# A REVIEW ON EXISTING SOLAR DISTILLATION SYSTEMS

**Nijith Mathew**
Dr. Jivraj Mehta Institute of Technology, Mogar

**Avdhoot N. Jejurkar**
Dr. Jivraj Mehta Institute of Technology, Mogar

**Prashant S. Nair**
Dr. Jivraj Mehta Institute of Technology, Mogar

## ABSTRACT
Desalination is the science of removing salt and impurities from saline or sea water for potable water, which has been used from ancient times till present day. Studies are conducted on various desalination systems to enhance the design and efficiency. Recorded and known history till date is a proof of the prominence that Desalination holds as a science. Among the various methods of desalination, Solar Distillation holds a special place due to its dependence on a renewable source of energy. Solar Distillation is further divided into active and passive, from which passive systems are more nature friendly due to lack of electrical or mechanical integration and total dependence on solar radiation. Passive systems have seen a lot of innovation in design, from a Conventional solar still to the most modern commercially sold conical stills. A Pyramid shaped solar has comparatively more productivity with respect to the basin area. A Thermal modelling to show its reduced heat loss coefficients confirms its dominance among other systems. A Thermo-economic comparison of all the major types of solar distillation systems, which takes into account all the economic and technical factors from construction to final output, furthermore asserts this claim.

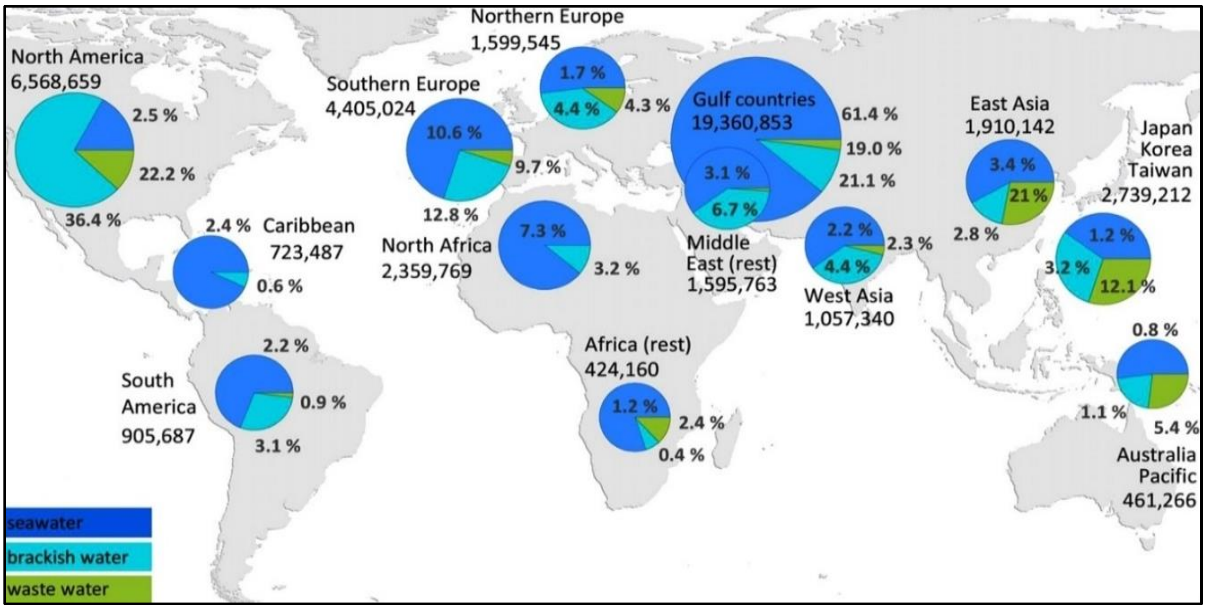
**Keywords: Desalination, Solar distillation, Passive System, Pyramid Solar Still.**

## 1. INTRODUCTION
Water is a universally consumed commodity; it is necessary for both, sustenance and domestic use. The desired quality of consumed potable water is lack of impurities. Water quality is measured in TDS (Total Dissolved Solids) whose unit is PPM (Parts Per Million) or PPT (Parts per Trillion) and TSS (Total Suspended Solids) whose unit is mg/l. Most of the water on the surface is in oceans and seas (97.5%) but it has very high amount of salinity and impurities [1]. Currently the amount of water that is available for potable use is very low (0.014%) in comparison to the actual amount of water on the surface of the Earth. If the potable water on the surface depletes due to global warming and other man-made calamities, then there is no other option than to use this Saline water from the large water bodies. But the increased salt level is very harmful to the human body when consumed in a larger amount. For this problem there is only one solution, Desalination [2].

## 2. DESALINATION
Desalination can be traced back to a very long time ago, almost around the Egyptian Era. During the fourth century B.C. Aristotle, during his time, had described a method to desalinate impure water by evaporation and condensation. Potable water was a matter of concern when long distance ships were built. About this Alexander of Aphrodisias accounted in 200 A.D. that early Greek sailors used to boil sea water in brass utensils and collected the evaporate from the mouth of the utensil with the help of sponges or cloth to obtain sweet water [4]. Many different civilisations came up with similar ideas to desalinate water by observing the water cycle in the nature. With the rise in globalisation through ships and long distance travels the use of desalination spread throughout the remaining civilisations.

In the modern world many different types of desalination were invented and applied. Today there are many types of desalination that are prevalent and are major sources of desalinated water. Desalination systems use different types of feed water are selected according to the capacity and principle of the desalination process involved. The main three types of water are Seawater, Brackish water and waste water. The daily desalination capacities of various countries are given in l/day in the figure 1. The percentage indicated nearby shows the percent of usage from total global usage [3]. Today there are different types of desalination systems adopted in the industry. Some of the prominent methods used in the industry are Reverse Osmosis, Multistage Flash Distillation, Multiple-effect Distillation, Electrodialysis Membrane, Membrane Distillation and Solar Distillation.

**Figure 1: Graphical representation of the type of feed water used by different countries**

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### *2.1 Reverse Osmosis (RO):*

Reverse Osmosis is the main source of desalinated water because of its hassle free functioning, low maintenance and higher output flow. It is also preferred more in urban areas because it runs on electricity which is easily available.RO accounts for more than 22.4 Million m$^3$ of desalinated water per day which is 51% of the total daily output of all the desalination systems in the world [3]. The principle of a RO system is based on the natural osmosis effect -flow of liquid from higher concentration to lower concentration- found in nature, which occurs without any external force. But in RO systems the direction of flow is reversed with the help of an external force -usually a pump- and a semi permeable membrane, through which only water can flow thus entrapping salts and minerals [5]. On an average a RO system purifies only one third of the input water and rejects the remaining water in concentrate form [6] [7]. Places having water scarcity cannot afford to lose this precious water.

### *2.2 Multi-Stage Flash Distillation (MSF):*

This is the second most used technology for desalination, after RO systems. It globally produces 14 Million m$^3$ of desalinated water per day which is 32% of the total daily output [3]. This technology is mostly used in Arab countries where power plants having steam generation convert steam energy to useful fuel for the MSF systems. A Multi-Stage Flash Distillation uses steam as its fuel of operation. The steam is used to increase the temperatures of the seawater and this seawater flows through consecutive chambers which have reduction in temperature. In each chamber evaporation occurs and the vapours are collected with the help of an outlet channel. The temperature decreases in each stage while moving away from the first chamber and because of this change, the internal pressure and condensate varies successively [7] [8].

### *2.3 Multiple-Effect Distillation (MED):*

In 1961 R. V. Dunkle published the first research paper on a roof type solar distillation unit. In that paper he discussed in detail about a Multiple Effect Diffusion Still [9]. Today MED provides more than 3.7 Million $m^3$ of desalinated water per day, which is 8% of the total daily output [3]. This technology is becoming obsolete day by day because of the increased amount of energy required for its functioning. Some of the major users of MED systems are Saudi Arabia, The United Arab Emirates and Kuwait (Kuwait is a country totally dependent on desalinated water and desalinates 100% of its water) [6]. The principle that a MED system runs on is similar to that of a simple Distillation System [9]. The main fuel of the system is steam that is obtained from a boiler installed for the exclusive purpose of the MED system or is the by-product of some other system [6] [7]. Saline water enters the system as hot water and passes through different chambers where the temperature increases. Evaporation occurs due to the heat of the input saline water, the reduced ambient pressures and the vapour of the previous chamber [8]. The number of chambers is dependent of the type the system. New MED systems are not installed anywhere due to its complex construction and the high installation and operating costs [10].

### *2.4 Electrodialysis Membrane (ED):*

Most of the desalinated water in the world (c. 90%) is obtained from the above said three systems. Electrodialysis membrane produces 1.6 Million $m^3$ of desalinated water per day, it is 4% of the total global output [3]. Electrodialysis Membrane system is limited to desalinate only brackish water [7]. An Electrodialysis Membrane System runs on direct current flowing through parallel channels divided by positive and negative membranes which act like An-ion membrane and Cat-ion membrane. When water passes through this electric field molecules of water and molecules of salts are separated [7]. The system functions due to an electric current, so only ionic compounds can be removed from the water, whereas RO and Distillation systems can remove all types of impurities [8].

### *2.5 Membrane Distillation:*

Membrane Distillation is also one the types of desalination which doesn’t have a widespread application due to its novelty and lack of research in the field [7]. The contribution due to MD is also very low in global desalination (less than 0.5%) due to these factors [8]. In a Membrane Distillation System, a hydrophobic, microporous membrane is used to separate impurities from water. Being hydrophobic in nature the membrane will pass out water vapour molecules, but it will capture the impurities in its pores [11]. Due to the temperature gradient between the feed water and the permeate flux is created in a direction which flow occurs [12].

### *2.6 Solar Distillation:*

Desalination of water, with the help of solar energy (Renewable energy) is called Solar Distillation. A Solar Distillation Unit or a Solar Still utilises Irradiance which passes through a transparent cover to heat the water in the basin. This water starts evaporating due to increasing temperature and controlled pressure inside the still. Water vapour rises upwards and starts to condensate on the inner side of the condensing cover and it is collected through outlet channels. The most basic type of Solar still is a Conventional solar still, also known as Single slope solar still, which has one basin and one condensing cover. Many variations were further invented to enhance the output of the solar still.

### *2.7 Other Technologies:*

**Freeze Thaw:**

In this system the feed water is fed through the heat exchanger. The ice in the form of crystals are separated or washed in a cycle outside the main refrigeration cycle. A counter flow of freshwater is forced on that mixture to further clean the ice from remaining brine. This ice then enters the Melter and freshwater is obtained from it [13] [8].

**Wave Powered Distillation:**

A Wave powered system uses a pump that is powered with the help of the waves forming in oceans or seas. The work required to be done on the system is mainly mechanical for a RO system so to fulfil this demand of work instead of using an electrical pump, a pump that can utilize the forces of the waves and convert it to useful mechanical work is applied [14].

**Vacuum Distillation:**

Vacuum distillation is a part of Membrane Distillation which uses vacuum to enhance the productivity of the membrane distillation system [13]. A vacuum pressure is maintained in the side having permeate and is most suitable when volatile substances needs to be removed from the freshwater [12].

**Vapour-Compression Distillation:**

A Vapour Compression Distillation system utilizes the heat from the vapour compression to evaporate the seawater, sometimes even at $70^0$. With the reduced pressure, the temperature required for boiling also reduces, this principle is utilized for a VCD system [13].

## 3. SOLAR DISTILLATION

The oldest report of using solar energy to desalinate water goes back to the time of Cleopatra the Wise, the Greek alchemist from Alexandria. He mentioned various distillers to obtain extracts from herbs and medicines using Alembics. Later on, Arab alchemists adopted these methods and found out new designs. Giambattista Della Porta (1535 -1615) wrote plenty of books in Italian. Many of those were translated to French and English, where he discusses about more than ten methods of desalination. Most significant among them was the method of desalination of water by using earthen pots exposed to sun rays to evaporate water and using vases to collect fresh water from underneath. Also, French chemist Lavoisier, in 1774, described a method of concentrating the sunrays with the help of crystal onto the distillation flasks for improved desalination [4].

In 1870, Norman W. Wheeler and Walton W. Evans were successfully granted a patent for a solar distillation unit based on their experimental works for distillation of alcohol and water. The complete design, functioning and the problems arising in the still were mentioned in detail in the patent, which can be said was very much progressive to be achieved at that time. In 1872, Carlos Wilson, a Swedish engineer built from his own designs, the first solar distillation unit in Las Salinas, Chile to obtain freshwater (22.70 $m^3$) and was functional for almost 40 years.

With the boom in technology during the $20^{th}$ Century many more scientists, engineers and organizations further developed solar distillation. Some of the notable names are Mouchat, Maria Telkes, Louis Pasteur, C. G. Abbot, G. O. G. Loef, Everett D. Howe, V. A. Baum and some important organisations are Massachusetts Institute of Technology (MIT), Office of Saline Water (OSW) – USA, McGill University – Canada, Technical University of Athens, Commonwealth Scientific and Industrial Research Organization (CSIRO) – Melbourne. Indian organisations are National Physical Laboratory – New Delhi and CSIR – Central Salt and Marine Chemical Research Institute in Bhavnagar.

### 3.1 Passive Solar – Distillation Systems

A passive solar distillation system utilizes only the direct radiation that is absorbed by its inner surface. No integrated system is used that augments its input irradiance. Such systems are only preferred when the economics of the systems are of much importance, usually when the system is a commodity that can be used in domestic purposes by people of low-income generating populations. There exist methods by which a distillation system, while remaining passive, can increase its productivity. For this design considerations are applied to the system which includes, creating grooves or segments in the basin, using wick to increase evaporation, using different types of polymer paints/materials to increase irradiance absorption, minimizing heat and mass loss or using nanoparticles in water to increase their temperature holding capacity.

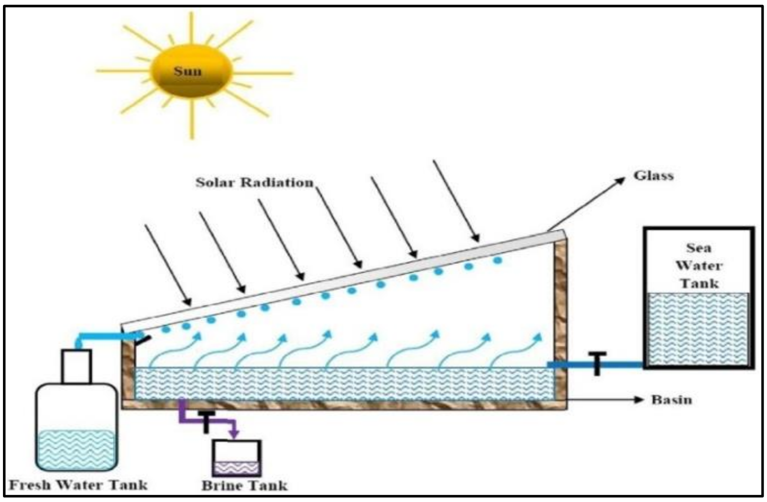
Thermal Storage Materials are also used to increase the productivity of a still during off sunshine hours. There are two divisions of thermal storage materials. Sensible heat storage materials absorb heat but do not change phase while doing so. Some of the material used are pebbles, marble, granite stones, metallic cubes. Latent heat storage materials absorb heat while changing phase. A few materials used are Phase Change Materials, wax, water, ammonia, eutectic salts.

#### *3.1.1 Single Slope Solar Still (Conventional Solar Still)*

A Single Slope Solar Still is the first type of Solar Still that was designed and incorporated foe freshwater production. That is why it gets the name Conventional Solar Still. Its basic design features are that it has a Single condensing cover and a single basin. Conventional Still holds an important place in the history of Stills as most of the modelling are based on the Conventional Still, but it became obsolete with increase in new designs and its low productivity.

A Single Slope Solar Still is placed in such a way that it always faces the Sun. The still uses the radiation from the Sun, which it collects in the Absorber plate as the source of input energy. This Absorber plate is usually painted black to absorb maximum insolation [15]. The Solar Still, being a covered box with controlled internal pressure starts boiling the water even at comparatively lower temperature. Due to boiling, evaporation occurs and those vapours rise above in the still and come in contact with the inner part of the condensing cover and undergo Dropwise Condensation in the beginning and eventually turn into Filmwise Condensation. The condensate is collected in the product line through which it is collected outside the still. The water collected from a distillation unit theoretically has zero PPM of TDS or TSS.

**Figure 2: Working principle of a Conventional solar still**

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### *3.1.2 Double Slope Solar Still*

A double slope solar still works on the same principle as that of a single slope solar still. The only difference is in the shape of the condensing cover. In a double slope solar still two condensing covers of same dimensions are placed on the top of the still, with joined edges giving, it an isosceles triangle type of design. This still is placed in such a way that the line joining the condensing covers are parallel to the longitude and the covers face east and west direction respectively [16].

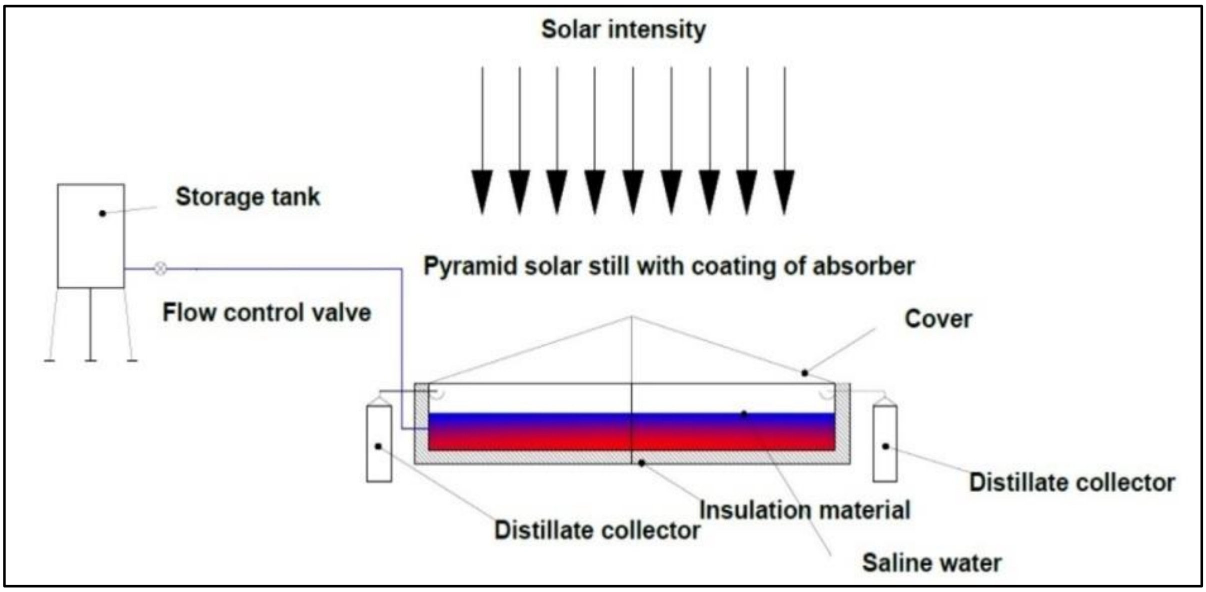
### *3.1.3 Triangular Pyramid Solar Still*

A Triangular Pyramid Solar Still has three sheets of triangle shaped condensing covers joined together at the top edges. There are usually three product lines to collect the distillate output. The main benefit of a Triangular shaped cover is that the direction of the still does not matter as sunrays can incident on the absorber plate from all around the still. So, usually, not always, the still is placed in such a way that one of the covers is facing the opposite hemisphere [17].

### *3.1.4 Pyramid Solar Still*

A Pyramid shaped solar still is shaped like the Square Pyramids of Giza, i.e. it has four triangular condensing covers of the same dimensions joined together at the top. The distillate is collected from 1, 2 or even 4 product lines as per the necessity. The benefit of such a cover is that sunrays can be incident on the absorber plate from every side of the still and if a lower basin depth is selected then almost entire absorber plate can get direct sunlight. Other importance is the increased productivity due to less distance between condensing cover and basin water and the increased condensing cover area.

**Figure 3: Working principle of a Pyramid solar still**

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### *3.1.5 Conical Solar Still*

A Conical Solar Still has an inverted cone as the condensing cover. A conical still also has the same benefits as that of a Pyramid still. It has a common product line which is a circular ring inside the cover at the bottom part. The productivity of this solar still is comparatively less because due to the complex shape of the condensing cover only plastic or fibrous materials can be used as and the heat transfer properties of these materials are very weak in comparison to glass [1]. Because of this reason the use of conical solar still is very limited.

#### *3.1.6 Hemispherical Solar Still*

A Hemispherical Solar Still has a spherical dome type condensing cover, usually in an exact hemispherical shape or a section of hemisphere [19]. The dome is usually made of Plastic or fibrous material and so has the same limitations as that of a conical solar still. Distillate can be collected from one product line but if need arises the number is increased.

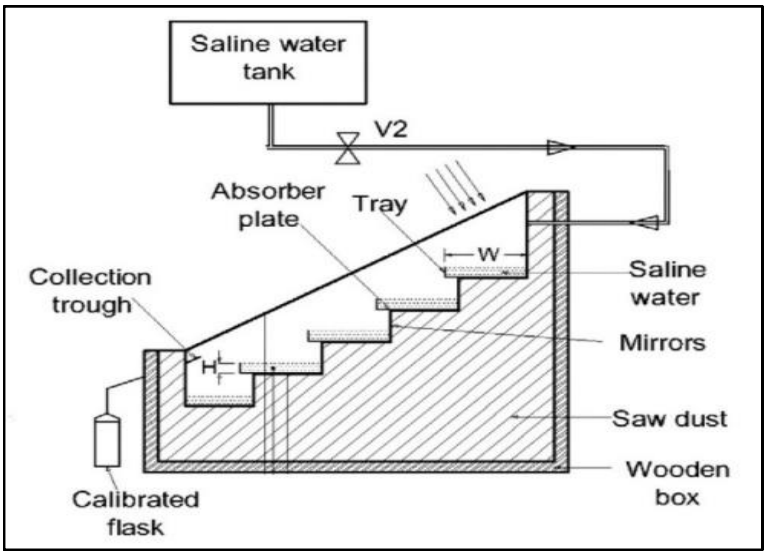
#### *3.1.7 Spherical Solar Still*

A Spherical solar still is a complete hollow sphere made of glass or transparent materials. It is supported with the help of a stand affixed on both the poles around the diameter. An open container filled with saline water and having an absorber plate at the bottom is suspended inside the sphere. Sunrays fall on the absorber plate to heat the water and its vapours rise inside the sphere and condense on the inner surface. This condensate is collected by a product line given exactly at the lowest point in the bottom hemisphere [20]. The productivity can be increased if a glass condensing cover is used, as the amount of direct radiation the absorber plate receives is of higher levels.

#### *3.1.8 Stepped Solar Still*

A Stepped solar still has a similar plain condensing cover as that of a Conventional Solar Still, but the difference is in the basin. The basin is inclined at the same angle as the condensing cover and has equidistant containments to separate water in sections. A Stepped solar still is proven to be one of the best methods of distillation for domestic and small-scale purposes [21]. It has Water inlet at the top part and a product line at the lower end of the condensing cover. Most of the radiation can be rapidly converted into heat for the water because of the separated water masses which can gain heat easily due to lesser quantity.

**Figure 4: Working principle of a Stepped solar still**

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#### *3.1.9 Tubular Solar Still*

A Tubular Solar Still, like a Spherical Solar Still, is completely transparent and is a long hollow cylinder with a similarly long water basin suspended in the centre. The radiation heats the water in the basin and this initiates evaporation. The condensing cover being a tube traps and condenses the vapour which in turn slides down towards the lower end of the slightly tilted tube. These still have only one product outlet [20].

## 3.2 Active Solar – Distillation Systems

Active solar distillation systems use integration of other irradiance absorbing/enhancing systems to increase the productivity of the system. These types of systems are comparatively costly and thus are used by Governments, advanced institutions and by very few domestic users who can afford such higher cost for better productivity. The key types of systems of integration to enhance the productivity are discussed below.

### *3.2.1 (Reflecting) Mirror*

Mirrors have been used to reflect solar radiation in solar and various other systems where just reflection is needed, not concentration. Mirrors are used solely to reflect radiation which in turn increases the irradiance on an absorbing surface. Mirrors are attached in solar distillation systems at an angle so that the radiation can be reflected on the absorber plate and the angle is changed according to the time of the day or the time of the year [22].

### *3.2.2 Flat Plate Collector*

Flat Plate Collectors are used to increase the absorber plate area of any given system without changing the design of the existing system. They are simple boxes with glass or fibrous material as the cover and have a basin of black colour to absorb more heat for the system. The Fluid (usually Air or Water) is streamed through the flat plate collector through Natural convection (gravity) or Forced convection (pump). This extra heated fluid is the used for the system, thus increasing the temperature of the inlet fluid and increasing the productivity of the system [23].

### *3.2.3 Evacuated Tubular Collector*

An Evacuated tube collector is the modernized design of a collector which is applied broadly in the industry because of its great efficiency. An ETC contains two concentric glass cylinders separated by vacuum in which the inner cylinder has a reflective coating which traps all the solar radiation inside it and the vacuum acts as insulation to prevent heat losses [24]. Generally, an array of ETCs kept parallel to each other, are integrated to a system. Because of vacuum insulation the capacity of the ETC increases to a much higher level in comparison to other collector systems.

### *3.2.4 Concentrators*

Concentrators come in various designs in which reflecting materials (generally mirror) are used to focus all the incident radiation to one specific point or line [25]. Sections of various shapes like, sphere, ellipse, parabola, cylinder, etc. are used as concentrators [26].

### *3.2.5 Solar Tracking*

Solar tracking can enhance the yield a solar system by rotating the entire system or just the radiation absorbing/reflecting surface according to the movement of the sun across the sky [27]. The benefit of solar tracking is that the radiation falling on the system is always incident at the equivalent or optimum angle which is subjected to the maximum irradiation.

From the above-mentioned systems, it is suitable to select a passive system, as the cost and the number of components of the system while being passive is the least. Also, environmental safety is promoted through passive solar systems. A Pyramid shaped solar still proves to be efficient among the passive systems as it has the maximum output-to-basin area ratio [18].

## 4. PYRAMID SHAPED SOLAR DISTILLATION UNIT

A Pyramid Shaped Solar Still, as discussed earlier has four triangular condensing covers of equal dimensions joined at the top vertices in the shape of a Pyramid. This increases the condensing cover area as well as provides means for more radiation to enter the basin. When various still configurations were compared, Pyramid solar still was at top of the list with 4.3 $l/m^2$ productivity [2]. For Pyramid solar stills the productivity is maximum when the glass cover inclination angle is equal to the latitude angle of that particular geographical location and it tends to decrease with change in the angle [19].

As the system functions due to heat, a thermal analysis best describes the effects of heat on various components and the water in the system -which undergoes phase change multiple times. A thermal modelling, best describes the system in terms of heat and mass transfer. While a pyramid still is selected as the better option in evaluation, its thermal modelling will further add to its qualities of better candidature.

A Thermal/Theoretical model for Pyramid shaped solar still was claimed, which is hugely dependent on the thermal modelling of a double slope solar still [28]. Most of the calculations for the basin area and the hourly output were based on those of a double slope solar still. There is lack of a real thermal modelling which takes into account the complex shape of the inner side of the pyramid shaped condensing cover and the rate of heat and mass transfer to and from that complex surface.

### 4.1 Thermal Modelling of Pyramid Shaped Solar Still

The most conventional method of coining a thermal modelling is through segmenting the main surfaces in whose contact heat and mass transfer occur. In any solar still the surfaces through which heat/mass transfer occur are (i) Basin, (ii) Saline water and (iii) Condensing cover. After segmentation, the energy balance equations are defined to find out heat loss and its coefficient [28]. With the help of these values efficiency of the solar distillation system and its hourly output is also calculated. The energy balance equations are:

#### *4.1.1 Energy balance equation for still basin*

Solar energy absorbed by the basin = Energy stored in the basin + energy lost to the water mass by convection + total energy lost to the surroundings [28]

$$I(t)\, A_b\, \alpha'_b \quad = \quad m_b C_b \frac{dT_b}{dt} + Q_{conv,\, b-w} + Q_{loss} \qquad (1)$$

Where, $I(t)$ is incident solar energy for solar still,
$A_b$ is area of the basin,
$\alpha'_b$ is the fraction of solar radiation absorbed by the basin,
$m_b C_b$ is heat capacity of the basin material and
$\frac{dT_b}{dt}$ is temperature gradient with respect to time in the basin.

Energy transfer by convection from basin to saline water in the basin is,

$$Q_{conv,\, b-w} \quad = h_{conv,\, b-w}\, A_b (T_b - T_w) \qquad (1.1)$$

Energy loss to the surroundings from the basin is,

$$Q_{loss} \quad = U_b A_b (T_b - T_a) \qquad (1.2)$$

Overall heat transfer coefficient for the basin is,

$$Ub = \left(\frac{y_{ins}}{k_{ins}} + \frac{1}{h_{t,b-a}}\right)^{-1} \qquad (1.3)$$

Where, $y_{ins}$ and $k_{ins}$ are the thickness of insulation and thermal conductivity of insulation material.

### *4.1.2 Energy balance equation for salt water surface*

Solar energy absorbed by the saline water + energy absorbed from the basin by convection = Energy stored in the saline water + energy loss to the inner surface of the condensing cover [28]

$$I(t)\, Aw\, \alpha'w + Qconv,\, b\text{–}w = mwCw\frac{dT_w}{dt} + Qt,\, w\text{–}c \qquad (2)$$

Where,
$A_W$ is area of the water surface that absorbs solar radiation,
$\alpha'_W$ is fraction of solar radiation absorbed by the saline water,
$m_WC_W$ is the heat capacity of saline water and
$\frac{dT_w}{dt}$ is temperature gradient with respect to time in saline water.

The heat transfer for the saline water is in three modes, viz. convection, evaporation and radiation. It is evident from the following equation,

$$Q_{t,w-c} = h_{t,w-c} A_W (T_W - T_c)$$

$$= (h_{conv,w-c} + h_{rad,w-c} + h_{evp,w-c}) A_W (T_W - T_c) \qquad (2.1)$$

Where,

$$h_{conv,w-c} = 0.884\, X\left[(T_W - T_c) + \frac{(p_W - p_c)\,.\,T_W}{268{,}900 - p_W}\right]^{\frac{1}{3}} \qquad (2.2)$$

$$h_{evp,w-c} = 16.273\, X\, 10^{-3}\,.\, h_{c,w-c}\,.\,\frac{(p_W - p_c)}{(T_W - T_c)} \qquad (2.3)$$

$$p = e^{\left[25.317 - \frac{5144}{T}\right]} \qquad (2.3.1)$$

$$h_{rad,w-c} = \varepsilon_{eff}\,\sigma\,(T_W + T_c)(T_W^2 + T_c^2) \qquad (2.4)$$

$$\varepsilon_{eff} = \left(\frac{1}{\varepsilon_W} + \frac{1}{\varepsilon_c} - 1\right)^{-1} \qquad (2.4.1)$$

### *4.1.3 Energy balance equation for condensing cover (Top Cover)*

Solar energy absorbed by the condensing cover + total energy received from the saline water by convection, evaporation and radiation = Energy stored in condensing cover + total energy lost to the surroundings [28]

$$I(t)\, A_c\, \alpha'_c + Q_{t,\, w-c} = m_cC_c\frac{dT_c}{dt} + Q_{t,c-a} \qquad (3)$$

Where, $A_c$ is area of condensing cover that absorbs the solar radiation,
$\alpha'_c$ is fraction of solar radiation absorbed by condensing cover,
$m_cC_c$ is heat capacity of the cover material and
$\frac{dT_c}{dt}$ is temperature gradient of condensing cover with respect to time.

The energy transfer of the condensing cover takes place by convection between the cover and the surroundings and by radiation from the sky,

$$Q_{conv,c-a} = h_{conv,c-a} A_c ( T_c - T_a ) \quad (3.1)$$

$$Q_{rad,c-sky} = h_{rad,c-sky} A_c ( T_c - T_{sky} ) \quad (3.2)$$

$$T_{sky} = T_a - 6 \quad (3.2.1)$$

Where,

$$h_{rad,c-sky} = \varepsilon_g \sigma ( T_c + T_{sky} )( T_c^2 + T_{sky}^2 ) \quad (3.3)$$

## 4.2 Results from the Thermal Modelling

From the thermal modelling important theoretical quantities of a solar still system is obtained. One such quantity is the theoretical values of temperatures at any given time, $T_w$, $T_c$ and $T_a$ which are the temperature of the saline water, condensing cover and the atmosphere respectively. These values become important in finding out the theoretical mass of distillate hourly obtained from the system. Which in turn helps define the overall efficiency of the passive system as well as the instantaneous efficiency of the system. [29]

$$m_{DW/Theoretical} = 0.012 (T_w - T_c) (T_c - T_a) - 3.737 \times 10^{-3} T_w (T_c - T_a) - 5.144 \times 10^{-3} T_c (T_c - T_a) + 5.365 \times 10^{-3} (T_c - T_a)^2 + 0.212(T_c - T_a) - 3.828 \times 10^{-3} T_w (T_w - T_c) - 5.015 \times 10^{-3} T_c (T_w - T_c) + 2.997 \times 10^{-3} (T_w - T_c)^2 + 0.217 (T_w - T_c) + 1.182 \times 10^{-3} T_c T_w + 1.663 \times 10^{-3} T_c^2 - 0.106 T_c - 0.065 T_w + 8.352 \times 10^{-4} T_w^2 + 1.992 \quad (4)$$

$$\eta_i = \frac{\dot{m}_w L}{I(t) As} \quad (5)$$

$$\eta_{passive} = [\frac{\Sigma \dot{m}_w L}{A_s \int I(t)dt}] X 100 \quad (6)$$

Where,
$m_{DW/Theoretical}$ is the theoretical mass of hourly distillate output
$L$ is the latent heat of evaporation of water
$\eta_i$ is the instantaneous efficiency of the system
$\eta_{passive}$ is the overall efficiency of the system

## 4.3 Techno-Economic Comparison of Various Solar Still Designs

All the important designs of solar stills were taken into consideration for the techno-economic evaluation to rank the stills according to their efficiency. To obtain design efficiency of the solar still various components of the manufactured still are considered. The components taken into consideration here are skilled labour (SL), land area requirement (LA), productivity (P), economic impact (EI), fabrication (FC), and commercial potential (CP) and technical complexity (TC). All these were found out using Multi-criteria Decision Model (MCDM). The following table is made using MCDM based on various input and output criteria with the help of a fuzzy analytical hierarchy process (AHP) model integrated with a Data Envelopment Analysis (DEA) [6].

**Table 1: Comparison of all the discussed types of solar stills**

| Sr. No. | Type of Solar Still (S.S.) | Efficiency | Efficiency Decomposition | | | | | | | Rank |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | SL | FC | LA | EI | CP | P | TC | |
| 1 | S.S. with wick and fin | 0.5504 | 0.8253 | 0.6034 | 0.3883 | 0.3129 | 0.4621 | 0.191 | 0.0341 | 12 |
| 2 | Transportable hemispherical S.S. | 0.2533 | 0.531 | 2.5976 | 0.8192 | 0.0748 | 0.1584 | 0.5804 | 0.1864 | 20 |
| 3 | Stepped S.S. with wick and sponge | 0.5277 | 0.6909 | 0.7273 | 0.4767 | 0.1573 | 0.1666 | 0.6107 | 0.0654 | 15 |
| 4 | Stepped S.S. with sun tracking system | 0.5269 | 0.1887 | 1.054 | 0.6551 | 0.0797 | 0.1689 | 0.6189 | 0.1325 | 16 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | Weir type S.S. | 0.6905 | 0.5712 | 0.4827 | 0.3942 | 0.1951 | 0.1378 | 0.5049 | 0.1622 | 8 |
| 6 | S.S. with sponge and pond | 0.5468 | 0.5591 | 0.5723 | 0.6973 | 0.0985 | 0.5549 | 0.3058 | 0.0409 | 13 |
| 7 | S.S. with shallow solar pond | 0.7279 | 0.3214 | 0.4512 | 0.6012 | 0.1477 | 0.1564 | 0.5732 | 0.1227 | 7 |
| 8 | S.S. with condenser | 0.6342 | 0.4821 | 0.4935 | 0.6012 | 0.1477 | 0.1564 | 0.5732 | 0.1227 | 10 |
| 9 | Single slope S.S. | 0.5809 | 0.6034 | 0.3657 | 0.7524 | 0.2218 | 0.1175 | 0.4304 | 0.2304 | 11 |
| 10 | Single slope S.S. with PVT | 1 | 0.1758 | 0.3856 | 0.4385 | 0.0399 | 0.1349 | 0.0372 | 0.7881 | **1** |
| 11 | S.S. with collector | 0.4858 | 0.5638 | 0.7914 | 0.7031 | 0.0496 | 0.5595 | 0.3083 | 0.0825 | 19 |
| 12 | S.S. with concentrator | 0.6368 | 0.5026 | 0.441 | 0.6268 | 0.2309 | 0.1631 | 0.4781 | 0.1279 | 9 |
| 13 | S.S. with sun tracking | 0.5129 | 0.624 | 0.5474 | 0.7781 | 0.3451 | 0.5096 | 0.0702 | 0.0752 | 17 |
| 14 | Pyramid shape S.S. | 1 | 0.4053 | 0.3087 | 0.286 | 0.3855 | 0.226 | 0.2941 | 0.0944 | **2** |
| 15 | Pyramid shape S.S. with collector | 0.5304 | 0.3157 | 1.1804 | 0.3891 | 0.0518 | 0.5836 | 0.3216 | 0.043 | 14 |
| 16 | S.S. with fin | 0.7437 | 0.6542 | 0.3826 | 0.3078 | 0.5344 | 0.1115 | 0.1795 | 0.1746 | 6 |
| 17 | S.S. with PCM | 0.7693 | 0.6806 | 0.2671 | 0.3522 | 0.2325 | 0.1231 | 0.4512 | 0.1932 | 5 |
| 18 | S.S. with Nano-PCM (paraffin+$TiO_2$) | 0.8846 | 0.5105 | 0.2677 | 0.3522 | 0.2325 | 0.1231 | 0.4512 | 0.1932 | 4 |
| 19 | S.S. with Nano-PCM (paraffin + GO) | 0.487 | 0.4704 | 0.801 | 0.7821 | 0.0704 | 0.1491 | 0.5465 | 0.234 | 18 |
| 20 | S.S. with Nano-PCM (paraffin + CO) | 0.8847 | 0.5105 | 0.2676 | 0.3522 | 0.2325 | 0.1231 | 0.4512 | 0.1932 | **3** |

**Source: Reference Number 6**

The results show that, single slope solar still integrated with a PVT has the highest efficiency taking into consideration all the thermo-economic aspects. And second is Pyramid shaped solar still, because of its higher output and lower cost of production and maintenance. But when looking for a system without integration, the Pyramid solar still will be the best system from all the discussed topics.

## 5. CONCLUSION

All dominant types of desalination were studied and among them Solar distillation was selected to be the topic of this review paper on the basis of an ecological point of view. Solar distillation has two sub categories, active and passive, which describe its integration with an electrical or mechanical component while increasing principal cost. From all methods of solar distillation discussed, pyramid shaped solar still had more distillate output. This is the reason for it to be discussed in detail in terms of thermal modelling and thermo-economic comparison. This highlights why the pyramid shaped solar still is more preferred in scientific terms with proven facts and figures.

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