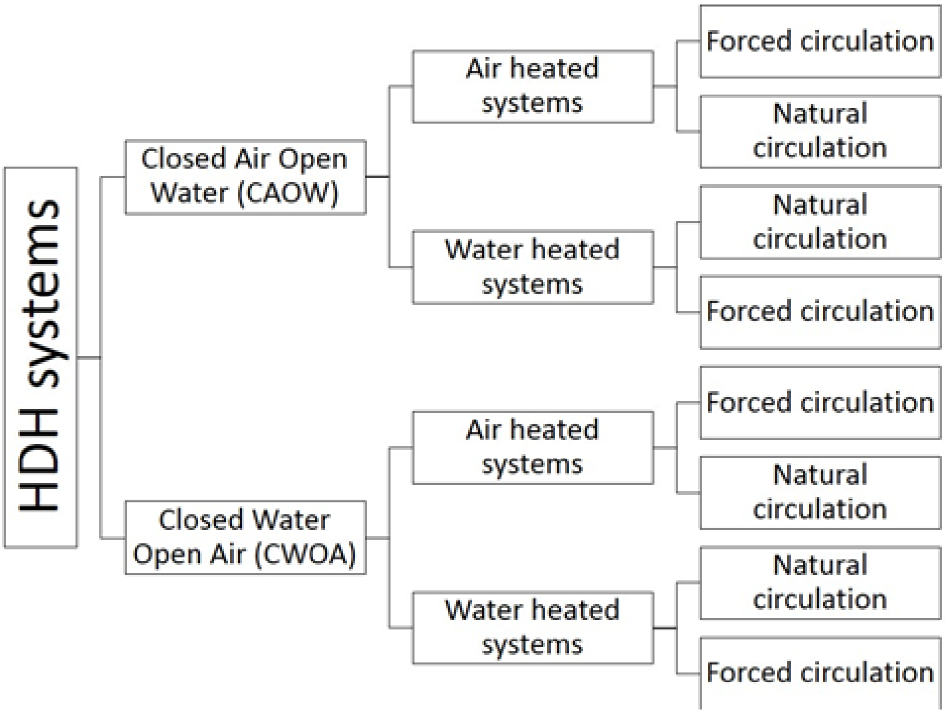

Figure 4. Classification of solar HDH systems

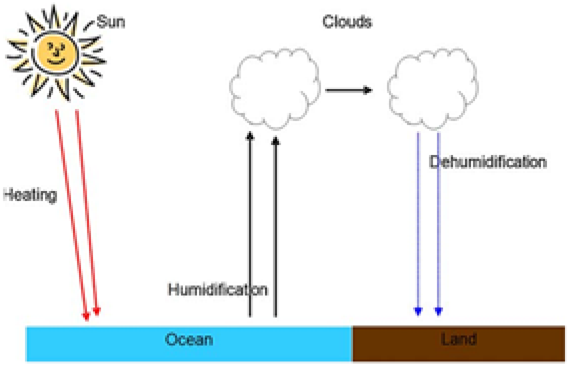

Figure 5. Rain cycle

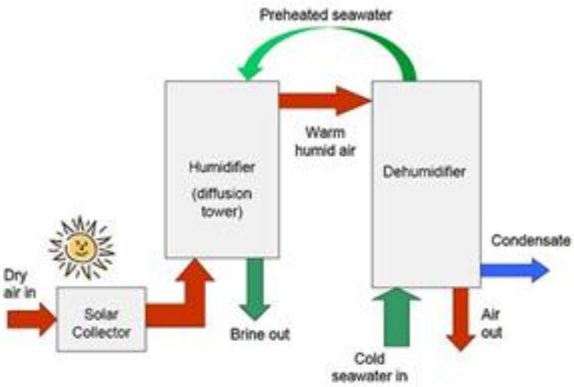

Figure 6. A simple humidification–dehumidification (HDH) process

The single-basin solar still is the simplest type of solar distillation systems. It is simple in construction, operation and maintenance. One of the main drawbacks of this design is the low yield, which is depending on season, the region and the intensity of solar radiation. The classification of solar stills is shown in Figure 3.

2.3. Humidification–dehumidification (HDH) solar desalination technology

Nature uses solar energy to desalinate ocean water by means of the rain cycle (Figure 5). In the rain cycle, seawater gets heated (by solar irradiation) and humidifies the air which acts as a carrier gas.

Then the humidified air rises and forms clouds. Eventually, the clouds ‘dehumidify’ as rain. The man-made version of this cycle is called the humidification–dehumidification desalination (HDH) cycle.

HDH systems are classified under three broad categories. One is based on the form of energy used such as solar, thermal, geothermal, or hybrid systems. This classification brings out the most promising merit of the HDH concept: the promise of water production by use of low-grade energy, especially from renewable resources.

The second classification of HDH processes is based on the cycle configuration (Figure 4). As the name suggests, a closed-water open-air (CWOA) cycle s one in which the air is heated, humidified and partially dehumidified and let out in an open cycle as opposed to a closed-air cycle wherein the air is circulated in a closed loop between the humidifier and the dehumidifier. The air in these systems can be circulated by either natural convection or mechanical blowers.

The simplest form of the HDH process is illustrated in Figure 6. The process consists of three sub-systems: (a) the air and/or the water heater, which can use various sources of heat like solar, thermal, geothermal or combinations of these; (b) the humidifier or the evaporator; and (c) the dehumidifier or the condenser.

3. Discussion

In previous sections, two type of solar based desalination systems, their advantages and disadvantages have been discussed.

The review on desalination systems will be incomplete if the problems associated with desalination units and its solutions are not discussed.

Table 1. Comparison of solar powered humidification–dehumidification desalination systems

Desalination plant	**Components of the plant**	**Visible outcome**
Closed/open air cycle humidification–dehumidification plant. Orfi et al. [16]	• Solar collector for heating water • Solar collector for heating air • Evaporation chamber • Condenser	•Performance of open air cycle was found to be better than closed air cycle •Annual water production 5791 l/m^2 for closed system and 6170 l/m^2 for open system
Open air cycle solar humidification–dehumidification system. Mohamed et al. [17]	• Solar parabolic trough collector • Heat exchanger • Air pre-heater • Humidifier and dehumidifier	•Distilled water production depends on season •Water production – 0.22 kg/kg of air in winter, 0.35 kg/kg of air in spring, 0.50 kg/kg of air in summer, 0.37 kg/kg of air in autumn
Multi stage heating/humidifying technique. Chafik [8]	• Solar air heater made of polycarbonate plate • inserted with aluminum strips • Humidifier • Heat recovery and dehumidification unit	• Optimum number of heating/humidifying stages was found to be 5 • Lower the air flow rate higher the plant efficiency • By Stepwise heating/humidifying technique humidity of air at 80 ˚C was found to be equivalent to humidity of air that be achieved using air heated to230˚C • Water production – 10 m^3/d • Water production cost –63.65 USD/m^3

Table 2. Advantages and limitations of solar still & HDH solar desalination systems

Solar still [17]	**Solar humidification–dehumidification[14,15]**
Solar stills can be constructed with locally available materials Minimum maintenance and operation cost Eco-friendly Product water is of High quality Low distillate yield per m^2 Requires large area Low overall performance Low efficiency	The system is more flexible Low installation and operation costs Any kind of low grade energy can be utilized Suitable for decentralized operation Requires large number of stages for efficient operation Capital cost is higher Water production cost is higher

Table 3. Performance comparison of desalination technologies

Desalination technology	Plant capacity(m3/d)	Specific energy consumption (kWh/m3)	Gain output ratio/performance ratio (GOR/PR)	Efficiency (%)	Recovery ratio (%)
Solar still [14,15,16]	<100	640	<1	30-40	NA
Solar humidification–dehumidification	1-100	31.1	0.5-2.75(GOR)	40-58	NA

This section deals with the discussion on problems associated with desalination units and its solution.

3.1. Water production cost

The water production cost of desalination units depends on (1) capital cost: cost of land, cost of equipment and installation cost and (2) operating cost: cost of energy, maintenance and replacement cost. The energy cost of the desalination units can be reduced by integrating desalination units with power plants or with renewable energy sources [16]. The water production cost of solar powered desalination units is shown in Table. 3.

3.2. Desalination and environment

Desalination plants play an important role in satisfying the fresh water demands of huge population around the globe but these technologies also have some negative impacts on environment. The negative impacts are mainly due to (1) leakage of sea water intake pipeline causing damage to aquifers, (2) brine and pre-treatment chemical disposal affecting marine ecosystem, (3) huge energy demands causing increased greenhouse gas emissions. High temperature and high dense brine disposal affects corals and grass prairies of sea bed which are habitat to fishes and invertebrates [10]. The reduction in greenhouse gases can be achieved by integrating desalination units with renewable energy and by using energy recovery devices. Impacts arising due to disposal of brine can be reduced by discharging brine in hydrodynamic turbulent conditions and by using the brine for aquaculture and irrigation (salt resistant crop cultivation) by reducing its salinity [10].

A comprehensive performance analysis of two desalination technologies in terms of various performance parameters such as specific energy consumption, performance ratio, efficiency and recovery ratio is illustrated in Table 3. It could be seen from Table 3 that the energy consumption of solar still is found to be larger due to loss of heat of condensation to the ambient.

3.3. General comments on solar operated desalination units

- Solar stills are cheap but occupies large area and are suitable only for small scale water production.
- For large capacity plants solar based humidification–dehumidification requires large number of stages for efficient operation which increases cost of the system hence this system is suitable for low capacity decentralized mode of operation.
- Rejected brine can be utilized for aquaculture and irrigation of salt tolerant crops after reducing their salinity by blending them with feed water.
- Use of corrosion free alloy materials can increase the life of desalination unit and can reduce the maintenance and water production cost.

4. Conclusion

Solar energy driven desalination units can cut off carbon emissions and can provide desalinated water in a sustainable way with minimal impacts on environment and are highly suitable for remote and rural areas where provision for power supply and fresh water pipe lines are not possible.

Solar humidification–dehumidification desalination technology and solar still has been reviewed in detail in this paper. From the present review it is found that the HDH system has other advantages for small-scale decentralized water production. These advantages include much simpler brine pre-treatment and disposal requirements and simplified operation and maintenance.

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