We are IntechOpen,
the world's leading publisher of Open Access books
Built by scientists, for scientists

6,900
Open access books available

185,000
International authors and editors

200M
Downloads

154
Countries delivered to

Our authors are among the

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

CLARIVATE ANALYTICS
BOOK CITATION INDEX
INDEXED

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Solar-Powered Desalination

Emrah Deniz

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/60436

Abstract

Drinkable fresh water, being a fundamental need of human beings, has become a serious concern for people especially living in crowded cities and countries with limited amount of water resources. Supplying fresh water is an energy intensive task especially when there is need for heating cold water to evaporate for distillation. Most of the big desalination plants around the world use fossil-based fuels as energy source to heat and vaporize the sea water or brackish water in order to produce fresh water.

However, environmental concerns along with decreasing oil reserves and increasing fuel costs call for reconsideration on the fuel types used in many areas as well as in desalination or distillation processes. There are a number of well-known alternative and renewable energy sources in the world like wind, geothermal, solar, biomass, etc. but achievability, availability when needed and energy storage are also very critical issues to operate the distillation plant effectively.

Since most of the desalination processes run on heat, solar energy can be used directly as heat source. Complex desalination systems which are all designed to improve the thermal efficiency and freshwater yield/productivity use many approaches such as multiple stage operation, pre-heating the feed water with the condensation energy, using additional heat sources (waste water from another process), concentrating solar energy to improve the operation temperature of the process, etc.

Solar desalination systems can be a good solution to the water scarcity, especially the Sunbelt region. However, dominant use of clean and renewable energy sources for desalination process and replacing the fossil fuel–based operations require more R&D studies to find more efficient and/or less costly power plants with continuous operation by the means of energy storage solutions.

Keywords: Desalination, solar energy, distillation, water scarcity, desalination methods

INTECH
open science | open minds

1. Introduction

Freshwater and energy are two inseparable and essential commodities for sustaining human life on earth. Rapid population growth and industrialization, especially in developing countries in the recent past, have placed pressing demands for both freshwater and energy [1]. Both are to be conserved and preserved for the sustainable development of the world. On the other hand, there is an acute shortage of both energy and water, especially in the third world countries [2]. Only less than 1% of the water is available for the society for direct use, out of which the maximum fraction has been polluted due to non-manageable industrial developments [2].

Due to the fast increase in the world population, the need for the energy increases rapidly. Various studies have been made to meet this extra energy demand. Most of these studies were focused on alternative energy sources. Solar energy is one of the most popular ones of these sources due to relatively less installation cost and long operation time without any need for maintenance [3]. Basically, all forms of the energy in the world, as we know it, are solar in origin. Oil, coal and natural gas is originally produced by photosynthetic processes, followed by complex chemical reactions, in which decaying vegetation was subjected to temperature and pressure over a long period of time [4].

Solar energy is so powerful and abundant that 30 min of solar radiation falling on earth is equal to the world annual energy demand. It is also cheap, environment friendly and nearly inexhaustible. Most of the world receives powerful solar radiation and has a good chance and opportunity to benefit from solar energy [3].

All ecosystems and every field of human activity depend on clean water and it is one of the most precious resources in today's world. Water is a primary need for life, health and sanitation, which brings it into the international agenda as a very important issue [2]. The lack of potable water poses a big problem in arid regions of the world where freshwater is becoming very scarce and expensive. Clean drinking water is one of the most important international health issues today [5]. Remote and arid to semi-arid regions depend on underground water for drinking. Unfortunately, underground water is not always considered to be fresh drinking water. In some instances, the salinity is too high for being drinkable, and it is called brackish water. In such cases, fresh water has to be either transported for long distances or connected with an expensive distribution water network at extremely high cost for, usually, a small population. Solar desalination can be a good solution for such a problem [6].

Desalination is one of mankind's earliest forms of water treatment, and it is still a popular treatment solution throughout the world today [5]. Distillation is one of the oldest and most rustic desalination techniques. In fact, it reproduces the natural process of the industrial desalination. Solar distillation is a thermal process that represents a sustainable solution to water shortages in the world. The desalination technique by solar energy, based on the principle of greenhouse is not new. Solar energy coupled to desalination offers a promising prospect for covering the fundamental needs of power and water in remote regions, where connection to the public electric grid is either not cost effective or not feasible, and where the water scarcity is severe [5].

2. Hydrologic cycle and water scarcity

The earth has a global water amount of about 1.38×10^9 km^3, 97.5% of which is salty and only 2.5% is fresh water. Most of the fresh water is either frozen in the poles or remains in the soil as moisture or lies in aquifers beyond the reach of human being. A tiny fraction of global water resource (~1%) is available to be used by human beings, animals and plants. Being one of the most critical and vital needs of all plants, animals and human beings, fresh water is created mainly by a continuous evaporation and condensation process called "hydrological (water) cycle" [7].

The water cycle is caused by solar energy which heats the water in oceans, seas, lakes, rivers and lands containing moisture. Water evaporates and becomes water vapour while ice, hail and snow can transit from solid to vapour phase directly which is called sublimation. An average of 16 million m^3 of water is evaporated every second and then the vapour is transported in the atmosphere to where it comes across cooler temperatures which will eventually cause the vapour to condense and precipitate as rain, sleet, snow or hail. Nearly, four-fifth of the evaporated vapour falls back into the oceans and some other flows through the ground surface to the sea. Some water also goes deep into the ground layers and fills aquifers, which are the long-term water storages. Some groundwater comes out as springs through openings in the ground. Eventually, the water returns to the ocean and joins to the water cycle again. Figure 1 shows a schematic illustration of the water cycle (This Figure adapted from http://www.srh.noaa.gov/jetstream/atmos/hydro.htm).
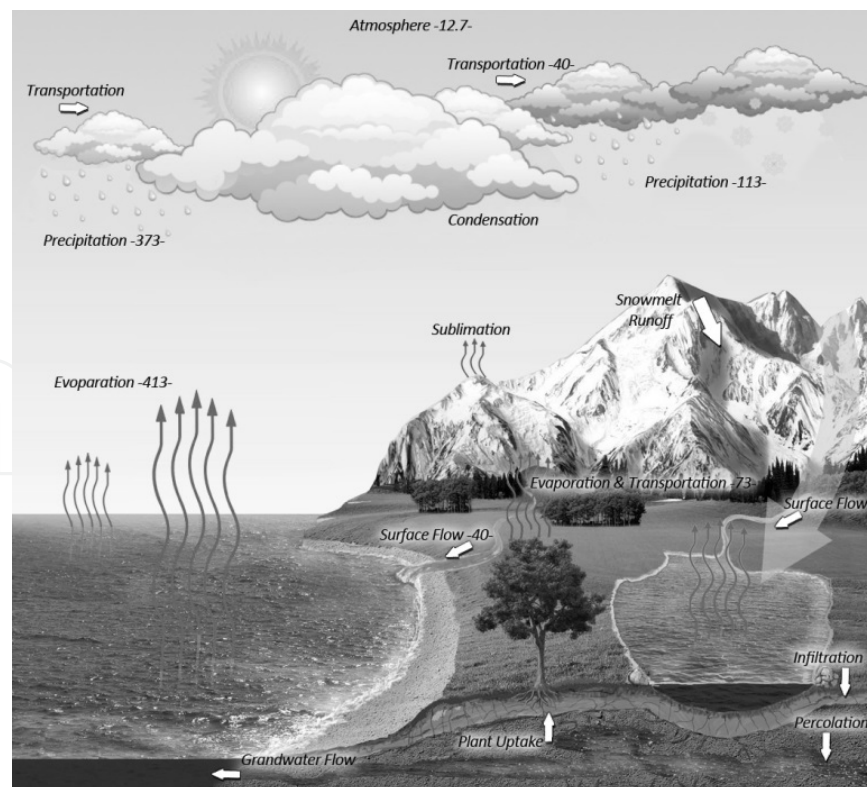

Figure 1. The global water cycle (the units are in 10^3 km^3. year^{-1}) [9]

Due to wind regimes and atmospheric conditions, water vapour and rain are not evenly distributed throughout all the earth land. Therefore some parts of the earth take much more precipitation than the others. This situation causes a failure to provide enough usable water for everyone living in a certain region which can be caused by mainly two reasons. If the water in that region is physically less than the amount of water required in order to meet the demands of people in that region for drinking, home use and agriculture, this situation is called "physical water scarcity". On the other hand, if the water resources are present but they are not effectively used due to lack of investment or absence of qualified personnel or just administrations to process the water to provide people with the water they need, it is called "economic water scarcity" [8].

Although all parts of the earth is exposed to solar radiation throughout a year, the equator zone between 35°N and 35°S latitudes receives much more solar energy compared to the other parts of the earth and is called "Sunbelt region" [10]. About four-fifth of the world population lives in this region. Having abundant solar energy on one side, the Sunbelt region countries experience a serious water scarcity problem. This scarcity is not only physical water scarcity, indeed it is an economic water scarcity especially in Africa, which means lack of investment in water infrastructure or the lack of personnel capacity to adequately meet the drinking and irrigation water demand of the population. Figure 2 shows a schematic illustration of the Sunbelt region and global water scarcity in the world.
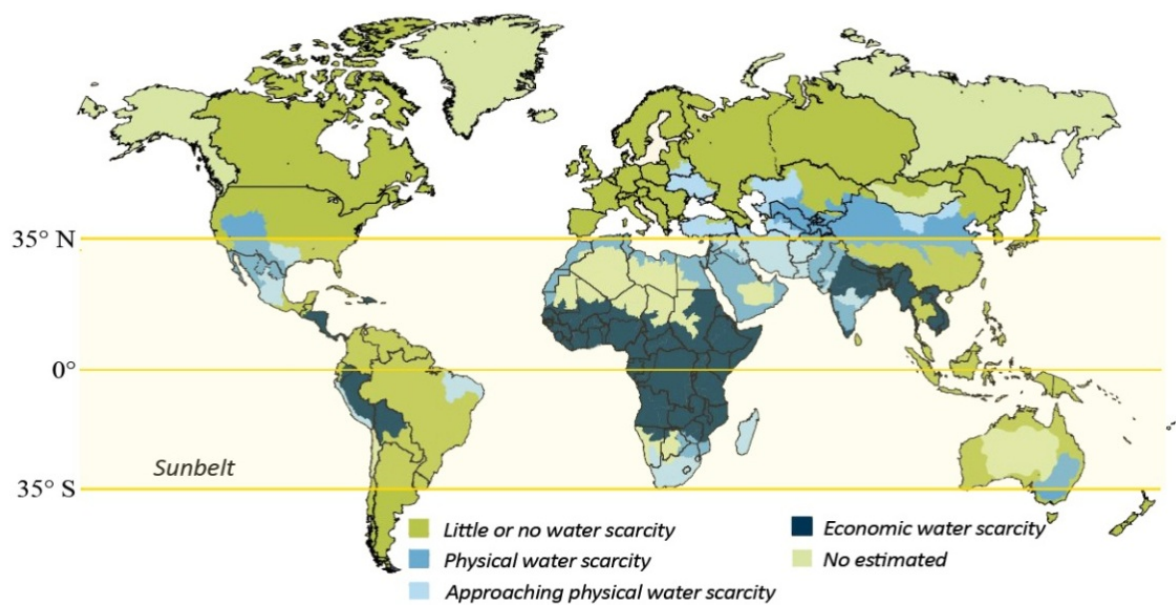

Figure 2. Global physical and economic water scarcity and Sunbelt region [10, 11]

One of the vital factors in combatting the economic water scarcity is a cheap, clean, affordable and environment friendly energy source which will be used to produce and distribute usable

and drinkable water. Renewable energy sources such as; solar, wind, geothermal, biomass, etc. is suitable for this purpose.

Sunbelt region is very suitable to use solar energy, which is a very popular and abundant energy source, to produce fresh water from saline water through a number of desalination methods, which will be discussed in detail later. 6 kWh/(m^2.d) of solar energy, which is easily reached in Sunbelt region, is equal to 0.6 l/m^2.d and 220 l/m^2.y of oil. Therefore it is practically possible to use solar energy instead of especially fossil fuels in this region [12].

3. Desalination and solar energy's place among the other energy sources for desalination

Total fresh water consumption in the world can be classified into three categories; about 70% is used for irrigation, 20% is used for industrial purposes, and only 10% of the fresh water is consumed for domestic uses as drinking and cleaning water. In case of a shortage of fresh water, desalination is a way to produce usable and drinkable fresh water from any source of saline water to meet the demand.

Desalination is the process of separating salt from saline water, which is a mixture of pure water and salt, in order to obtain fresh water. Water salinity due to dissolved salts can be expressed in four classes as; fresh water (<0.05%salinity), brackish water (0.05–3% salinity), saline water (3–5% salinity) and brine (>5% salinity) [13]. The most important property of the desalinized water and thus the parameter observed through the process is salinity. Salinity can be expressed in particles per million (ppm) or salt mass fraction (mf_s). 1000 ppm salinity equals to a salinity of 0.1%, or a salt mass fraction of mf_s = 0.001.

Although about two-third of the feed water for desalination process is the sea water, waste water (about 6%), river water (about 8%) and brackish water (about 19%) are also used as desalination water especially at places distant from the sea [14]. Actually, feed water with low salt concentration is preferable for the stills, where available, since it causes less contamination and scale formation in the system. The installed capacity of desalinated water system in year 2000 was about 22 million m^3/day and has drastically increased to 71.7 million m^3/day by the year 2010. It can be estimated that 71.7 million m^3/day desalination requires about 650 million tons of oil/year as energy source [15].

This means that; using renewable energy sources in desalination processes instead of fossil fuels, a significant amount of pollution, greenhouse gas and global warming contribution can be avoided. Desalination process is mainly of two types: phase-changing processes and single-phase processes (Table 1). In addition to these two types of desalination, there are hybrid processes that employ both phase change and separation at the same time. Hybrid systems may be comprised of one unit in which both phase change and separation steps take place or they may have two units for two steps. Reverse osmosis combined with MSF or MED are two examples for hybrid process.

Phase-change processes	Single phase processes
1. Multi-stage flash (MSF)	1. Reverse osmosis (RO)
	– RO without energy recovery
	– RO with energy recovery (ER-RO)
2. Multiple effect distillation (MED)	2. Electrodialysis (ED)
3. Vapour compression (VC)	
4. Freezing	
5. Humidification/dehumidification	
6. Solar stills	
– Conventional stills	
– Special stills	
– Cascaded type solar stills	
– Wick-type stills	
– Multiple-wick-type stills	

Table 1. Desalination processes [16]

Since changing the phase of saline water requires considerable amount of heat, solar energy is a very practical and readily available energy source along with geothermal and wind energy where available. Solar energy, wind energy and geothermal energy are used in renewable energy powered desalination plants with the percentages of 42%, 37% and 21% respectively. Solar power is used as both thermal energy and electricity through photo-voltaic panels.

4. Solar technologies used in desalination

Energy is the most vital need for living. Obtaining the usable forms of energy may cause both economic and environmental problems. Especially the fossil fuels have relatively high costs and environmental impacts which inevitably lead to seek for developing alternative methods. Using renewable energy sources is a good way to cope with energy and environmental problems. Renewable energy sources can easily replace fossil-fuels in the near future especially in stationary plants. Depleting reserves of fossil-fuels and environmental problems make it necessary to use the reserves more carefully. Solar energy has great potential in space heating for buildings owing to its low-grade energy characteristics and is the most important alternative to fossil fuels. Solar systems with feasible design and installation have very short payback periods and meet the energy demand very effectively.

Solar energy is widely used for drying, cooking, distillation, hot water and electricity production which are the very daily life needs of the people. Several methods using solar energy can be used easily to produce potable water from salt water to save people and agriculture from water scarcity. Main requirement of desalination process is thermal energy, and it can be provided through thermal and PV applications of solar energy systems. This energy can be integrated with various types of structure and capacity distillation systems to produce fresh water.

4.1. Salt Gradient Solar Pond (SGSP)

Salt gradient solar pond (SGSP) is a low cost method of capturing and storing solar energy at relatively low temperatures. A SGSP has mainly three layers of water filled in a pond in an order of salinity and relative mass from the bottom to the top.

1. The first and deepest layer of the pond is filled with a very salty water (about 20%), which is called Lower Convective Zone (LCZ). This layer is salty as much as possible to increase the relative mass of the water compared to the next upper layer which is called Non-Convective Layer (NCZ). This is accomplished by gravitational force that traps the water which takes the heat from the solar radiation and from the bottom of the pond, which absorbs the insolation passing through the transparent all UCZ, NCZ and LCZ layers, and tries to go upwards into the NCZ following normal convection process. Since NCZ layer has a relatively light water, convection process is suppressed and inhibited by the gravity of the LCZ water. Thus a transparent convective insulation is formed by the NCZ layer.

2. NCZ layer is structured as multilayer with a salinity gradient from bottom to top in order to slow down convective heat transfer to the upward direction. Slices of water layers with decreasing salinity provide insulation for the heat trapped in LCZ by eliminating convection between the NCZ layers.

3. UCZ is the top water layer of the pond with lowest salinity. UCZ layer is at near ambient temperature. It should be kept thin (about 30 cm) and should be protected from fluctuations caused by wind and wave which leads to mixing of NCZ and UCZ. Wind barriers or mash type covers can be used for big applications.

Solar ponds can provide thermal energy for domestic heating for space and water or power generation and desalination processes. The heat from a solar pond can be used in a Rankine cycle to produce mechanical energy and electricity. Figure 3 illustrates the structure and average heat losses to the ground and atmosphere.
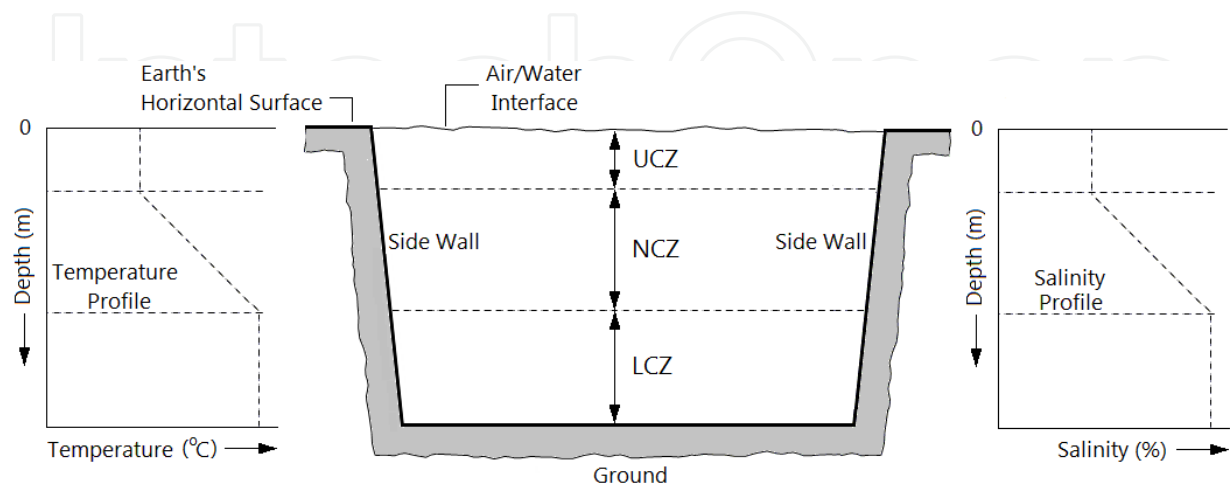

Figure 3. Cross section of the salt gradient solar pond [17]

4.2. Heat pipe systems

A heat pipe is essentially a passive heat transfer device with an extremely high effective thermal conductivity which allows a two-phase heat transfer mechanism resulting in enormous heat transfer capabilities nearly one thousand times that of an equivalent copper piece. The heat pipe in its simplest configuration is a closed, evacuated cylindrical vessel with the internal walls lined with a capillary structure called wick that is saturated with a working fluid.

A heat pipe has three regions namely; evaporator, condenser and adiabatic region. Heat is absorbed through the evaporator part of the heat pipe and transferred into the working fluid to vaporize some fluid. Vaporizing fluid pushes the vapour above towards the condenser part which is always above the evaporator region. The latent heat of evaporation contained in the vapour is transferred to the relatively cold surface of condenser causing the vapour to condensate on the surface of the condenser covered by a porous liner called wick, which serves as a passive pump to draw the fluid back to the evaporator by capillary effect. Then the heat is provided by the condenser to a fluid or gas through its surface. The middle section of heat pipe is called adiabatic region in which vapour travel from the evaporator to the condenser without any significant heat transfer to the pipe wall. Heat pipes can be designed to operate in evacuated tube collector, flat plate collector or directly at different working conditions and temperatures. Heat pipes needs to be installed at a minimum tilt angle of 25° to provide the backflow of the working fluid inside the heat pipe from condenser to evaporator.

4.3. Solar collectors

Solar water heating (SWH) collectors are heat traps that absorb solar energy and transfer the heat into another medium. Changing the shape, design and materials, they have three major parts in common integrated to each other. The first and the most important part is collector which is exposed to solar radiation at an optimum inclination angle allowing to take maximum radiation throughout the solar season. The second part is a transfer medium that transfers the heat collected by the collector to the third part, storage tank. This medium should be fluid and generally made of water-glycol mixture. Storage tank, the third main part, is a simple heat exchanger (liquid-to-liquid) like collector (gas-to-liquid), which transfers the heat from the transfer fluid to the water to be heated and used. The transfer fluids have to be circulated in order to carry the heat continuously coming into the collector as solar radiation. This circulation is accomplished by mainly two ways:

- *Natural circulation* which is driven by the difference between the relative gravities of hot fluid in the collector and relatively cold fluid which gave its heat to the water in the storage tank. This type of design requires the storage tank to be located higher than the collector.

- *Forced circulation* method employs a water pump to circulate the fluid in a closed cycle instead of letting it to circulate slowly by means of the small difference between the gravities of hot water in the collector and warm water in the storage tank.

There are many types of solar water heating (SWH) systems. Stationary type solar water heaters include flat plate collectors (FPC), evacuated tube collectors (ETC) and compound parabolic collectors (CPC). FPC and ETC are widely used for heating domestic use water. These

collectors convert solar radiation directly and indirectly into thermal energy. ETCs have a higher efficiency than FPCs but they cost much more than FPCs.

4.3.1. Flat plate collector

Flat plate collectors are the most widely used solar systems today. They are made of three main parts. An insulated collector case holds the tubes, metal plate and glass cover. A sheet metal plate of aluminium, copper or steel can be painted or coated black. Metal tubes (usually aluminium or copper) that bonded onto the metal plate so as to provide good heat conduction, and are all connected to a common tube at both ends called header tubes. Bottom side of the collector case is well insulated to minimize thermal loses and the top side which is exposed to the sunlight is covered with a glass tightly to ensure a high level of greenhouse heating inside the collector. The pipes and copper are enclosed in an insulated metal frame, and topped with a sheet of glass (glazing) to protect the absorber plate and create an insulating air space.Figure 4. shows a cross section of a flat plate collector and solar water heaters with natural circulation and heat pipe.
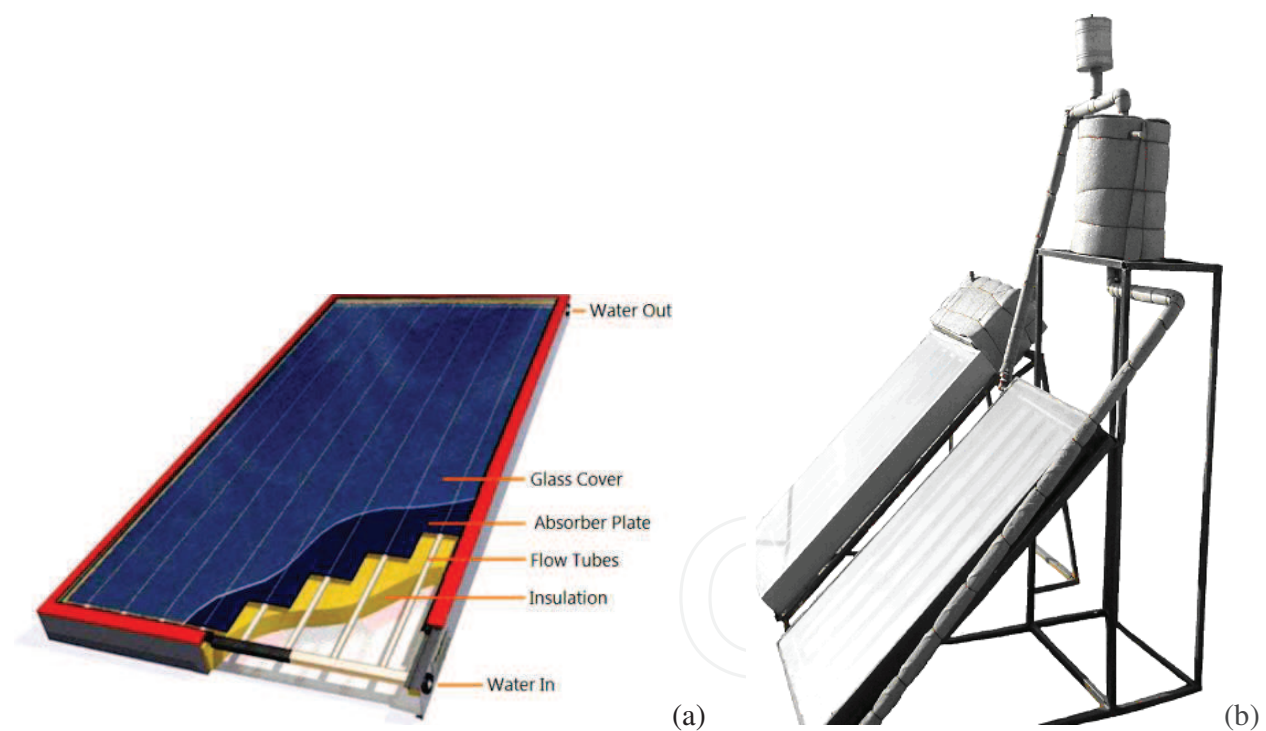

(a)   (b)

Figure 4. (a) Cross section of the flat plate solar collector [18], (b) solar water heaters with natural circulation and heat pipe [19]

Sunlight falling onto the collector surface passes through the glass cover and hits to the black plate and tubes inside the collector casing. The heat absorbed by the tubes and the plate is transferred to the fluid circulating inside the tubes. The fluid which can either be a working fluid which circulates in a closed loop between the collector and storage tank where it transfers its energy to the water that will be used, or running water can be directly routed through the

collector tubes. The circulation of the water inside the collectors can be driven by the difference between the specific gravity of heated water inside the collector and cooled water inside the storage tank, which is called natural circulation. This type of collector has some installation requirements such as installing the storage tank higher than the collector to provide cold water to flow downward replacing the hot water. Forced circulation on the other hand makes it possible to install the storage tank to almost any place lower than the collector which allows more aesthetic and convenient designs on the roof.

4.3.2. Evacuated tube collector

Evacuated-tube collector is a later generation of flat plate collectors which was first seen in 1970s. Main difference of evacuated tube from the flat plate collector is that it employs a vacuumed glass tube with an absorber inner surface. Vacuum layer serves as insulation much more superior than the air trapped between the glass cover and absorber plate in the flat plate collectors. Evacuated tube collectors are mainly two types as direct flow and heat piped system. Using a reflector improves the heat absorption performance of the collector.

Heat pipe evacuated-tube collectors use a copper heat pipe attached to an absorber plate and a vacuum tube. Tubes can be changed one by one without dismantling and emptying the whole system which makes it easy to perform installation, maintenance and repair tasks more easily. Some heat pipe collectors have overheat protection system that blocks the way fluid flows from the condenser to the evaporator region by a temperature triggered spring.

4.4. Concentrating solar systems

Concentrating solar systems are mainly used for power generation. They concentrate the solar energy to a point or a line at which heat energy is collected at medium or high temperatures depending on the type of the system and used for power generation in a conventional heat-driven power plant. Installed global capacity of concentrating solar thermal power plants according to years are 0.4 GW in 2004, 2.5 GW in 2012 and 3.4 GW in 2013, clearly showing an increasing trend [20]. Most popular types of concentrating solar power technologies include Linear Fresnel, dish, parabolic trough and solar towers Figure5.

Parabolic trough collector technology (PTC) is just like a parabolic semi-pipe which is cut off longitudinally and oriented from north to south. The parabolic reflective surface made of a polished metal or mirror concentrates the solar radiation onto a single focal line at which a tube is located to contain a thermal fluid for energy absorption and transfer to an associated plant that employs a heat engine to generate electricity. Parabolic trough is equipped with a solar tracking mechanism which allows the focal line hold on the pipe throughout the daytime. The temperature of the thermal fluid inside the tube (thermal oil, pressurized water or molten salt) can rise up to 400, 500 and 550°C, respectively. The hot working fluid can be used in Rankine cycle to produce mechanical energy or electricity. Pressurized water is useful for producing steam.

Linear fresnel collector technology (LFC) is another example of line focus technique like parabolic trough technology. It costs less than parabolic trough which is because of requiring
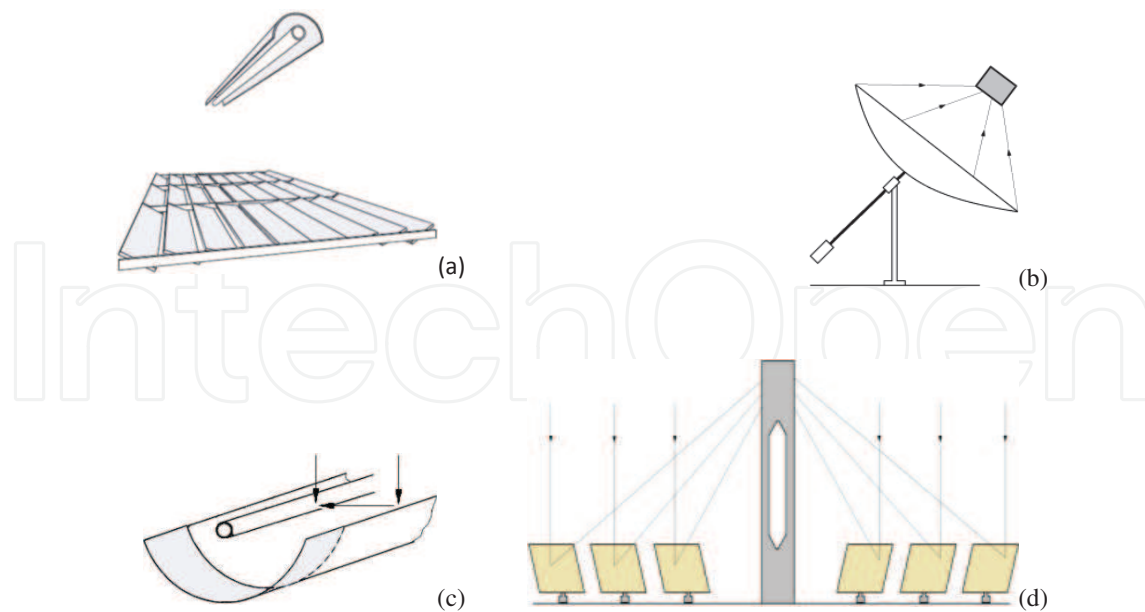
Figure 5. Concentrating solar power technologies (a) Linear fresnel collector, (b) dish collector, (c) parabolic trough collector and (d) solar towers[21]

a lighter structure for flat reflectors. The receiver is also fixed and does not rotate with the reflector assembly which is tracking the sun from morning to evening. Only moving part of this system is the reflector units which lay longitudinally at north south direction. These modular units are rotated throughout day at the exact angle to keep the focal line on the receiver pipe located above the central line. Cosine loss is a drawback of this technology, caused by the intervention of module sides as to shade the solar light on the next mirror especially in the morning and afternoon. Flat mirror modules are not capable of focusing light as good as a parabolic mirror. Receiver located above the mirrors' plane shades onto the mirrors except for the noon time. There are several options of heat transfer fluid in this system as in parabolic trough, but water is widely used because linear Fresnel collectors are well suited to produce steam. Collectors are able to produce steam at 250°C temperature and 50 atm. pressure directly, without using exchanger.

Tower solar power technology (TSP) is mainly a combination of a central receiver mounted on top of a tower and many mirrors distributed around the tower on the ground as to form arrays of sun-tracking mirrors which reflect the solar irradiation to the receiver unit on the tower. These mirrors called heliostat can track the sun at two axis. Solar towers can reach high temperature concentrations since it is a point focus technology instead of linear focusing. The heat is absorbed by transfer fluid similar to above-mentioned solar sys‐ tems. Water can be directly converted to superheated steam and used in a Rankine heat engine and to power an electric generator. Another advantage of the tower technology compared to parabolic trough collector is its ability to operate with various heat transfer fluids such as molten salt, open air, superheated steam, and pressurized air. A brayton cycle can also be driven by hot pressurized air.

Solar dish collector technology (SDC) is a unified version solar towers which hold the parabolic mirrors and a Rankine or Sterling engine attached to the receiver that is located at

the focal point of the mirrors to utilize the concentrated heat. The mirror and engine assemble is mounted on a single body equipped with two axis solar tracking mechanism. Focal concentration ability of solar dish makes it possible to achieve as high as 1000°C of receiver temperature. Attaching the engine directly to the receiver plate eliminates loses during the transfer of heat from the receiver to the generator which makes solar dishes more efficient than the other systems. On the other hand, it is not so easy to integrate solar dishes with energy storage systems and other energy sources.

Among these concentrating solar technologies, parabolic trough is the most widely used technique in the world today. PTC and TSP technologies are able to store heat more than 10 hours through direct or indirect energy storage systems. There are 76 concentrating solar power projects in the world with 2.88 GWe of total capacity. Although PTC plants are very dominant among the currently operational solar power plants (95.7%), under construction projects will increase the ratio of LFC from 2.07% to 5.74%, TSP from 2.24% to 20.82% and SDC from 0% to 0.052%, decreasing the ration of PTC from 95.7% to 71.43% [22].

4.5. Photo-voltaics

Photovoltaic (PV), as its name implies, is an extraordinary phenomenon that converts light to instantly ready direct current. Semiconductor materials inherently have this physical property and are easily used in production of PV cells. PV cells have two or more layers of semiconducting material, commonly silicon. When the photons in sunlight hits onto this semiconductor layers electrical charge is generated and this charge can be harvested by using metal contacts resulting in DC current. The smallest unit of this arrangement is called solar cell. Solar cells have a very small output capacity but they can easily be connected to each other to form a bunched structure called PV panel. PV panels can also be connected to each other in any size and number to produce a desired power output. PV panels have no emission, no noise and no moving parts. Also, their installation and maintenance tasks are very easy [23]. The main drawback of PV panels is their cost which is decreasing rapidly. Affordable prices boosted the use of PV panels in recent years. Global installed capacity of PV plants was 2.6 GW in 2004, increased to 100 GW in 2012 and become 139 GW by the year 2013 [20].

5. Solar desalination

Desalination of sea water or other salty ground waters is a practical and proven method of producing fresh water where it is needed. The main issue for this desalination process is a low cost, environment friendly, readily available energy to drive the process. Solar energy is one of the best sources of this type and it is abundant throughout the year especially in solar belt region at which most of the water scarcity is suffered by about 5 billion people. Solar water desalination is a well-known and proven technique which has been used for a long time at remote areas and places suffering from shortage of potable quality water. There are many variations of solar driven desalination systems. Figure 6 shows a pull classification and integrated big picture view of desalination processes and the place of renewable energy among

the other methods. These systems can be classified mainly into two groups as direct and indirect desalination systems which will be described below.

5.1. Indirect systems

Most of the large solar desalination plants are driven by indirect solar energy. Indirect solar desalination systems can be classified into thermal, mechanical or electric driven technologies. Solar energy is collected through concentrating (PTC, LFC, TSC, SDC) or non-concentrating (FPCs, HPC, SP) collectors to run thermal desalination processes such as MSF, MED, thermal vapour compression (TVC) and membrane desalination (MD). Another indirect use of solar energy in desalination system is producing electricity from solar irradiation via PV panels and use to run ED which is the only desalination technology using electricity directly to produce fresh water. RO and freezing desalination techniques require mechanical energy which can be obtained from solar energy through heat engines (Rankine, sterling and brayton) or PV panels. Figure7 shows the shares of desalination technologies in indirect solar desalination plants installed worldwide.
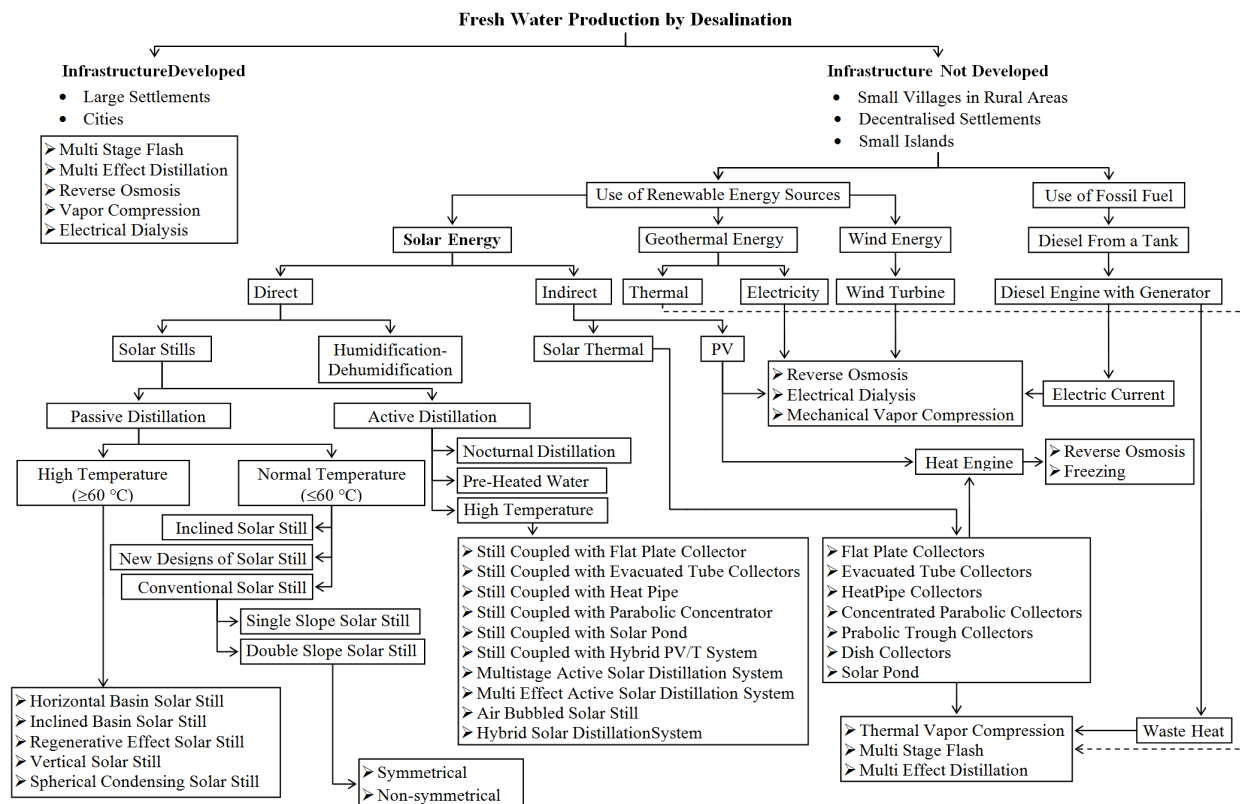

Figure 6. Desalination techniques used for fresh water production [1, 2, 12, 24]

Reverse osmosis (RO), which is the dominant indirect solar desalination techniques (about 52%) has the potential to improve the sustainability of desalination process by replacing solar energy with fossil fuels and reducing operational cost significantly [24]. It is a pressure driven process which forces the salt water through a semi permeable membrane where concentrated brine is separated from the feed water producing fresh water as the output of the membrane. RO

membranes can separate more than 98% of the salt contained in the sea water. Required feed water pressure for brackish and seawater is 10–15 bar and 55–65 bar, respectively. Typical RO desalination systems can recover 45–50% of seawater and 90% of brackish. Membrane which is the core element of RO process losses its performance due to fouling and scaling [25].
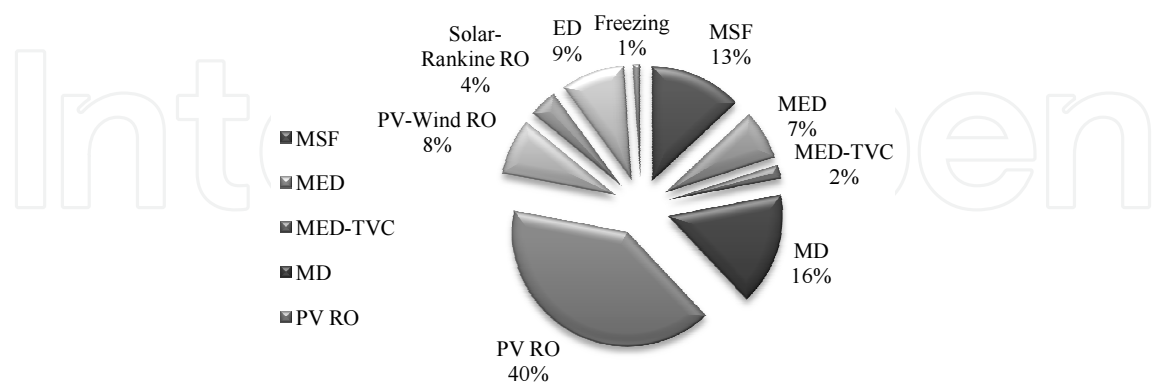
Figure 7. Shares of desalination technologies in indirect solar desalination plants installed worldwide [24]

Pressurized feed water required for RO process can be provided by using either sterling or Rankine engine using solar heat, or using electric motor powered by PV panels. Since the usability of solar energy depends on season or weather conditions, sustainable and continuous production of fresh water requires taking some additional measures like energy storage such as thermal energy storage and battery, or hybridization with other energy sources like wind, geothermal and diesel, or with another desalination method combined with RO. Although the pre-treatment of water before the RO membrane reduces the energy efficiency, it is still more efficient than phase change thermal processes. Separated brine water with high pressure can be rejected after passing through a pressure exchanger to recover some of the wasted energy. Figure8illustrates a basic RO system powered by a solar-heated Rankine turbine. The waste heat of the cycle may be reused to preheat the feed water.
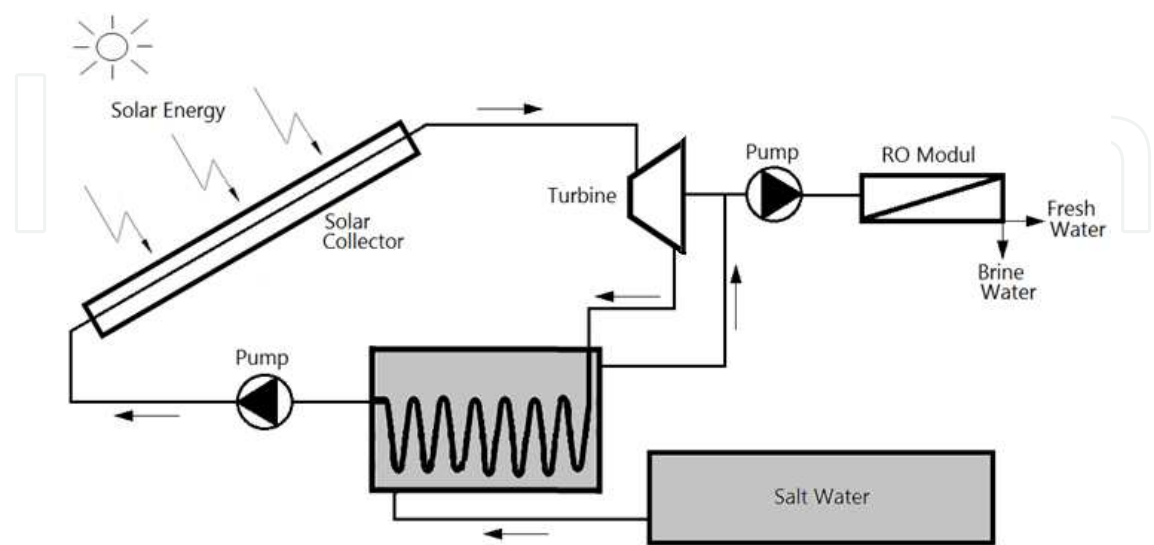
Figure 8. Basic diagram of a reverse osmosis system powered by a solar-heated Rankine cycle [26]

Multiple stage flash distillation (MSF) system has a number of adjacent vessels with an internal heat exchanger and collector for condensed water. Each of these vessels is called stage. Stages have their own inside pressure from high to low in order. Different pressure in each vessel means different boiling points with a decrement of 2–5°C from high to low. Figure 9 shows a schematic view of one-stage and two-stage flash distillation systems. Operation of an MSF plant at brine temperatures as high as possible theoretically increases the efficiency of the plant. However, avoiding scale formation and accelerated corrosion of metal surfaces in contact with seawater require limiting the top brine temperature at about 120°C.

As shown in Figure 9, cold salt water travels through the stages from cold side to hot side absorbing heat inside the vessel to cause condensation of steam and formation of distilled water. The vessels here serve as an evaporator as the brine evaporates inside. Although higher number of stages increases efficiency, it also increases the installation costs. Therefore, there are about 19–28 stages in modern large MSF plants. Preheated salt water exits the hottest (or the first) stage and enters to the collector to absorb additional heat and enters to the first stage vessel. The first stage vessel is adjusted to a certain pressure that the entering hot brine is over the boiling temperature for that pressure. Therefore, a portion of the incoming brine water suddenly evaporates which is called the "flash". Steam produced by this flash hits to the condenser above and becomes liquid condensate which drops on a fresh water collector and taken out as fresh water through a controlled valve. Demister is used to trap the water particles that may burst up during the flash and mix with the fresh water [27].

MSF plants can be integrated to any heat sources including solar concentrating (PTC, LFC, TSC, SDC) collectors, solar pond and flat plate, evacuated and heat piped collectors and any type of waste heat at moderate temperatures (from a steam or gas turbine power plant etc.).
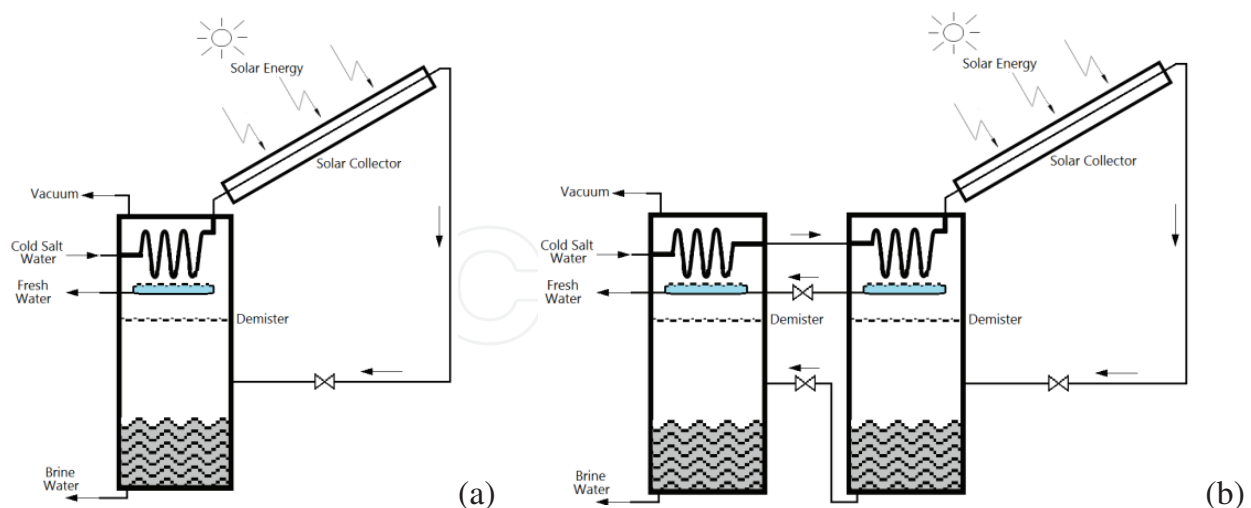

Figure 9. Schematic view of (a) one stage flash distillation, (b) two stage flash distillation [27]

Multi effect distillation (MED) units are a practical and promising way of water distillation because of its ability to use renewable energy (solar, wind, geothermal, etc.) and reuse low-grade waste heat from any source (from a steam or gas turbine power plant, etc.). Solar-assisted

MED process consumes both thermal energy (thermal vapour compression) and mechanical energy (mechanic vapour compression) to produce distilled water [28]. Figure 10 shows the typical arrangement of an MED with thermo compression (MED-TVC). Steam is produced using a thermal energy source and ejected through a thermo-compressor into a distillation cell drawing some vapour from the last cell of MED-TVC system. In solar-assisted MED desalination systems heat exchangers are widely used, and circular tubes are the most commonly adopted heat transfer elements. The heat and mass transfer processes play important roles, which usually lead to bulky horizontal or vertical tube arrays heat exchangers. Salt water is sprayed onto these exchangers in each cell. Hot steam passes through the heat exchanger in the first cell and condenses to become distilled water. Latent heat of condensing water is transferred to the sprayed salt water and some of this water evaporates while the rest accumulates at the bottom of the cell. Vapour produced in the first cell is transferred into the heat exchanger of the next cell and transfers its energy to the salt water sprayed on the exchanger of second cell just like in the first cell. Same process repeated until the last cell and the vapour produced in the last cell is sucked by thermo-compressor to recycle the vapour.

MED system is also able to operate by mechanical vapour compression (MED-MVC) when there is no usable heat. A mechanical compressor sucks the vapour from the last cell producing vacuum which promotes evaporation and compresses the vapour before sending to the heat exchanger of first cell with elevated temperature caused by the compression which also increases the evaporation rate in the first cell. MED-MVC system operates similar to MED-TVC cycle except for the mechanical compressor.
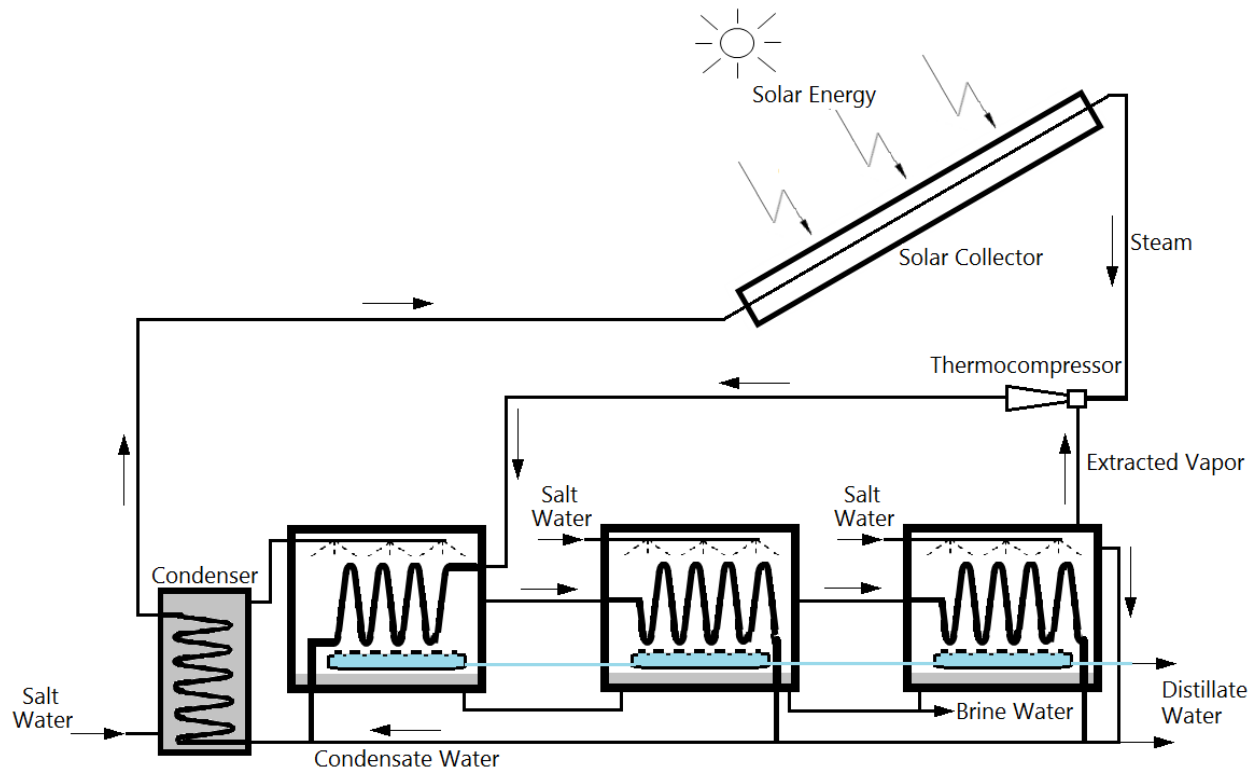

Figure 10. Typical arrangement of a multiple effect solar distillation with thermo-compression (MED-TVC) [28]

5.2. Direct system applications

Direct solar desalination methods make use of the heat energy contained in the solar irradiation directly to produce fresh water without association with any other mechanical or electrical devices. Direct systems are low cost and suitable for small applications. Since their operation temperature and steam pressure is low, they have smaller production rates than indirect desalination systems. There are mainly two types of direct desalination technique such as humidification-dehumidification method and solar stills. Solar stills have also two variants as active and passive distillation methods.

5.2.1. Solar Humidification-Dehumidification (HD-DHD)

A gigantic scale HD-DHD method is used in the nature for millions of years to produce fresh water from the seas and oceans using the sun as the heat source [29]. As shown in Figure 1, water evaporates and humidifies the above air. Air flows in the atmosphere carries the vapour to where it will condense and dehumidify to form fresh precipitation called rain, snow or hail. HD-DHD distillation method is the small scale replication of this process.

The productivity of HD-DHD system is about five times the productivity of an equivalent basin type solar still at the same climatic conditions. HD-DHD process is also named as the multiple-effect humidification-dehumidification process; multiple-effect humidification (MEH) or solar multistage condensation evaporation cycle (SMCEC).

In HD-DHD system atmospheric air is heated through a solar air heater. Because the water vapour holding capacity of air increases by the temperature (about 100 gr vapour/ kg dry air at 60°C and 500 gr vapour/kg dry air at 80°C) [30]. Warm dry air enters in to the humidification chamber and absorbs vapour from sprayed salt water. It passes through a pipe into dehumid-ification in which cold salt water passes through another pipeline which acts as a condenser for incoming warm humid air. Thus the salt water is preheated by the heat, recovered from condensing vapour, to utilize evaporation in the humidification chamber and the warm air is dehumidified leaving fresh water at the bottom of dehumidification chamber. Figure 11 shows the schematic illustration of HD-DHD system. Building and operating an HD-DHD system is simple safe and low-cost making it a very suitable desalination process among the small capacity plants [31].

5.2.2. Solar stills

Solar stills can be used to produce fresh water from salt water in a very cheap, simple and easy way [32]. They are preferred for small-scale fresh water needs of people in remote places instead of transporting fresh water. A very fortunate aspect of the solar water distillation technique is that when fresh water demand is at its peak, solar insolation is also high (especially hot seasons) [6].

Solar irradiation passes through a cover and falls onto the black bottom surface of the still causing the surface and contained salt or brackish water to warm up. Heated water evaporates and rises up until it touches to the inner side of the cover where it condenses and forms fresh
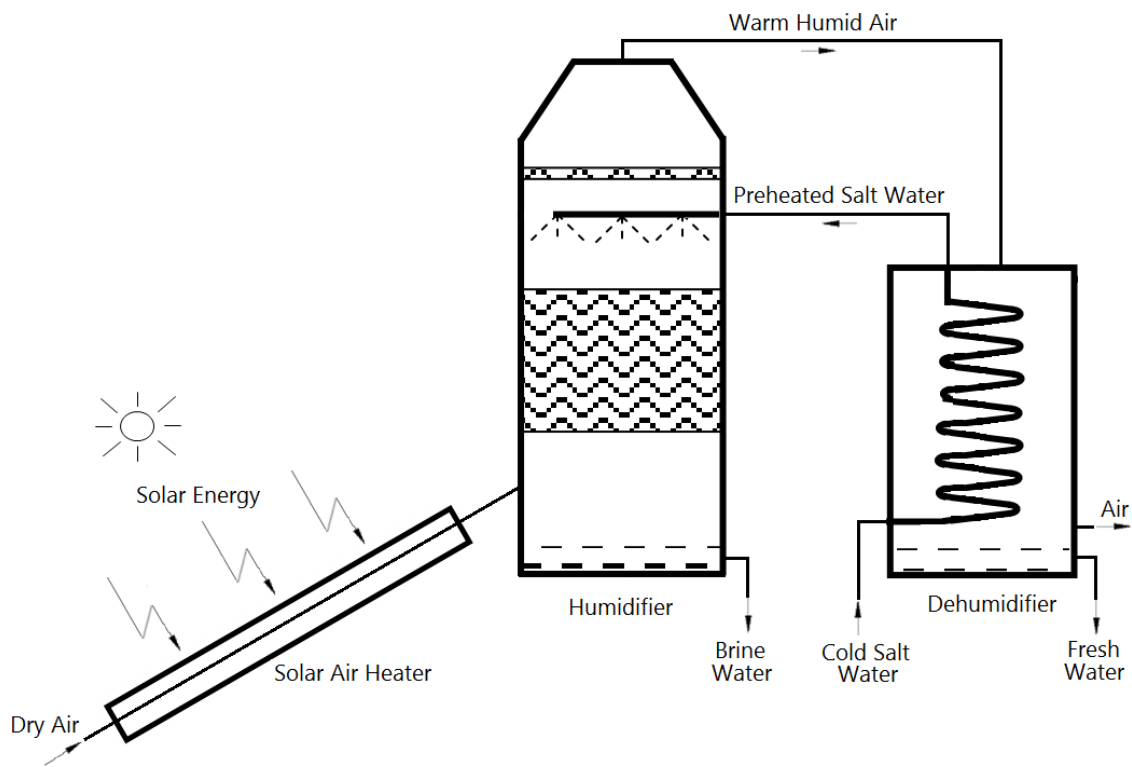
Figure 11. Schematic diagram of humidification-dehumidification system [29]

water drops. Since the cover of the still is designed with a tilt angle, these drops are moved by gravitational forces towards the distilled water collecting channels. Figure 12 shows the schematic view of a double-slope symmetrical basin still (also known as, roof type or greenhouse type). The weak point of solar stills is the significant amount of heat loses because its large surfaces are in contact with the ground and air.
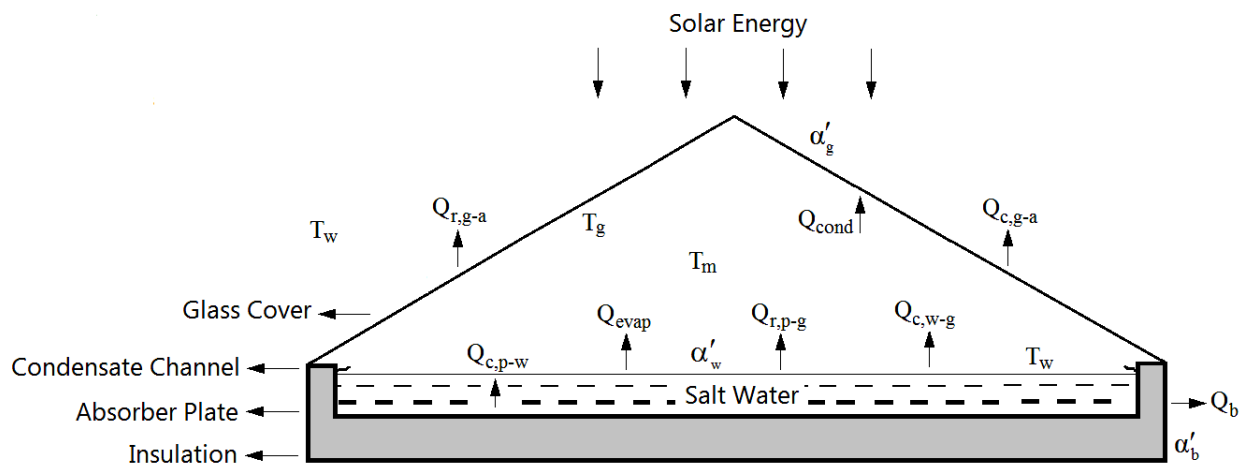

Figure 12. Distribution of the solar energy falling on a double slope symmetrical basin still [33, 34]

Ground side can be insulated to some extent. However, the upper side which has to be exposed to solar irradiation cannot be insulated and there is serious amount of heat lose through radiation, convection and condensation of vapour on the cover surface. The performance of a solar still is closely related to the thermo physical properties of the material to be used in the still, tilt angle of cover, spacing between cover and water surface, insulation, vapour tightness and absorbance-transmittance properties of still, etc. as well as operating parameters such as water depth in the basin, initial water temperature, water salinity, etc.

Figure 12 shows the distribution of the solar energy falling on a basin still system. T_a, T_b, T_g and T_w in the figure are ambient temperature, basin temperature, glass temperature and water temperature, and α'_b, α'_g and α'_g are; the solar fluxes absorbed by the basin liner, glass cover and the water mass respectively.

h_{wg}, h_{ga} and h_{wb} are the heat transfer coefficients from the water surface to glass, from the glass to the environment and from the water to basin liner respectively, given by Tiwari [35]. h_{ew} is the coefficient of heat loss by evaporation from water surface, P_g is the glass saturated partial pressure, and P_w is the water saturated partial pressure [35, 36].

$$h_{wg} = 8.71 + h_{ew} \tag{1}$$

$$h_{ew} = 4.0 \frac{P_w - P_g}{T_w - T_g} \tag{2}$$

$$P_g = e^{\left(25.317 - \frac{5144}{T_g}\right)} \quad a$$
$$P_w = e^{\left(25.317 - \frac{5144}{T_w}\right)} \quad b \tag{3}$$

$$h_{ga} = 5.7 + 3.8V \tag{4}$$

$$h_{wb} \approx 130 \ \text{W/m}^2 \text{°C} \tag{5}$$

Energy balance

Following Kumar et al. [37], the energy balance equations for different components of an active solar still are given as follows:

Glass cover

Sum of the radiation absorbed by the glass surface and the heat transferred from the water to glass surface is equal to the heat transferred from glass surface to the ambient.

$$\alpha'_g I_{eff} + h_{wg}\left(T_w - T_g\right) = h_{ga}\left(T_g - T_a\right)$$ (6)

Water mass

Sum of the usable energy coming from the collector, the radiation absorbed by the water mass and the heat transferred from the basin liner (glass cover) to the water equals to the sum of heat stored in the water and the heat transferred from the water surface to the glass surface.

$$\dot{Q}_u + \alpha'_w\left(1 - \alpha'_g\right)I_{eff} + h_{wb}\left(T_b - T_w\right) = \left(MC\right)_w \frac{dT_w}{dt} + h_{wg}\left(T_w - T_g\right)$$ (7)

Basin liner

Solar radiation absorbed by the basin liner is equal to the sum of the heat transferred to the water by convection and the heat transferred from the surface to the ambient.

$$\alpha'_b\left(1 - \alpha'_g\right)\left(1 - \alpha'_w\right)I_{eff} = h_{wb}\left(T_b - T_w\right) + h_b\left(T_b - T_a\right)$$ (8)

If the rate of useful energy coming from the collector (W) is zero ($\dot{Q}_u = 0$), Equation 7 becomes energy balance equation for a passive solar still. Evaporative heat transfer correlation is given as follows:

$$Q_{ew} = h_{ew}\left(T_w - T_g\right)$$ (9)

Hourly output of still is [35, 38]

$$\dot{m}_{ew} = \frac{h_{ew}\left(T_w - T_g\right)}{L}.3600$$ (10)

The efficiencies were calculated by the following equation [35, 39]:

$$\eta\left(\%\right) = \frac{Q_{ew}}{I_{eff}.A}$$ (11)

Solar stills are mainly of two types according to their operation modes and modifications as active or passive solar stills. Active solar stills typically use a secondary external heat sources such as; collector/concentrator panel, solar pond, hybrid PV/T systems, waste thermal energy from any chemical/industrial plant, etc. If there is no supplementary external heat source, the system is called a passive solar still [40].

5.2.2.1. Passive distillation

Passive distillation systems are divided into two groups such as high temperature (≥60°C) and normal temperature (≤60°C) distillation systems. High temperature passive distillation systems are horizontal basin still, inclined basin solar still, regenerative effect solar still, vertical solar still and spherical condensing solar still. Normal temperature passive distillation systems are inclined solar still, new designs of solar still and conventional solar still. Basin type is the most widely used solar stills today. Basin type solar stills have been modified into several types according to their cover designs such as; single slope, double slope, V type and hemispherical as shown in Figure 13. Average distillate production rate of a standard single-basin still is between 0.005 and 0.011 m^3 m^{-2} day^{-1} depending on the insulation quality [32].

Different designs of basin type solar stills have been developed and tried to find an optimum solar still which; can be transported to the site and assembled easily, does not require rare materials that cannot be found easily, has an acceptable service life, can operate by itself without any need for external power support, has a rainfall collecting facility and does not pollute or contaminate the fresh water and of course with low cost.

The basic components of a solar still are briefly described below:

Glazing should transmit the solar irradiation to coming inside the still and resist to thermal radiation going outside. The glazing also needs to be abrasion resistant and hydrophilic. Readily available, easy to handle and assemble glazing material is preferable. Commonly used materials are glass or treated plastic.
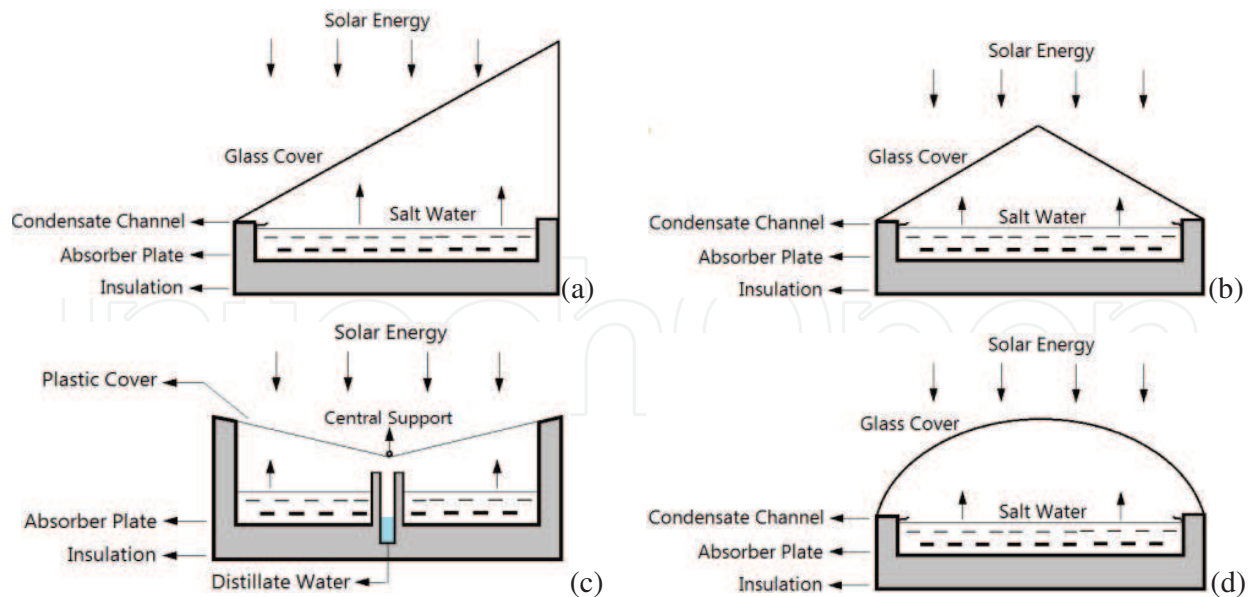

Figure 13. Common design of solar stills: (a). single-slope basin still, (b). double-slope basin still, (c). V-type solar still, (d). Hemispherical type solar still [41]

Liner is used to absorb the solar irradiation and give the heat to the water. Since it is in contact with warm salt water and basin tray, it should be impermeable to warm salt water, durable

and easily cleanable. Preferred materials are asphalt matt, black butyl rubber, black polyethylene etc.

Sealant should be easy to apply, durable and low cost. Common materials are putty, tars, tapes silicon and sealant.

Basin tray forms the main base of the system. Therefore it should have long life high level of corrosion resistance and low cost. Preferred materials are wood, galvanized iron, steel, aluminium, asbestos cement, masonry bricks, concrete, etc.

Condensate channel is the channel through which condensed fresh water is collected and directed to distillate water tank. *Preferred materials are* aluminium galvanized iron, concrete, plastic material, etc.

Side walls make the still robust and rigid along with providing thermal resistance against the heat transfer from the heated salt water in the basin to the outside. It should be made of a material that can hold the top cover without any failure for long years. A low thermal conductivity is also a key property of side walls. Mostly preferred side wall materials include wood, concrete, reinforced plastic, etc.

Integrating a separate external condenser with the still as in Figure 14 decreases the convective heat loss through the still cover and provides an effective heat sink for the condensing vapour which increases the distillate yield by about 50–70%.Some of the evaporating water condenses on the cover surface and a fraction of the vapour passes to the condenser chamber by the effect of pressure difference causing the pressure in the still chamber to drop. Lowered pressure decreases the formation rate and number of vapour droplets on the inside surface of the still cover which allows more solar radiation to reach the water in the still basin and improves evaporation.

Using nano fluids along with external condenser is another contemporary method to further increase the productivity by about 115% [42]. External condenser accumulates the latent heat of condensing vapour which can be used to preheat salt water before entering the still or to prolong the distillation process during night hours. Using external condenser makes it possible to use a cover with very low inclination Figure 14a [43].
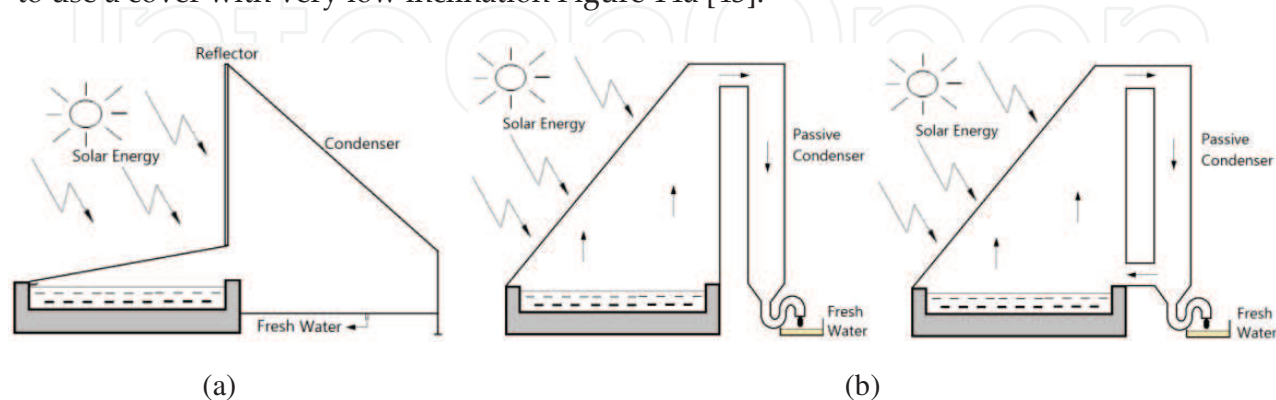

(a)   (b)

Figure 14. (a) Schematics of the solar still with minimum inclination, coupled to an outside condenser [44], (b) solar still with passive condenser [45]

Conventional basin type solar stills have significant disadvantages; horizontal water surface inevitably causes cosine loses especially at higher latitudes and large thermal capacity of the water in still basin limits fresh water output. Many researchers and new designs have been done to minimize or overcome these drawbacks of solar stills [46].

Stills with inclined absorber surfaces are reported to have significantly higher productivity compared to basin-type stills. In an inclined still, water flows from the top to the bottom of the absorber surface. To maintain uniform thickness of water, a wick is used to draw water by capillary effect. The productivity of a solar still is affected by the temperature difference between the water and condensing surfaces. A higher temperature difference between these surfaces yields higher productivity. To maintain this temperature difference, various methods were proposed [47].

In inclined stills feed water coming from the tank comes to the collector in pipes, passes through the drilled holes and drops onto the black absorber plate to evaporate by taking heat from the plate which is heated by solar irradiation. Vapour goes up and touches to the glass cover which is cool enough to condense on. Fresh water distillate accumulates on the inner surface of the glass cover and flows downwards to the condensate outlet port by gravitational forces.

Water droplet falling onto the absorber plate does not distribute perfectly on the absorber plate surface. Using a wick on the absorber plate helps to distribute water more evenly over the absorber plate using capillary effect which improves evaporation rate. Another way of improving the performance is to cool glass cover to ease condensation. Shaded plate is a simple yet effective solution (Figure 15). One fourth of the glass surface is shaded from the top leaving a gap of several centimetres between the shading plate and the glass. This arrangement provides a chimney effect in this gap and improves convective heat transfer to the atmosphere which cools down this part of the glass and increases the condensate production rate [47].

A good way to solve the cosine loss problem of basin type solar still is to design an inclined structure with cascaded weirs (Figure 16) [48]. Salt water is fed from the top and condensate is collected from the bottom end. Feed water flows through the weirs and fills all the weirs evenly. There is a small distance between the cover and absorber plate which quickens the saturation and condensation processes making the cascade system more efficient more than other solar stills.

Weir-type cascade solar stills do not suffer from dry spot or channelization problems since the brine is forced to flow each step one by one without leaving any dry surface on the absorber plate. Water flow way is longer than a normal or wicked inclined type stills and accordingly the solar exposition time is longer which increases the efficiency. It has the advantages of both basin type and inclined type solar stills. Further development of these weir-type cascade stills include using wick on each cascaded steps and phase change material (typically paraffin wax) beneath the absorber surface to store energy when it is abundant and give it back to the salt water when it is needed in cloudy days or evening times [48].

Another well-designed still is a combination of a glass cylinder and a tray or trough inside the cylinder (Figure 17a). Salt water is fed into the tray and the water travels through the tray. Incoming solar energy heats the tray and water to cause evaporation of salt water and consequently condensation of the vapour on the cylinder surface. Water droplets slip down
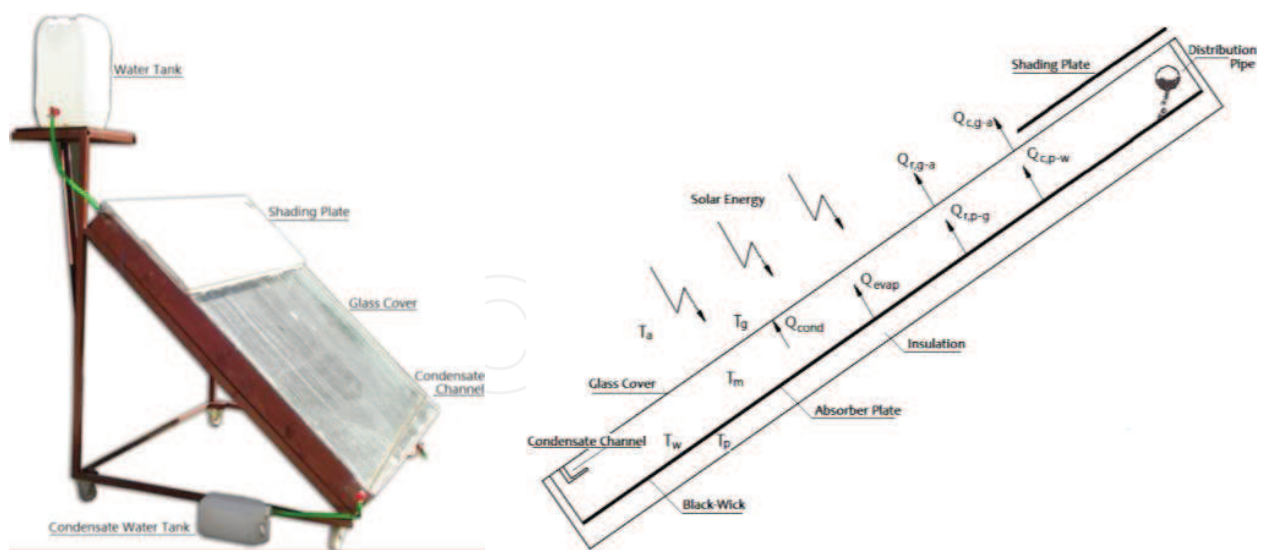
Figure 15. Inclined solar water distillation system and schematic diagram of the system [47]
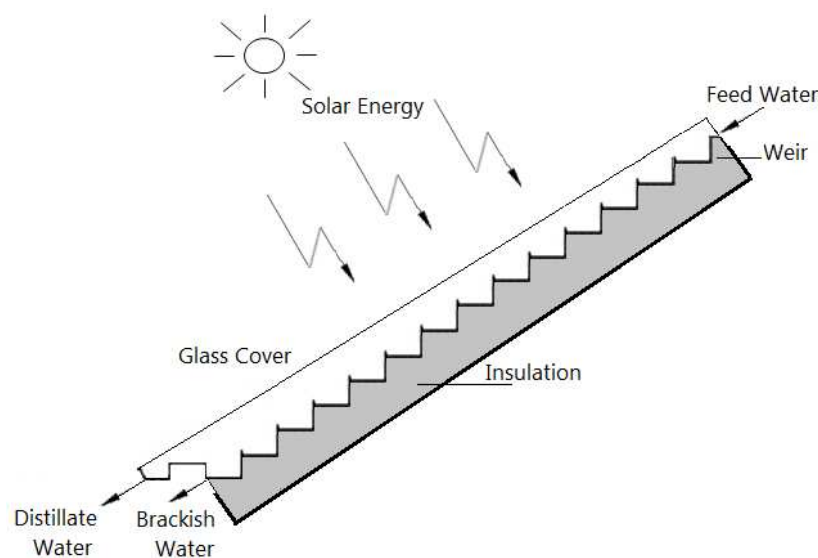

Figure 16. Schematic view of a weir type cascade solar still [49]

and accumulate at the bottom of glass cylinder and collected through the fresh water outlet. Cylindrical tube type stills are compact, robust and have high yield per unit are compared to the conventional basin still design [50]. There is a similar design in which wick is used in the tray to absorb salt water and diffuse throughout the tray with capillary effect. Wick lies along an incline, with the upper edge dipped in a saline water reservoir and there are two outlets, one for the excess water and the other is for condensate. Capillary suction of the cloth fibers used as wick produces a thin water film which can easily evaporate by the incoming solar radiation. The condensing surface area of the cylindrical glass over the evaporation tray is much more than that of a flat surface and this results in a relatively colder glass cover faster condensation rate [46].

A similar approach uses a sphere instead of cylinder as the still housing. A black painted of covered metallic plate is located at the centre plane of the spherical glass (Figure 17b). Spherical solar stills works like cylindrical ones and they are about 30% more efficient than an equivalent conventional solar still. Spherical stills have even more condensation area per evaporation surface compared to cylindrical solar stills but it is not scalable as easy as cylindrical ones [46].
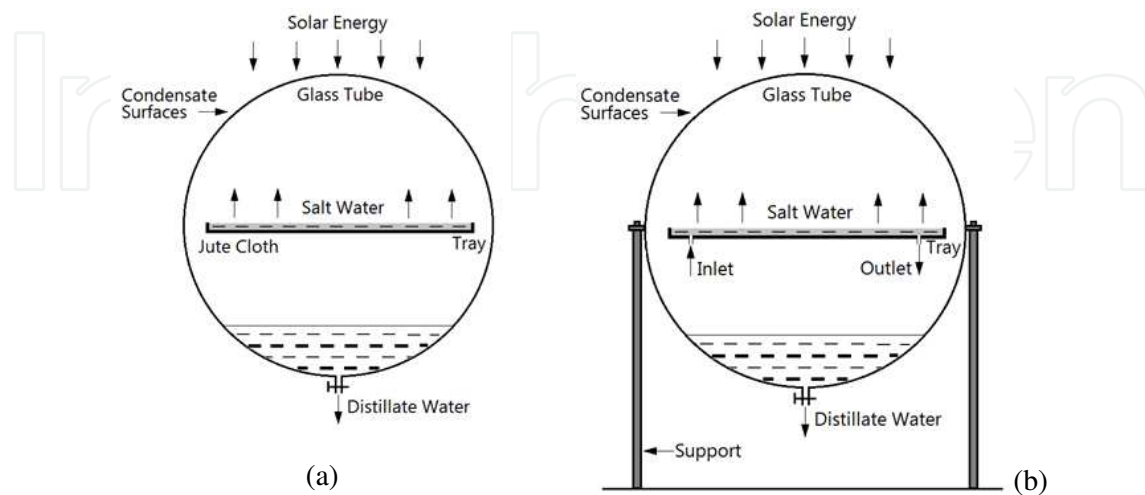

(a)   (b)

Figure 17. Schematic representation of (a) tubular solar still (front view) [51], (b) a spherical condensing solar still [46]

5.2.2.2. Active distillation

Many investigations have been conducted in attempt to improve the efficiency and productivity of solar stills. Some of these techniques are decreasing the depth of water in the basin, mixing black dye with the salt water, using better insulation to minimize the heat losses, improving the vapour tightness, proper orientation of the still as to receive more solar irradiation, etc.

Apart from the above-mentioned passive methods, there are a number of active methods of improving thermal efficiency such as integrating a still with a solar heater of concentrator. Active solar stills receive additional thermal energy from an outer source to the water in the basin which improves the rate of evaporation. A detailed classification of active and passive solar stills is given in Figure 6. Active solar stills are classified according to the integration type and operation principles of the solar stills. The main classification categories are: nocturnal distillation, pre-heated water distillation and high-temperature distillation solar stills.

Nocturnal production solar stills are able to operate when there is no sunlight. This can be achieved by mainly two ways: storing extra energy during day-time and using the stored energy at night, and making use of waste heat from another source. In order to store energy, still basin is filled to a depth that is more than required for full evaporation in an average day. At the end of the day some warm water would still remain in the basin of the still and continue to evaporate during no-sunshine hours of the day, which is called nocturnal distillation. This evaporation can be provided by feeding hot water from another heat source during night.

Pre-heated water application solar stills make use of waste heat from an external plant such as paper industries, chemical industries, thermal power plants and food processing industries to

heat the water in the basin through a heat exchanger or use the warm water directly in the basin to improve evaporation rate.

High temperature distillation stills increase the basin water temperature from about 20–50°C to 70–80°C by coupling an external solar system such as FPC, ETC, HPC, PSC, SP and PV/T hybrid system. In addition to these methods, some other methods with different operation properties are used with high temperature distillation method like multistage active, multi-effect air-bubbled solar still and hybrid solar distillation [52]. Figure 18 shows how a passive distillation system (a) can be converted to an active distillation system by addition of an external energy supply plant which can be integrated by natural circulation (b) or forced circulation (c).

Latent heat of condensation is one of the most significant heat losses of solar distillation systems. Finding a way for the re-utilization of this heat would greatly increase the thermal efficiency of the solar distillation system, which is defined as the daily production per square meter. One of those ideas is re-using the latent heat of condensation at the cover of a basin to heat the water in another basin [46]. Such a design is called multi-basin solar stills (Figure18). In multi-basin design, two or more basins are constructed like the floors in an apartment building. The bottom-most basin is covered by an absorber plate while the upper basins are transparent to allow solar radiation to reach the bottom plate. Condensing vapour at each basin cover heats up the cover by the latent heat of condensation. Heated cover of a basin forms basin of the upper still section and heats the water on it by that latent heat by re-utilizing the waste heat. Each section has its own condensate collection and salt water feeding channels.
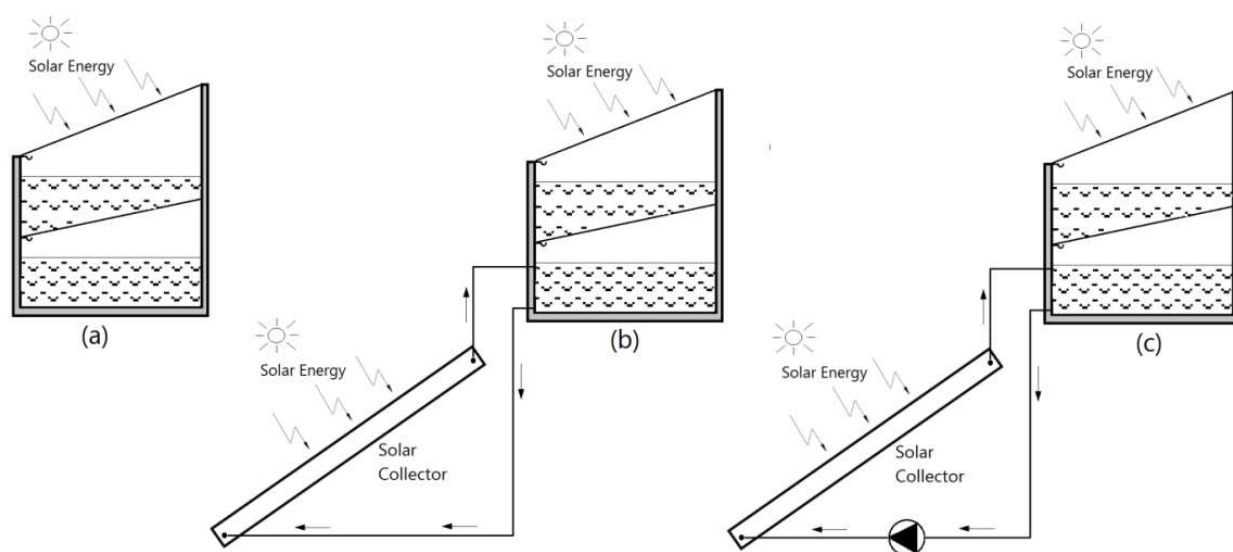

Figure 18. Schematic view of a double basin solar still. (b) Double basin still coupled to a collector in the natural circulation mode. (c) Double basin coupled to a collector in the forced circulation mode [52]

As shown in Figures 19 and 20, flat plate collectors and evacuated collectors can be used in active solar distillation systems. Solar collectors have high efficiency and improve the amount of distillation. However, the collector should be used in closed cycle to avoid precipitation of salt and other contaminants in the tubes and demolish the performance of the collector. Instead, a heat exchanger should be used (Figure 20) to transfer the heat to the basin water of the still [34].

Figure 19. Vacuum tube collector assisted solar distillation system [34]
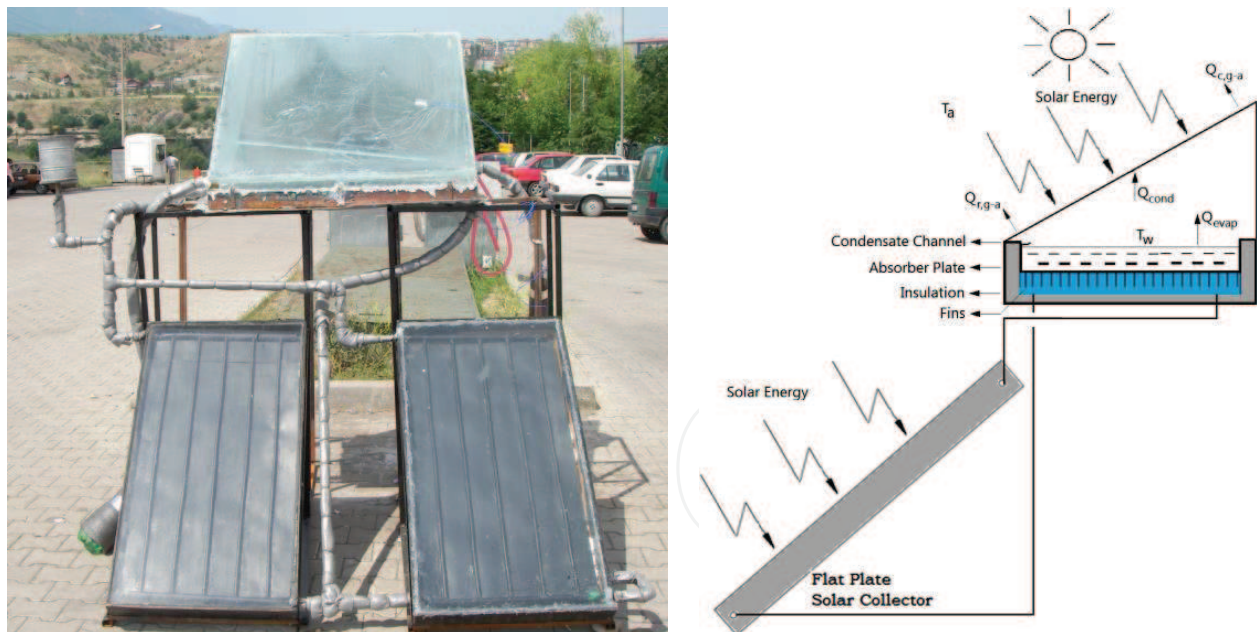

Figure 20. Flat plate solar collector assisted active distillation system and its schematic view

Solar stills can be successfully integrated with parabolic solar concentrators (Figure 21). Solar tracking parabolic concentrators concentrate the solar irradiation falling on a large area onto a small receiver area at high temperatures. High temperature and low heat loss area of the still basin which is located on the focal point of parabolic concentrator greatly improves the efficiency of the still. Salt water can be supplied to the still by natural or forced circulation [52].
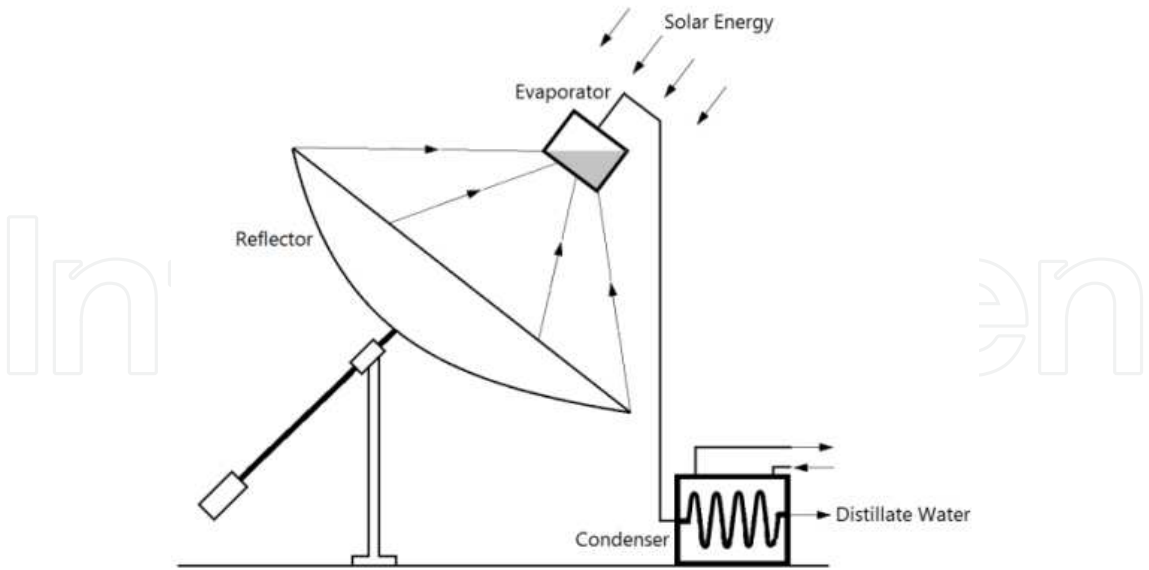
Figure 21. Schematic of a concentrating collector still [52]

Since the most critical stages of distillation process are evaporation and condensation, any measures that helps these two stages increases the efficiency significantly. A clever idea for promoting the evaporation at a certain temperature is forced air bubbling which causes an instantaneous atomization of water towards the air and a rapid evaporation. If it is possible to pre-heat the air that will be used for bubbling evaporation would be much better since the air that will carry the vapour also has the extra heat that evaporation process requires instantly during the bubbling effect (Figure 22). Another effective way of improving the still efficiency is cooling the cover surface [46, 52].
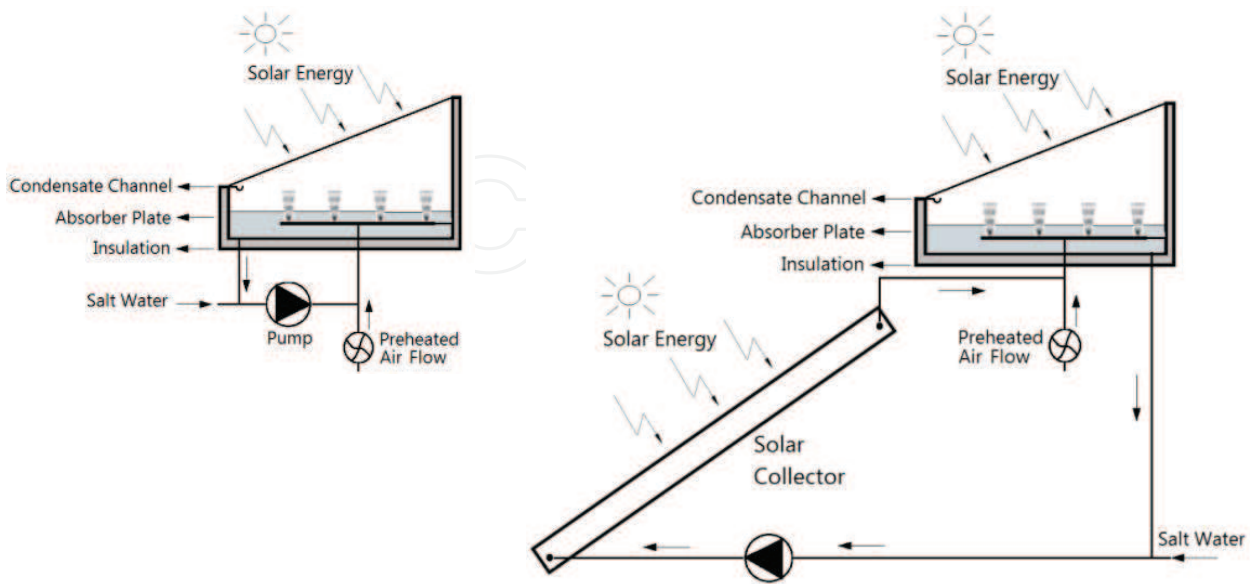

Figure 22. Air-bubbled solar still [46]

In a recent design, evacuated solar collector is hybridized with wicks/solar still to improve the productivity of still (Figure 23). Using single layer or double layer wick on absorber plate and integrating a feed water tank to feed hot salt water which is heated by solar collector during the daytime made up of a great combination of wick, inclined solar heating and energy storage which boosted the thermal performance and operation time of the still [53].
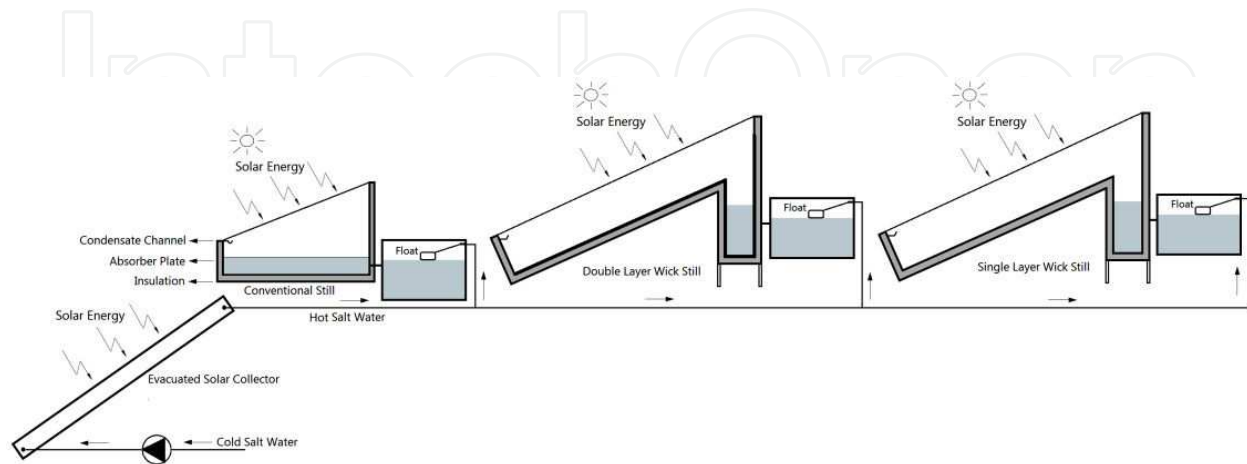

Figure 23. Schematic diagram of hybrid desalination system using wicks/solar still and evacuated solar water heater [53]

5.2.2.3. General considerations on solar stills

Making a general consideration of the solar stills, some common results can be concluded:

- Fresh water yield of a solar still depends on several parameters like solar insolation, ambient air temperature, wind speed, atmospheric humidity, sky conditions etc.

- The inclination angle of cover should be equal to the latitude of the installation site to minimize the cosine loses.

- Increasing water depth in the still basin decreases the distillate production rate.

- Each type of solar still has its own advantages and disadvantages. None of them is perfect.

- Increasing salinity of the salt water decreases the distillate production rate especially at low concentration range.

- Due to inclination angle single slope passive solar stills are better than double slope passive solar stills.

- FPC with forced circulation mode increase the performance solar still more than thermo syphon mode.

- Wind can slightly increase the total production.

- Although from morning to noon the highest distillate output are obtained at the highest water temperature times, more outputs can be observed at less water temperatures which can be attributed to the cooling glass cover before the system itself.

- Double slope passive solar still has a higher thermal efficiency than double slope active solar still.

- In active double effect solar stills lower basin gives the maximum yield because of the high noon temperature.

- The amount of fresh water produce in the still is closely related with thermal conductivity of condensing cover material.

6. Conclusion

Drinkable fresh water, being a fundamental need of human being, has become a serious concern for people especially living in crowded cities and countries with limited amount of water resources. Supplying fresh water is an energy intensive task especially when there is need for heating cold water to evaporate for distillation. Most of the big desalination plants around the world use fossil-based fuels as energy source to heat and vaporize the sea water or brackish water in order to produce fresh water. However, environmental concerns along with decreasing oil reserves and increasing fuel costs call for reconsideration on the fuel types used in many areas as well as in desalination or distillation processes. There are a number of well-known alternative and renewable energy sources in the world like wind, geothermal, solar, biomass etc. but achievability, availability when needed and energy storage are also very critical issues to operate the distillation plant effectively.

A very fortunate aspect of the issue is the coincidence of fresh water need and abundant solar energy. Most of the places with severe water scarcity are about the equator region where people needs more water due to highest degrees of air temperature in the world. Therefore, especially for these countries located in solar belt region, solar energy is a readily available, cost-free and abundant energy source which does not require transportation or very sophisticated technology to benefit from. Since most of the desalination processes run on heat, solar energy can be used directly as heat source which decreases the installation and operation costs significantly. Apart from simple solar powered stills, of course there are more complicated, yet much more efficient solar powered stills. Complex desalination systems which are all designed to improve the thermal efficiency and freshwater yield/ productivity use many approaches such as: multiple stage operation, pre-heating the feed water with the condensation energy, using additional heat sources (waste water from another process), concentrating solar energy to improve the operation temperature of the process etc.

Solar desalination systems can be a good solution to the water scarcity of especially the Sunbelt region. However, dominant use of clean and renewable energy sources for desalination process and replacement of the fossil fuel-based operations require more R&D studies to find more efficient and/or less costly power plants with continuous operation by the means of energy storage solutions.

Nomenclature

A_c	Area of collector (m²)
A	Absorptivity
CPC	Compound parabolic collectors
c_w	Specific heat of water in solar still (J/kg K)
ED	Electro dialysis
ETC	Evacuated tube collector
FPC	Flat plate collector
F_R	Heat removal factor
h_b	Overall heat transfer coefficient from basin liner to ambient air through bottom and side insulation (W/m² °C)
HD-DHD	Humidification-dehumidification
h_{ew}	Heat loss coefficient by evaporation from water surface (W/m²K)
h_{wg}	Heat transfer coefficient from the water surface to the glass (W/m²K)
h_{ga}	Heat transfer coefficient from the glass to the ambient (W/m²K)
h_{wb}	Heat transfer coefficient from the water to the basin liner (W/m²K)
HP	Heat pipe
I_c	Solar intensity on the glass cover of the solar collector panel (W/m²)
I_{eff}	Effective solar radiation intensity (W/m²)
L	Latent heat of vaporization (J/kg)
LCZ	Lower Convective Zone
LFC	Linear Fresnel collector technology
MED	Multiple effect distillation
MED-MVC	Mechanic vapour compression MED
MED-TVC	Thermal vapour compression MED
MEH	Multiple-effect humidification
M_w	Mass of water in basin (kg)
$\dot{m}_{ew}$	Hourly output of still (kg/m²h)
mf_s	Salt mass fraction
MSF	Multi-stage flash
NCZ	Non convective zone
P_g	Glass saturated partial pressure (N/m²)
P_w	Water saturated partial pressure (N/m²)
PTC	Parabolic trough collector
Q_{ew}	Evaporative heat transfer (W)

$\dot{Q}_u$	Rate of useful energy from collector (W)
RO	Reverse osmosis
SDC	Solar dish collector technology
SGSP	Salt gradient solar pond
SMCEC	Solar multi-stage condensation evaporation cycle
SWH	Solar water heating
T	Transmittance
T_a	Ambient air temperature (K)
T_b	Basin temperature (K)
T_g	Still glass cover temperature (K)
T_w	Still water temperature (K)
TSP	Tower solar power technology
UCZ	Upper convective zone
U_L	Overall heat transfer coefficient (W/m² °C)
V	Wind speed (m/s)
VC	Vapour compression
α'_b	Solar flux absorbed by the basin liner
α'_g	Solar flux absorbed by glass cover
α'_w	Solar flux absorbed by water mass
Subscripts	
c	Collector

Author details

Emrah Deniz*

Address all correspondence to: edeniz@karabuk.edu.tr

Department of Mechanical Engineering, Karabuk University, Karabuk, Turkey

References

[1] Gude VG, Nirmalakhandan N, Deng S. Renewable and sustainable approaches for desalination. Renewable and Sustainable Energy Reviews. 2010;14(9):2641–54.

[2] Shankar P, Kumar S. Solar distillation – A parametric review. VSRD International Journal of Mechanical, Automobile & Production Engineering. 2012;2(1):17–33.

[3] Yılmaz S, Deniz E. The comparison of efficiencies between two phased protected zone and indirect solar water heaters. Technology. 2009;12(4):259–66.

[4] Kalogirou SA. Solar thermal collectors and applications. Progress in Energy and Combustion Science. 2004;30(3):231–95.

[5] Qiblawey HM, Banat F. Solar thermal desalination technologies. Desalination. 2008;220(1):633–44.

[6] Akash BA, Mohsen MS, Nayfeh W. Experimental study of the basin type solar still under local climate conditions. Energy Conversion and Management. 2000;41(9):883–90.

[7] Chahine MT. The hydrological cycle and its influence on climate. Nature. 1992;359(6394):373–80.

[8] Managing Water Under Uncertainty and Risk [Internet]. UNESCO; 2012. Report No.: 4. (accessed 10 February 2015): http://unesdoc.unesco.org/images/0021/002156/215644e.pdf

[9] Trenberth KE, Smith L, Qian T, Dai A, Fasullo J. Estimates of the global water budget and its annual cycle using observational and model data. Journal of Hydrometeorology. 2007;8(4):758–69.

[10] Ondraczek J, Komendantova N, Patt A. WACC the dog: The effect of financing costs on the levelized cost of solar PV power. Renewable Energy. 2015;75:888–98.

[11] Bilton AM, Wiesman R, Arif AFM, Zubair SM, Dubowsky S. On the feasibility of community-scale photovoltaic-powered reverse osmosis desalination systems for remote locations. Renewable Energy. 2011;36(12):3246–56.

[12] Koschikowski J. Water desalination: When and where will it make sense? [Internet]. Fraunhofer Institute for solar energy systems ISE; 2011. (accessed 10 February 2015): https://ec.europa.eu/jrc/sites/default/files/jrc_aaas2011_energy_water_koschikowski.pdf

[13] Gupta B, Mandraha TK, j Edla P, Pandya M. Thermal modeling and efficiency of solar water distillation: A review. American Journal of Engineering Research (AJER). 2013;2(12):203–13.

[14] Mezher T, Fath H, Abbas Z, Khaled A. Techno-economic assessment and environmental impacts of desalination technologies. Desalination. 2011;266(1):263–73.

[15] Li C. Innovative desalination systems using low-grade heat [Internet] [PhD Thesis]. University of South Florida; 2012. (accessed 10 February 2015): http://scholarcommons.usf.edu/cgi/viewcontent.cgi?article=5322&context=etd

[16] Kalogirou SA. Seawater desalination using renewable energy sources. Progress in Energy and Combustion Science. 2005;31(3):242–81.

[17] Kurt H, Özkaymak M, Deniz E. Experimental investigation of heat storage characteristic of urea and borax salt gradient solar ponds. Pamukkale University Engineering College, Journal of Engineering Sciences. 12:449–55.

[18] Acar B. Düz ısı borulu güneşli su ısıtma sistemleri ile birleşik ısı borulu güneşli su ısıtma sistemlerinin performans değerlerinin kıyaslamalı olarak belirlenmesi [Msc Thesis]. [Fen Bilimleri Enstitüsü]: Zonguldak Karaelmas Üniversitesi; 2007.

[19] Deniz E, Buğutekin A, Kaşifoğlu S, Öz ES, Binark AK. Güneş kollektörlerinde soğutucu akışkan R-404a kullanımı ve sistem verimine etkileri. Isparta, Turkey; 2006. sayfa 158–66.

[20] Renewables 2014, Global Status Report [Internet]. (accessed 10 February 2015): http://www.ren21.net/Portals/0/documents/Resources/GSR/2014/GSR2014_KeyFindings_low%20res.pdf

[21] Ghaffour N, Bundschuh J, Mahmoudi H, Goosen MF. Renewable energy-driven desalination technologies: A comprehensive review on challenges and potential applications of integrated systems. Desalination. 2015;356:94–114.

[22] Baharoon DA, Rahman HA, Omar WZW, Fadhl SO. Historical development of concentrating solar power technologies to generate clean electricity efficiently–A review. Renewable and Sustainable Energy Reviews. 2015;41:996–1027.

[23] Tzen E, Perrakis K, Baltas P. Design of a stand alone PV-desalination system for rural areas. Desalination. 1998;119(1):327–33.

[24] Ali MT, Fath HE, Armstrong PR. A comprehensive techno-economical review of indirect solar desalination. Renewable and Sustainable Energy Reviews. 2011;15(8):4187–99.

[25] Ghermandi A, Messalem R. Solar-driven desalination with reverse osmosis: the state of the art. Desalination and Water Treatment. 2009;7(1-3):285–96.

[26] García-Rodríguez L, Delgado-Torres AM. Solar-powered rankine cycles for fresh water production. Desalination. 2007;212(1):319–27.

[27] Saidur R, Elcevvadi ET, Mekhilef S, Safari A, Mohammed HA. An overview of different distillation methods for small scale applications. Renewable and Sustainable Energy Reviews. 2011;15(9):4756–64.

[28] Hamid MOA, Zhang B, Yang L. Application of field synergy principle for optimization fluid flow and convective heat transfer in a tube bundle of a pre-heater. Energy. 2014;76:241–53.

[29] Narayan GP, Sharqawy MH, Summers EK, Lienhard JH, Zubair SM, Antar MA. The potential of solar-driven humidification–dehumidification desalination for small-scale decentralized water production. Renewable and Sustainable Energy Reviews. 2010;14(4):1187–201.

[30] Kabeel AE, Hamed MH, Omara ZM, Sharshir SW. Water desalination using a humidification-dehumidification technique—A detailed review. 2013 (accessed 10 February 2015): http://file.scirp.org/Html/8-2000200_33877.htm

[31] Parekh S, Farid MM, Selman JR, Al-Hallaj S. Solar desalination with a humidification-dehumidification technique—a comprehensive technical review. Desalination. 2004;160(2):167–86.

[32] Hanson A, Zachritz W, Stevens K, Mimbela L, Polka R, Cisneros L. Distillate water quality of a single-basin solar still: laboratory and field studies. Solar Energy. 2004;76(5):635–45.

[33] Haruna IU, Yerima M, Pukuma AD, Sambo II. Experimental investigation of the performance of basin type single-slope solar still. (accessed 10 February 2015): http://www.ijstr.org/final-print/mar2014/Experimental-Investigation-Of-The-Performance-Of-Basin-Type-Single-slope-Solar-Still.pdf

[34] Deniz E. An experimental and theoretical analysis of a vacuum tube solar collector-assisted solar distillation system. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 2012;34(17):1637–45.

[35] Mowla D, Karimi G. Mathematical modelling of solar stills in Iran. Solar Energy. 1995;55(5):389–93.

[36] Badran OO, Abu-Khader MM. Evaluating thermal performance of a single slope solar still. Heat and Mass Transfer. 2007;43(10):985–95.

[37] Kumar S, Tiwari GN. Estimation of convective mass transfer in solar distillation systems. Solar Energy. 1996;57(6):459–64.

[38] Tripathi R, Tiwari GN. Thermal modeling of passive and active solar stills for different depths of water by using the concept of solar fraction. Solar Energy. 2006;80(8):956–67.

[39] Rubio E, Fernández JL, Porta-Gándara MA. Modeling thermal asymmetries in double slope solar stills. Renewable Energy. 2004;29(6):895–906.

[40] Tiwari GN, Singh HN, Tripathi R. Present status of solar distillation. Solar Energy. 2003;75(5):367–73.

[41] AnfasMukram T, Suneesh PU. Experimental analysis of active solar still with air pump and external boosting mirrors. International Journal of Innovative Research in Science, Engineering and Technology. 2013;2(7):3084–904.

[42] Kabeel AE, Omara ZM, Essa FA. Enhancement of modified solar still integrated with external condenser using nanofluids: an experimental approach. Energy Conversion and Management. 2014;78:493–8.

[43] El-Bahi A, Inan D. Analysis of a parallel double glass solar still with separate condenser. Renewable Energy. 1999;17(4):509–21.

[44] El-Bahi A, Inan D. A solar still with minimum inclination, coupled to an outside condenser. Desalination. 1999;123(1):79–83.

[45] Muftah AF, Alghoul MA, Fudholi A, Abdul-Majeed MM, Sopian K. Factors affecting basin type solar still productivity: A detailed review. Renewable and Sustainable Energy Reviews. 2014;32:430–47.

[46] Arjunan TV, Aybar H, Nedunchezhian N. Status of solar desalination in India. Renewable and Sustainable Energy Reviews. 2009;13(9):2408–18.

[47] Deniz E. An investigation of some of the parameters involved in inclined solar distillation systems. Environmental Progress & Sustainable Energy. 2013;32(2):350–4.

[48] Zoori HA, Tabrizi FF, Sarhaddi F, Heshmatnezhad F. Comparison between energy and exergy efficiencies in a weir type cascade solar still. Desalination. 2013;325:113–21.

[49] Sivakumar V, Sundaram EG. Improvement techniques of solar still efficiency: A review. Renewable and Sustainable Energy Reviews. 2013;28:246–64.

[50] Chen Z, Yao Y, Zheng Z, Zheng H, Yang Y, Hou L, vd. Analysis of the characteristics of heat and mass transfer of a three-effect tubular solar still and experimental research. Desalination. 2013;330:42–8.

[51] Ahsan A, Fukuhara T. Mass and heat transfer model of tubular solar still. Solar Energy. 2010;84(7):1147–56.

[52] Sampathkumar K, Arjunan TV, Pitchandi P, Senthilkumar P. Active solar distillation—A detailed review. Renewable and Sustainable Energy Reviews. 2010;14(6):1503–26.

[53] Omara ZM, Eltawil MA, ElNashar EA. A new hybrid desalination system using wicks/solar still and evacuated solar water heater. Desalination. 2013;325:56–64.