Design, Construction and Performance Analysis of a Solar Powered Dual Mode Desalination System for Water Purification

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Candidate's Declaration

I confirm that this thesis represents my own work; the contribution of any supervisors and others to the research and to the thesis was consistent with normal supervisory practice. External contributions to the research are acknowledged.

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Session: 2006-2007

Institute of Energy

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Date: ________________

Supervisor's Declaration

The MS level thesis report titled by **"Design, Construction and Performance Analysis of a Solar Powered Dual Mode Desalination System for Water Purification"** has been carried out and dissertation was prepared under my supervision. Herby I confirm that, to the best of my knowledge the thesis represents the original research work of the candidate; the contribution made to the research by me, by others of the University was consistent with normal supervisory practice, and external contributions to the research are acknowledged.

I believe the thesis to be in a suitable presentational form and is ready for examination.

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Abstract

Human life is based on water. Safe drinking water is one of our fundamental needs. Water is one of the most abundant resources on earth covering 75% of the planet's surface. About 97% of the earth's water is salt water in the oceans, and a tiny 3% is fresh water.

Sea water contains large amount of salts. The salts exist in the form of chloride, sulfate, sodium, magnesium, potassium etc. Chloride and sulfate contribute to about 55% and 31% of sea salts respectively. Eating small quantities of saline water are not harmful, but more can be dangerous, ultimately producing fatal seizures, heart arrhythmias and kidney failure. Other than salts, there are many other unwanted elements, like bacteria, Parasites and heavy metals in the water.

Major parts of Bangladesh do not have access to safe drinking water. Fresh water which was once obtained from rivers, lakes and ponds in plenty is now becoming scarce because of industrialization and population explosion. Increased irrigation of land for producing larger amount of food adds to the fresh water scarcity. Also, the available portable water is now increasingly being polluted by industrial and sewage waste.

Therefore, there is need to purify the water to make suitable for drinking. It would be feasible to address the water-shortage problem with seawater desalination; however, the separation of salts from seawater requires large amounts of energy which, when produced from fossil fuels, can cause harm to the environment. Therefore, there is a need to employ environmentally friendly energy sources in order to desalinate seawater.

As a part of my thesis, I have made a single basin single slope desalination device, where I used dual mode thermal energy for quick vaporization. One is the thermal energy trapped from solar radiation through a transparent top cover. Another one is the thermal energy of DC heaters powered by Photovoltaic module. Designed device is renewable energy (Solar) based and environmentally-friendly. This can be used for water heating, desalination and purification.

This report covers introduction into desalination, comparative analysis of current desalination technologies. Some general concepts are given for the proper selection of desalination method. Description of designed desalination device is given in detail. After that, its construction, total cost, performance, efficiency and results are given here. Device maintenance, drawbacks and few related points etc. are also studied.

From this research, I have concluded that, solar powered dual mode desalination may not be a viable option at the present price structure, further research for efficiency improvement of device could make solar assisted desalination one of the most economically advantageous device.

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Introduction

1.1 Water

Water (chemical formula: **H_2O**) is a transparent fluid which forms the world's streams, lakes, oceans and rain, and is the major constituent of the fluids of organisms. Water is the major component of human's body. Almost in every organism, nutrients and other enzymes are transported with the help of water. Human body consists of about 66% of water [a].

As a chemical compound, a water molecule contains one oxygen and two hydrogen atoms that are connected by covalent bonds. Water is a liquid at standard ambient temperature and pressure, but it often co-exists on Earth with its solid state, ice and gaseous state, steam (water vapor). It also exists as snow, fog, dew and cloud.

Fig–1: Water and It's chemical formula [b]

Water moves on Earth continually through the water-cycle of evaporation and transpiration, condensation, precipitation and runoff, usually reaching the sea. Evaporation and transpiration contribute to the precipitation over land. Water used in the production of a good or service is known as virtual water [c].

The total water supply of the world is 1.400.000.000 km^3 (A m^3 of water equals 1,000 litres). Each year 119.000 km^3 of water precipitates on land and 74.200 km^3evaporates into the atmosphere, by transpiration from soil and vegetation. On ocean and sea surface 450.000 km^3 of water fall every year and 502.800 km^3 evaporates. Of the freshwater on Earth, about 2.200 km^3 flows into the ground [1].

Fig-2 shows the Natural water cycle

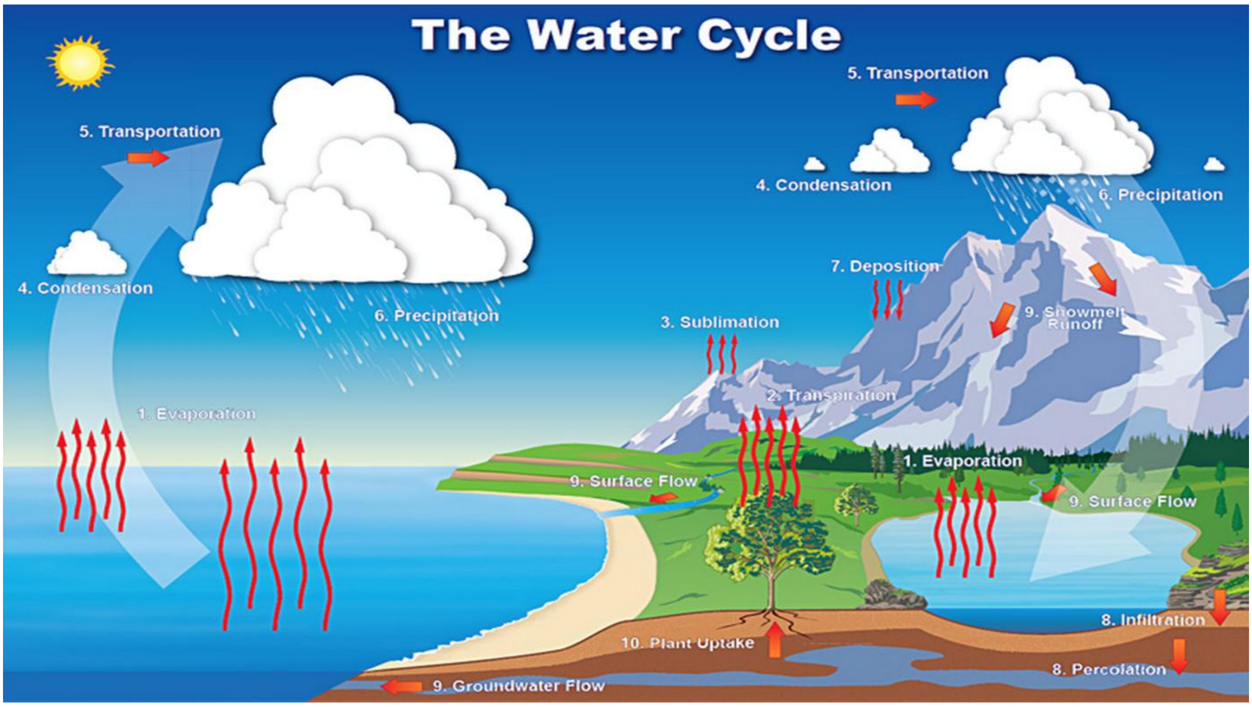


Fig-2: Natural water cycle [c]

1.2 The importance of water

Water is a basic necessity of man along with food and air. This is one of the most important substances on earth. All plants and animals must have water to survive. If there was no water there would be no life on earth [a].

Apart from drinking it to survive, people have many other uses for water. These include -

- Cooking;
- washing their bodies;
- washing clothes;
- washing cooking and eating utensils;
- keeping houses and communities clean;
- recreation; such as swimming pools;
- keeping plants alive in gardens and parks;

Fig-3: Plants and animals need water [a]

1.3 Water resources

Fresh water resources usually available are rivers, lakes and underground water reservoirs. Water covers about 71% of the Earth's surface. It is vital for all known forms of life. On Earth, 96.5% of the planet's crust water is found in seas and oceans, 1.7% in groundwater, 1.7% in glaciers and the ice caps of Antarctica and Greenland, a small fraction in other large water bodies, and 0.001% in the air as vapor, clouds (formed of ice and liquid water suspended in air), and precipitation. Only 2.5% of this water is fresh water, and 98.8% of that water is in ice (excepting ice in clouds) and ground water. Less than 0.3% of all freshwater is in rivers, lakes, and the atmosphere, and an even smaller amount of the Earth's freshwater (0.003%) is contained within biological bodies and manufactured products. A greater quantity of water is found in the earth's interior [1].

Human uses fresh water. About 97% of the water on the Earth is salt water and only three percent is fresh water; slightly over two thirds of this is frozen in glaciers and polar ice caps. The remaining unfrozen fresh water is found mainly as groundwater, with only a small fraction present above ground or in the air [a].

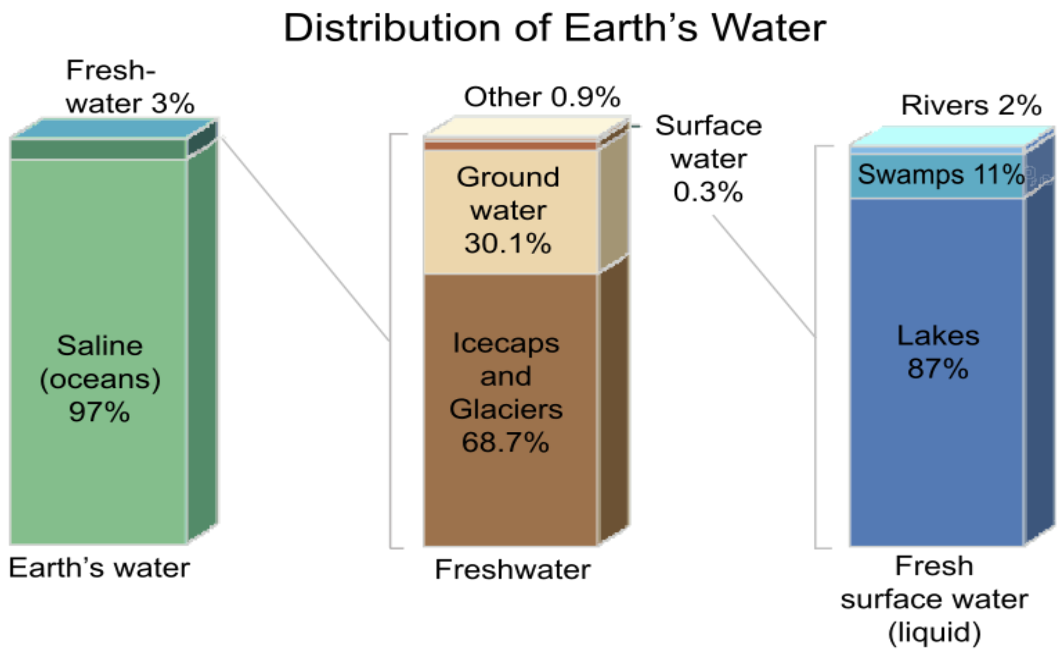


Fig- 4: Earth's water distribution [d]

The total amount of global water reserves is about 1.4 billion cubic kilometers. Oceans constitute about 97.5% of the total amount, and the remaining 2.5% fresh water is present in the atmosphere, polar ice, and ground water. This means that only about 0.014% is directly available to human beings and other organisms [d].

According to World Health Organization (WHO), the permissible limit of salinity in water is 500 parts per million (ppm) and for special cases up to 1000 ppm, while most of the water available on earth has salinity up to 10,000 ppm, and seawater normally has salinity in the range of 35,000–45,000 ppm in the form of total dissolved salts [1].

1.4 Types of water

Fresh water- Fresh water is naturally occurring water on

- Earth's surface in ice sheets, ice caps, glaciers, ice bergs, ponds, lakes, rivers and streams.
- Underground as ground water in a aquifers and underground streams.

Fresh water is generally characterized by having low concentrations of salts and other dissolved solids. The term "sweet water" has been used to describe fresh water. The term fresh water does not have the same meaning as potable water. Much of the surface fresh water is unsuitable for drinking without some form of purification because of the presence of chemical or biological contaminants.

Drinking water- Drinking water, also known as potable water is safe enough for drinking and food processing. Water is essential for life. The amount of drinking water required is variable. It depends on physical activity, age, health issues, and environmental conditions. Water makes up about 60% of weight in men and 55% of weight in women. Infants are about 70% to 80% water while the elderly are around 45%. Reduction of waterborne diseases and development of safe water resources is a major public health goal in developing countries.

Sea water- Saline water or saltwater, is water from a sea or ocean. Seawater in the world's oceans has a salinity of about 3.5% (35 g/L). Seawater is denser than both fresh water and pure water. Seawater pH is typically limited to a range between 7.5 and 8.4. Although the vast majority of seawater has a salinity of between 3.1% and 3.8%, seawater is not uniformly saline throughout the world. Saline water contains a significant concentration of dissolved salts (mainly NaCl). The salt concentration is usually expressed parts per million (ppm). The saturation level is dependent on the temperature of the water.

Brackish water- Brackish water is water that has more salinity than fresh water, but not as much as seawater. It may result from mixing of seawater with fresh water.

Brine- Brine is a solution of salt in water. In different contexts, brine may refer to salt solutions ranging from about 3.5% up to about 26%. Other levels of concentration are called in different names.

Salinity			
Concentration of salt in water measured in grams per liter or parts per thousand.			
Fresh Water	**Brackish Water**	**Saline Water**	**Brine**
Less than 0.5 g/l Desalinated Water	0.5-30 g/l Underground Water	30-50 g/l Sea Water	More than 50 g/l Desalination Plants Rejection

Table-1: Water salinity based on dissolved salts [a]

1.5 Characteristics of Raw Waters

Salinity is a term related to the electrical conductivity of the water, and it gives a bulk measurement of the total dissolved solids (TDS, typically in ppm or mg/kg). Well developed standards define the salinity of seawater through an electrical measurement [2], and these standards are robust over the various oceans of the Earth [3]. For other waters, a chemical analysis of the raw water is usually needed to determine which ions are present and in what concentration; for example, the ions in ground waters will depend upon the rock formations from which the water is drawn. Table-3 shows the concentrations of ions in representative seawater of 34,500 ppm and in representative brackish ground waters [4]. The ion concentrations of water from a typical fresh surface water supply as distributed to end users are shown for comparison.

Water quality standards fix the maximum allowable concentrations of various contaminants in potable water by considering the health effects of each substance, but some ions found in saline water will produce undesirable taste or color at concentrations well below those at which a specific health effect is of concern. In general, a TDS of no more than 500 ppm is recommended in municipal supplies under US EPA secondary regulations, and so a desalination process aims to lower the concentration of all ions in the raw water [5].

Substance (amounts in mg/kg)	**Standard seawater**	**High brack-ish water**	**Low brack-ish water**
Sodium, Na^{+}	10,556	1837	90
Magnesium, Mg^{2+}	1,262	130	11.7
Calcium, Ca^{2+}	400	105	96
Potassium, K^{+}	380	85	6.5
Strontium, Sr^{+}	13	nr	nr
Chloride, Cl^{-}	18,980	2970	191
Sulfate, SO_4^{2-}	2,649	479	159
Bicarbonate, HCO_3^{-}	140	250	72.6
Bromide, Br^{-}	65	nr	nr
Boric acid, $B(OH)_3$	26	nr	nr
Fluoride, Fl^{-}	1	1.4	0.2
SiO_2	1	17	24
Nitrate, NO_3	nr	5.0	nr
Total dissolved solids	**34,483**	**5881**	**647**

Table-2: Representative ion concentrations for standard seawater, high and low salinity brackish water [4]

1.6 Water Impurities

Water contaminants are divided into two main types [5] -

- Biological— include waterborne pathogens and algae
- Chemical—metals(arsenic, mercury) , salts

Suspended particles- Suspended solids refer to small solid particles which remain in suspension in water as a colloid or due to the motion of the water. Suspended solids are important as pollutants and pathogens are carried on the surface of particles. Removal of suspended solids is generally achieved through the use of sedimentation and/or water filters (usualy at a municipal level).

Dissolved inorganic salts - Compounds that do not contains carbon. E.g. - Sodium chloride, sodium sulphate, magnesium chloride, magnesium sulphate, calcium chloride, calcium sulphate.

Dissolved organic compounds - Compound that contains carbon. E.g. – Hydro-carbons.

Micro-organisms - E.g.- Fungi, Algae, Bacteria etc.

Pyrogens - Fever inducing substances.

Dissolved gases- E.g. - Argon, Methane, Ethylene, Carbon Mono-oxide, Carbon dioxide, Hydrogen, Helium, etc

Water resources can be classified into five different categories, according to the total solids dissolved in it, as shown in table 2.

Water sample	Total dissolved solids, mg/l
Well water	300-500
Typical river water	200-750
Typical brackish water	1500-6000
Typical seawater	36000
Water for irrigation	1000

Table-3: Classification of water resources [5]

1.7 Water Scarcity

Today fresh water demand is increasing continuously, because of the industrial development, intensified agriculture, improvement of standard of life and increase of the world population. Only about 3 % of the world water is potable and this amount is not evenly distributed on the earth. Large quantities of fresh water are required in many parts of the world for agricultural, industrial and domestic uses. Lack of fresh water is a prime factor in inhibiting economic development. The supply of drinking water is a growing problem for most parts of the world. More than 80 countries, which between then have 40 % of the world's population are being suffered from this problem [d].

Many countries are increasingly facing shortage of water, especially potable water. Shortage is caused by many factors. The quantum of rainfall an area receives is basically determined by its geographical location, topography and terrain. Rainfall and topographical aspects also impact the availability of ground water resources. While some countries are naturally endowed with ample fresh water resources, there are others with limited or very little water. Water availability has been generally dwindling in most of the countries due to industrialization, disposal of industrial and chemical waste into water, traditional systems of flood irrigation along with heavy fertilizer usage, failure to recycle water, lack of water harvesting, over-use, construction of too many dams and so on. Changing weather patterns affecting rainfall patterns and frequent droughts are other causes.

Water scarcity is the lack of sufficient available water resources to meet water needs within a region. It affects every continent and around 2.8 billion people around the world at least one month out of every year. More than 1.2 billion people lack access to clean drinking water.

Most of the human diseases are due to polluted or non-purified water resources. Even today, developed countries and developing countries face a huge water scarcity because of unplanned mechanism and pollution created by artificial activities. The shortage of drinking water is expected to be the biggest problem of the world in this century due to unsustainable consumption rates and population growth. Pollution of fresh water resources (rivers, lakes and underground water) by industrial wastes has heightened the problem [1].

Causes of water crisis

There are several principal manifestations of the water crisis-

- Inadequate access to safe drinking water for about 884 million people
- Inadequate access to sanitation for 2.5 billion people, which often leads to water pollution
- Groundwater over-drafting (excessive use) leading to diminished agricultural yields
- Overuse and pollution of water resources harming biodiversity
- Regional conflicts over scarce water resources sometimes resulting in warfare.

Waterborne diseases caused by lack of sanitation and hygiene are one of the leading causes of death worldwide. For children under age five, waterborne diseases are a leading cause of death. According to the World Bank, 88 percent of all waterborne diseases are caused by unsafe drinking water, inadequate sanitation and poor hygiene.

1.7 Water purification

Water purification is the process of removing undesirable chemicals, biological contaminants, suspended solids and gases from contaminated water. The aims of the treatment are to remove unwanted constituents in the water and to make it safe to drink or fit for a specific purpose in industry or medical applications [4].

The methods used include physical processes such as filtration, sedimentation, and distillation; biological processes such as slow sand filters or biologically active carbon; chemical processes such as flocculation and chlorination and the use of electromagnetic radiation such as ultraviolet light [6].

There are four possible ways of purifying water for drinking purpose:-

- Distillation
- Filtration
- Chemical Treatment
- Irradiative Treatment

Considering the areas where the technology is intended to be used we can rule out few of the above mentioned methods based on the unavailability of materials or costs. Chemical treatment is not a stand-alone procedure and so is irradiative treatment. Both can act only remove some specific impurities and hence can only be implemented in coordination with other technologies.

This analysis leaves us with two methods – Distillation and Filtration. By weighting the Positive and negatives of both the methods we decided to go by the first one. The most important considerations were that of complexity, higher maintenance and subsequent costs coupled with need of other sophisticated supporting equipments.

The main water desalination or purification methods are distillation, reverse osmosis and electro-dialysis. For bigger systems, reverse osmosis and electro-dialysis are more economical, but for smaller ones, simple solar stills could be preferred because of their low costs. These days, in a number of countries including West-Indian Islands, Kuwait, Saudi Arabia, Mexico and Australia, these types of distillation units exist.

Benefits of Distillation

- It produces water of high quality.
- Maintenance is almost negligible.
- Any type of water can be purified into potable water by means of this process.
- Wastage of water will be minimum.

Purified water has been processed to remove impurities and make it suitable for use. Distilled water has been the most common form of purified water, but, in recent years, water is more frequently purified by capacitive-deionization (CDI), reverse-osmosis, carbon-filtering, ultraviolet-oxidation or electro-deionization. The choice of method will depend on the quality of the water being treated, the cost of the treatment process and the quality standards expected of the processed water [6].

Water purification may be done using solar radiation to destroy harmful elements in water.
Solar purification process created an essential appeal for water treatment by using direct irradiation. In solar water purification method, contaminated water is taken into our device and exposed to the sun for few hours. During this time UV radiation of the sun kills diarrhea causing pathogens and thereby is saving lives of people. So the people find the safe drinking water and improve their health for long time [2].

1.8 Water Desalination

Desalination refers to the process of removing the salt and other minerals from seawater, which turns the water into fresh drinking water to make it suitable for human consumption and industrial use. In addition to the removal of minerals, the process removes most biological or organic chemical compounds. Desalting technologies can be used for many applications. The most prevalent use is to produce potable water from saline water for domestic purposes, but use of desalination and desalination technologies for industrial applications is growing, especially in the oil & gas industry [2].

Solar desalination is used by nature to produce rain, which is the main source of fresh water supply. Solar radiation falling on the surface of the sea is absorbed as heat and causes evaporation of the water. The vapor rises above the surface and is moved by winds. When this vapor cools down to its dew point, condensation occurs and fresh water precipitates as rain. All available man-made distillation systems are small-scale duplications of this natural process [e].

In desalination process we have two phases of operation. They are:

(1) Vaporization of Saline Water: This is done by heat from any energy sources. Such as heater, solar radiation etc. In this case, the salt left behind at bottom of basin.

(2) Condensation of water: The vapor become condensed and collected as distill water.

1.8.1 Basic Theory of Desalination

In the past, the water was vaporized by means of any burner .Then it was being collected to another jar. A channel was used for condensation. It is still being used. But the problem is it needs much energy and it pollutes environment.

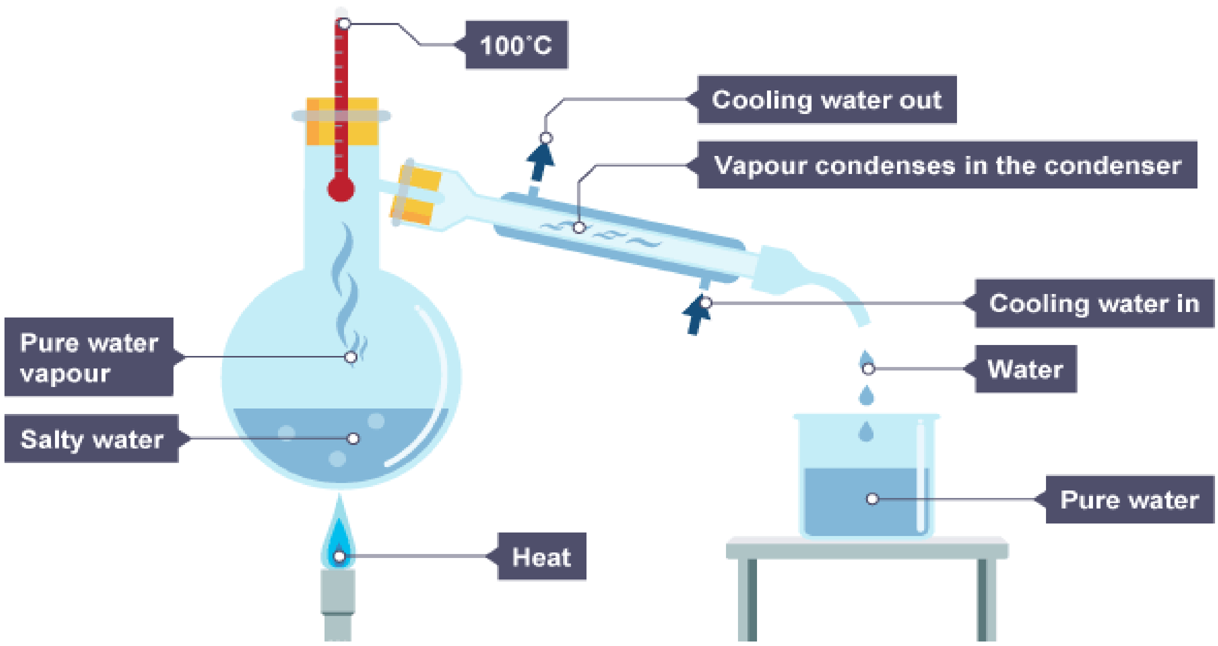


Fig-5: Method of desalination [e]

1.9 Objective of this thesis

Desalination covers a wide range of applications, from agricultural and industrial to domestic use. This study focuses on the production of clean water supplies from sea or brackish water sources. We are not focusing on specialized applications, such as the production of ultra pure water for the medical industry, or partly desalinated water for cooling of power plants. Rather the study focuses on processes that can be integrated into the systems of municipal and rural water use. We are also not focusing on general waste-water treatment or water reuse.

Some of the areas where desalination can play the greatest role are also some of the countries with least resources for the deployment of such technologies. At the same time, given that existing infrastructure is either inadequate or non-existent, these economies have the opportunity to invest in altogether new water infrastructure, gaining access to the latest generation of desalination technologies. Coinciding with a global push toward renewable energy, a key question therefore emerges: which desalination technologies are developed with a focus on integration of renewable energy integration?

This patent landscape of desalination technologies therefore looks at two dimensions:

- A stock take of the overall patent landscape around key desalination technologies
- A particular focus on the integration of desalination and renewable energy Technologies

The goal of this work is to design a dependable way to purify water in locations that are off the grid and don't have constant sources of clean water. The design also needs to be able to be built on a low budget considering that most of the places that don't provide potable water to its citizens are frequently in the poor regions of the world.

The objective of this project is to design and construct a water purification system. The design parameters of this project include:

- The system must kill all microorganisms in the water to make it safe for consumption.
- The system must provide a source of power for portable use in remote locations.
- The system must have a low construction cost.
- The system must be durable for outdoor conditions.
- The system must provide enough potable water for an average sized family.

Chapter 2
Water Purification and Desalination

2.1 History of desalination and water purification process

Solar water distillation is a solar technology with a very long history built over 2000 years ago, although to produce salt rather than drinking water. Documented use of solar stills began in the sixteenth century. An early large-scale solar still was built in 1872 to supply a mining community in Chile with drinking water. Mass production occurred for the first time during the Second World War when 200,000 inflatable plastic stills were made to be kept in life-crafts for the US Navy [f].

The classic Greece philosopher Aristotle described the water cycle in nature and remarked that when salt water turns into vapor and the vapor condenses, it does so in the form of sweet water. However, historically probably one of the first applications of seawater desalination by distillation is depicted at the drawing shown in Fig. Phoenician sailors which travelled along the Mediterranean Sea were already making use of the solar thermal radiation to convert seawater into fresh drinking water. The drawing illustrates an account by Alexander of Aphrodisias in AD 200, who said that sailors at sea boiled seawater and suspended large sponges from the mouth of a brass vessel to absorb what is evaporated. In drawing this off the sponges they found it was sweet water [7, 8].

Fig-6: Sailors producing fresh water with sea water distillation [f]

During medieval times, solar energy was used to fire alembics to concentrate dilute alcoholic solutions or herbal extracts for medical applications, to produce wine and various perfume oils. The stills or alembics were discovered in Alexandria, Egypt, during the Hellenistic period [9].

Cleopatra the Wise, a Greek alchemist, developed many distillers [9]. One of them is shown in Fig. The Arabs who overtook science and especially alchemy about the seventh century, named the distillers Al-Ambiq, from which came the name alembic [10].
Mouchot [11] the well-known French scientist who experimented with solar energy, mentions in one of his numerous books that in the 15th century Arab alchemists used polished Damascus concave mirrors to focus solar radiation onto glass vessels containing salt water to produce fresh water.[11].

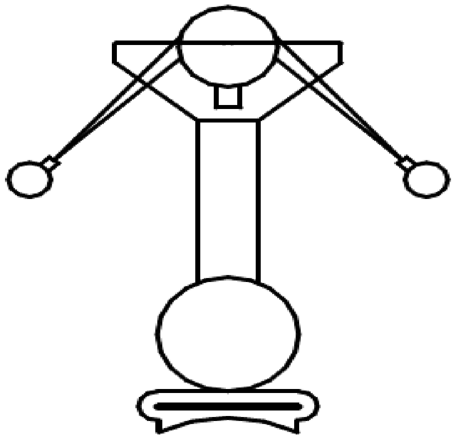


Fig-7: The Cleopatra's alembic [f]

During the Renaissance, Giovani Batista Della Porta (1535–1615), wrote many books which were translated into French, Italian and German. In one of them, Magiae Naturalis (1558), he mentions three desalination systems [10]. In second edition, he mentions seven methods of desalination. The most important of them is a solar distillation apparatus that converted brackish water into fresh water. He also describes a method to obtain fresh water from the air.

French chemist Lavoisier (1774) used large glass lenses to concentrate solar energy on the contents of distillation flasks [10]. The use of silver or aluminium coated glass reflectors to concentrate solar energy for distillation has also been described by Mouchot.

In 1870, first American patent on solar distillation was granted to Wheeler and Evans. The basic operation of solar stills and corrosion problems is described in that patent. They described the greenhouse effect, cover condensation, re-evaporation and the dark surface absorption [13].

Two years later, in 1872, an engineer from Sweden, Carlos Wilson, designed and built the first large solar distillation plant, in Las Salinas, Chile [14], thus solar stills were the first to be used on large-scale distilled water production. The plant was constructed to provide fresh water to the workers and their families of a saltpeter mine and a nearby silver mine.

Interest grew stronger during World War II, when hundreds of Allied troops suffered from lack of drinking water in North Africa, Islands and other isolated places. Then a team from MIT, led by Maria Telkes, began experiments with solar stills [15]. At the same time, the US National Research Defense Committee (NRDC) sponsored research to develop solar desalters for military use at sea. Many patents were granted [16–18] for individual small plastic solar distillation apparatuses that were developed to be used on lifeboats or rafts. Telkes continued to investigate various configurations of solar stills including glass covered and multiple-effect solar stills [20–22].

In 1952, the Office of Saline Water (OSW) was established in US. OSW promoted desalination application through research. Five demonstration plants were built, and among them was a solar distillation in Daytona Beach, Florida, where many types and configurations of solar stills (American and foreign), were tested [23].

Loef, as a consultant to the OSW in the fifties, also experimented with stills, such as basin-type stills, solar evaporation with external condensers and multiple-effect stills, at the OSW experimental station in Daytona Beach [f].

Experimental work on solar distillation was also performed at the National Physical Laboratory, New Delhi, India and in the Central Salt and Marine Chemical Research Institute, Bhavnagar, India [10]. In Australia, the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Melbourne, carried out a number of studies on solar distillation. In 1963, a prototype bay type still was developed, covered with glass and lined with black polyethylene sheet [25]. Using this prototype still, solar distillation plants were constructed in the Australian desert, providing fresh water from saline well water for people and livestock. At the same time, Baum in the USSR was experimenting with solar stills [26–28].

Between the years 1965 and 1970, solar distillation plants were constructed on four Greek Islands to provide small communities with fresh water [29–32]. The design of the stills was done at the Technical University of Athens, was of the asymmetric glass covered greenhouse-type with aluminum frames. The stills used seawater as feed and were covered with single glass. Their capacity ranged from 2044 to 8640 m^3/day. In fact the installation in the island of Patmos is the largest solar distillation plant ever built. In three more Greek Islands another three solar distillation plants were erected. These were plastic covered stills (ted-lar) with capacities of 2886, 388 and 377 m^3/day that met the summer fresh water needs of the Young Men's Christian Association (YMCA) campus [f].

By the early 1970s, the state-of-the-art of solar stills was declared understood from the standpoints of thermodynamic and geometric effects. Some modified types of solar stills had shown to improve the productivity (tilted wicks; inclined trays; solar stills with forced convection; stills with external condensation or multiple-effect solar stills with latent heat reuse), sometimes achieving twice that of a simple-basin. However, at that time, none of those improvements could be justified on an economic basis. Also, long-term testing of the materials was needed and long life with minimum maintenance had to be demonstrated.

In the 40 years since then, a very large amount of experimental solar stills have been constructed and their performance sufficiently demonstrated. Research on solar stills has continued and only in the 21st century more than 2000 scientific papers have been published so far dealing with solar stills. Although the basic knowledge and state-of-the art has not changed dramatically in the last 40 years, there are some interesting new designs and modified solar stills with increased efficiency, as well as validated models of their thermodynamics and performance. [f].

2.2 Desalination Processes

Desalination can be achieved by using a number of techniques. Techniques based on the type of energy used are given below-

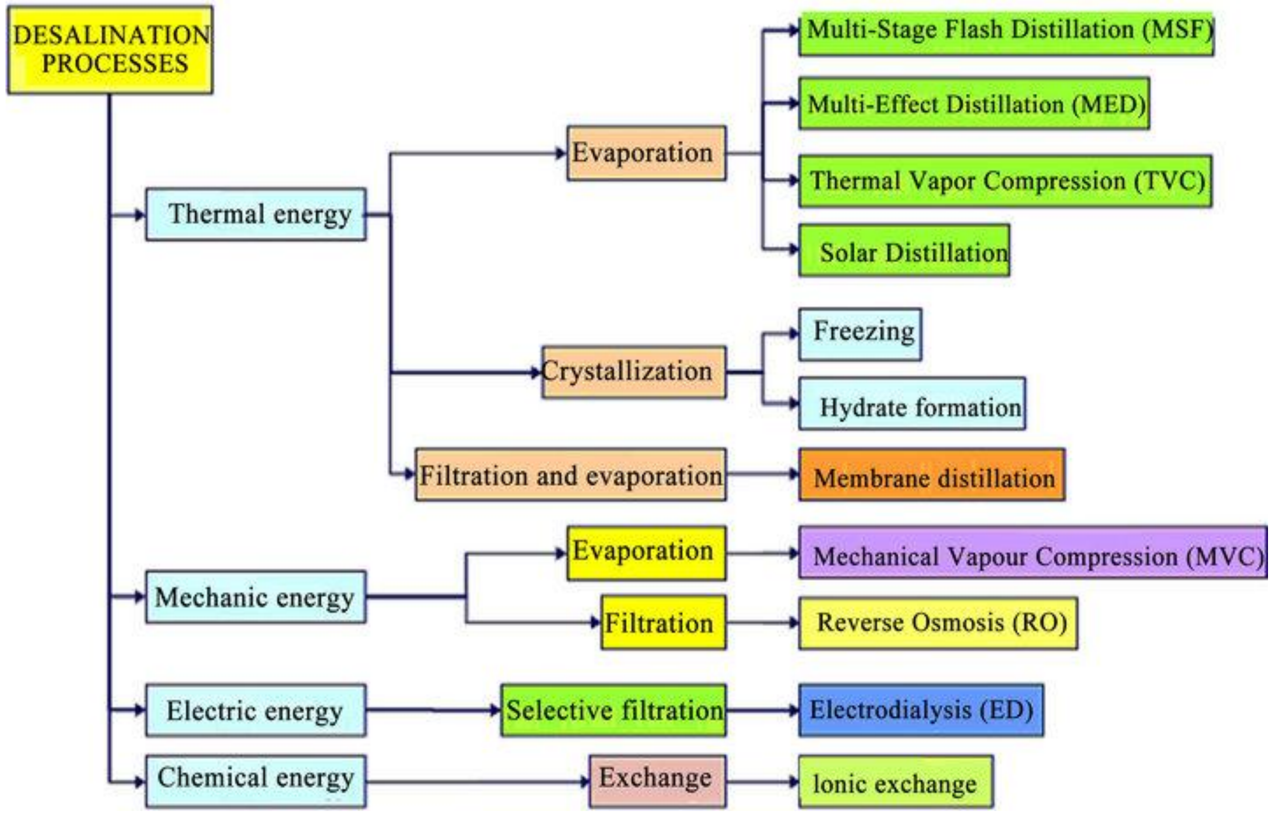


Table-4: Different Desalination Techniques [g]

Desalination techniques may be classified into the following categories:

- Phase-change or Thermal processes and
- Membrane or Single-phase processes.

All processes require a chemical pre-treatment of raw seawater to avoid scaling, foaming, corrosion, biological growth, and fouling and also require a chemical post-treatment [33].

There are three other processes which are not considered as desalination processes but are relevant.

- Microfiltration (MF)
- Ultra filtration (UF)
- Nano filtration (NF)

Ion exchange is not regarded as a desalination process. It is generally used to improve water quality for some specific purpose. E.g. - Boiler Feed water [32-34].

In Table-5, the most important technologies in use are listed. In the phase change or thermal processes, the distillation of seawater is achieved by utilizing a thermal energy source. The thermal energy may be obtained from a conventional fossil fuel source, nuclear energy, or a non-conventional solar energy source or geothermal energy. In the membrane processes, electricity is used for either driving high-pressure pumps or ionization of salts contained in the seawater.

Desalination Technologies and processes	
Phase- Change Processes	***Membrane Processes***
- Multi-Stage Flash Distillation (MSF)	- Reverse Osmosis(RO)
- Multi-Effect Distillation (MED)	- Electro-dialysis(ED)
- Vapor Compression Distillation (VCD)	
- Freezing	
- Humidification/Dehumidification	
- Solar stills	

Table-5: Main Desalination and water purification Technologies

Energy requirements for thermal processes are normally defined in terms of units of water produced per unit of steam consumed. This is known as the performance ratio (P.R). For power consuming processes the energy consumptions are usually expressed in KWh/m^3.

Feed water for desalination

Feed water for desalination plants is classified by total dissolved solids (TDS mg/l). Seawater varies considerably in concentration and more importantly there can be major local variations [33-34].

Feed water classified by total dissolved solid water TDS (mg/l) [5]

- Potable water < 1 000
- Low salinity brackish water 1 000 – 5 000
- High salinity brackish water 5 000 – 15 000
- Seawater 7 000 – 50 000

Brackish water located in aquifers or in inland lakes. Seawater can be taken directly from the sea or from a coastal aquifer. This second alternative is preferable, as the intake water is naturally filtered by the ground. However it can be polluted with undesirable components dissolved from the ground, but usually of a more consistent quality than directly from the sea.

After pre-treatment the feed water is passed through semi-permeable membranes where fresh water and brine is separated under hydraulic pressure. For higher quality, this system is augmented with a micro, ultra or Nano membrane.

2.2.1 Multi-Stage Flash (MSF)

The most commonly used method for desalination of sea water is Multi Stage Flash Distillation. MSF process uses low pressure and low temperature steam. The seawater entering the system is preheated by passing through tubes in the evaporation stages. Steam is used to heat the seawater which is then passed into the evaporators where a vacuum exists, causing evaporation. Water condenses on the cold seawater tubes and is collected. The temperature decreases and the vacuum increases, and further evaporation take place in each stage [h].

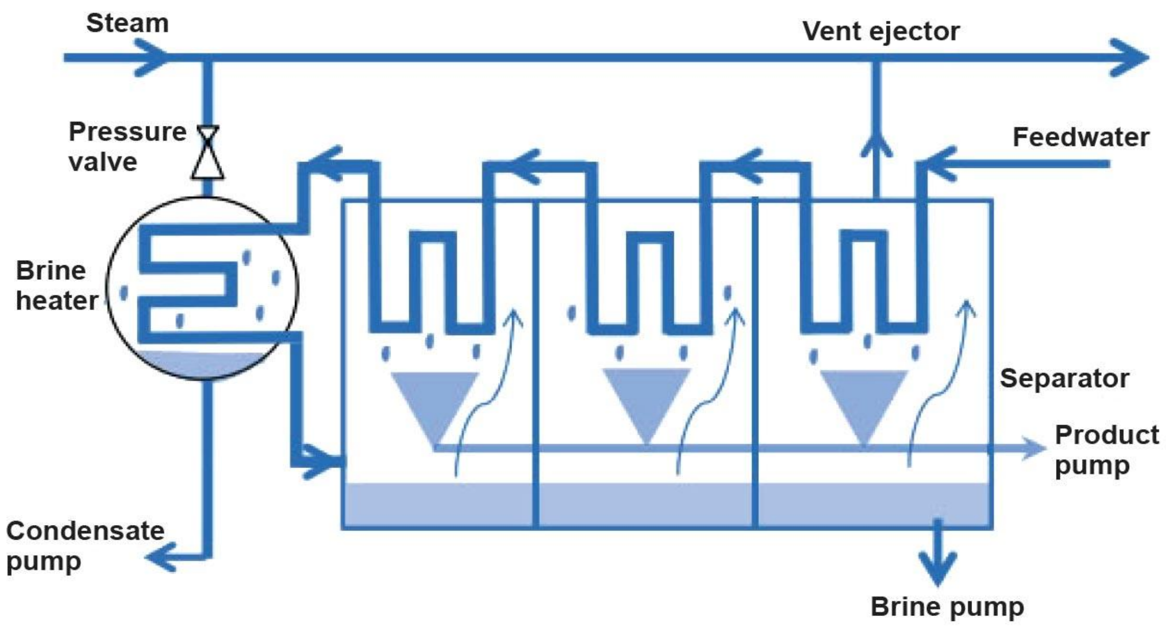


Fig-8: Multi-Stage Flash (MSF) [h]

A brine heater heats the sea water to around 90 to 110 deg C. Before reaching the brine heaters the cold sea water passes through condensing coils in the vacuum flash chambers.

This has the dual function of

- Preheating the cold sea water before entering the brine heater and
- Condensing the flashed steam in the chambers to produce fresh water.

The hot brine then enters the flash chamber which is at a vacuum. Since the entering water temperature is higher than the boiling temperature at that vacuum pressure, a part of the water flashes to steam. The steam rises to the upper part of the chamber and on contact with condensing coils condenses to form pure water. The salt and other impurities still remain with balance of the brine at the bottom of the chamber. Steam ejectors produce the necessary vacuum in the flash chambers. The balance brine goes to the next chamber where the process repeats. Multiple chambers increase the quantity of the water product. The balance brine returns to the sea.

The energy requirement is in two stages: Electrical energy for pumping the water and Steam energy for heating the brine. Flashing of the steam forms scales and deposits on the tubes. Periodic cleaning and removal is required.

Advantage- Relatively low investment costs.

Disadvantage- High maintenance cost, since it requires extensive training.

2.2.2 Multiple-Effect Distillation (MED)

This method was widely used before the MSF method. In an MED system, the evaporation in first stage occurs by heat supplied from an external source such as a fossil fuel boiler, waste heat from a power plant, industrial waste heat, or solar energy. The required top brine temperature (TBT) of this process ranges from 64^o to 70^{o}C and the process continues in the subsequent stages until the vapor temperature drops to about 30^o–40^{o}C. This process operates on the principle of reducing the ambient pressure at each successive stage, allowing the brine to undergo multiple boiling without the need of additional heat. The vapor resulting from each stage is condensed in following stage, where it can be used as a thermal source for evaporation. Thus, the process proceeds in a chain-reaction form, with each evaporator also serving as a condenser for the vapor resulting from the previous stage. The vapor resulting from the last stage is condensed and released into the cooling system [i].

The MED process consists of a series of stages, ranging from 2 to 16. Due to subsequent lower temperature operation and pressure reduction, energy consumption is lower than the MSF process.

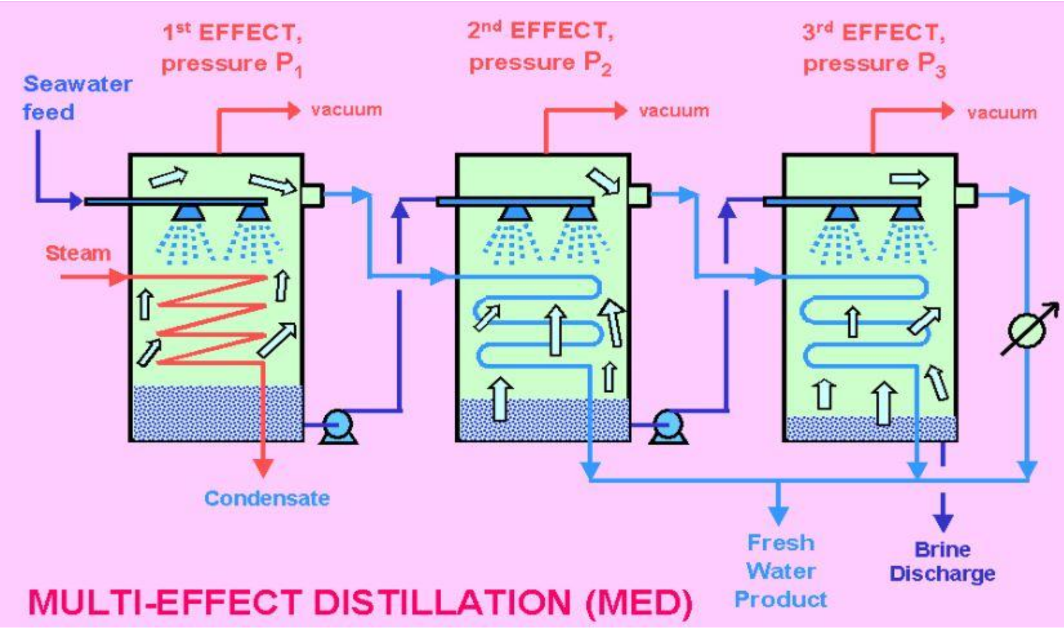


Fig- 9: Multiple Effect Distillation (MED) [i]

Each stage reuses energy from the previous stage in order to heat the incoming brine. When water evaporates in one stage, that steam flows through tubes to the next stage. Thus the heat from that evaporated water is used to heat and evaporate even more water at the next stage. This works because each stage has a lower and lower temperature; the boiling point of water decrease as pressure decreases, so less and less energy is needed to heat the next stage. This is why MED requires less energy that MSF Desalination- only the first stage with the highest pressure requires an external source of heat.

MED is thermo-dynamically efficient compared to MSF and that it is cheaper. This is because, as stated above, MED requires significantly less energy input that MSF since the only external energy needed is in the first stage.

2.2.3 Vapour compression distillation (VCD)

Vapor compression desalination refers to a distillation process where the evaporation of sea or saline water is obtained by the application of heat delivered by compressed vapor. Since compression of the vapor increases both the pressure and temperature of the vapor, it is possible to use the latent heat rejected during condensation to generate additional vapor. The effect of compressing water vapor can be done by two methods.

The first method utilizes an ejector system motivated by steam at mano-metric pressure from an external source in order to recycle vapor from the desalination process. The form is designated Ejecto or Thermo Compression. Using the second method, water vapor is compressed by means of a mechanical device, electrically driven in most cases [j].

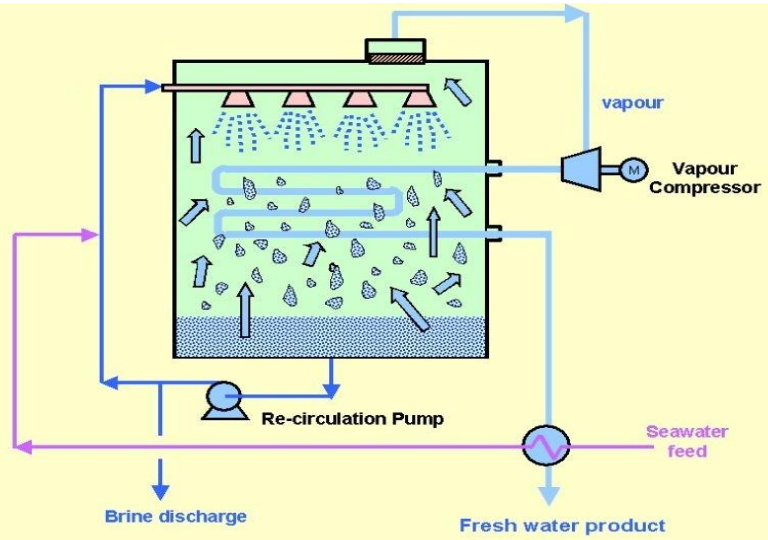


Fig-10: Vapor Compression Distiller (VCD) [j]

The VC distillation process is based on the principle of reducing the boiling-point temperature by reducing the pressure. Two methods are used to create the low pressure to evaporate: a mechanical compressor (MVC), which is electrically driven; and a steam jet (TVC), which is driven by low-temperature heat.

In MVC process, compressor creates a vacuum in evaporator, which results in partial water evaporation; then the vapor is compressed inside the tube of the heat exchanger to exchange heat with the feed seawater sprayed on the surface of the heat exchanger. This will condense the vapor inside the heat exchanger and partially evaporates some of the sprayed feed seawater.

In TVC process, a thermo-compressor creates the same effect of the mechanical compressor and extracts water vapor from the evaporator. The extracted water vapor is compressed by the steam jet to the tube of the heat exchanger. This water vapor condenses inside the tube walls to provide the low-heat energy to evaporate the feed seawater sprayed on the other side of the tube walls in the evaporator.
The MVC unit, the only energy requirement is mechanical power to drive the compressor and the pumps, whereas in the TVC unit, low-temperature steam in needed for the thermal compressor and electricity to drive the pumps.

2.2.4 Freezing Process

Desalination processes fall into two categories: those that remove the fresh water, leaving concentrated salt water behind and those that remove the salts and leave behind the fresh water. The freezing method falls within the first category. Salt waters have a certain critical temperature which is a function of its salinity. When the salt water is reduced to this temperature, ice crystals composed of fresh water are formed. It is then possible to mechanically separate the ice crystals from the solution and re-melt them to get fresh water. This is the basic principle on which freezing desalination methods are based on [k].

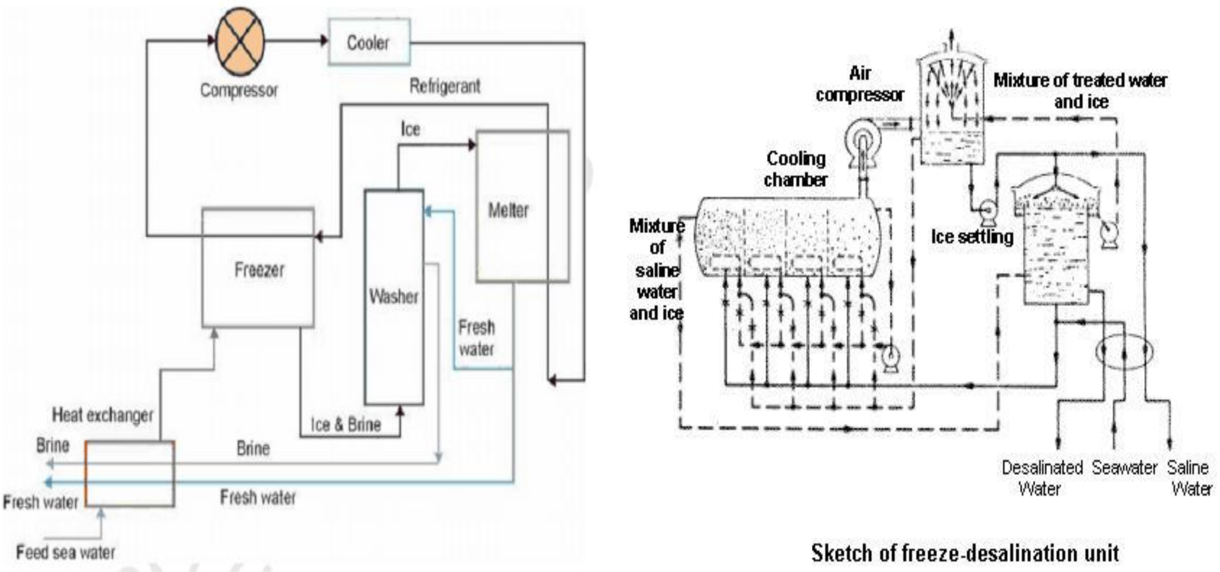


Fig-11: An indirect freezing process [k]

With the freeze desalination technology, the water solution is partially frozen and the dissolved particles are extracted. It is based on the concept that when water freezes, the salt particles it contains do not freeze. Thus, salt-free water is obtained when the ice melts. The frozen crystals are washed to remove the particles, and melted again to produce pure water (Figure 48). On an operational level, the water is passed through different stages of cooling. This allows for complete utilization of the temperature differences between the liquids in the different stages without any losses. This increases the size of the units and the initial construction costs, but decreases the operational costs. Due to its complexity, and because the costs of cooling water are much more than the cost of heating it, in regard to energy requirements, the use of this technology is still limited. Few desalination plants using this technology have been constructed.

The operating temperature is below the freezing temperature of water. At these temperatures, scaling and corrosion are greatly reduced.

The main problem lies in the economical aspects of the initial capital costs and the maintenance costs. The second problem is the thermodynamic efficiency relative to up-scaling the process.

2.2.5 Solar humidification-dehumidification Process

The solar humidification-dehumidification (HDH) process (also called the multiple-effect humidification-dehumidification process, *solar multistage condensation evaporation cycle* (SMCEC) or multiple-effect humidification (MEH), is a technique that mimics the natural water cycle on a shorter time frame by evaporating and condensing water to separate it from other substances. The driving force in this process is thermal solar energy to produce water vapor which is later condensed in a separate chamber. In sophisticated systems, waste heat is minimized by collecting the heat from the condensing water vapor and pre-heating the incoming water source. This system is effective for small- to mid- scale desalination systems in remote locations because of the relative inexpensiveness of solar collectors.

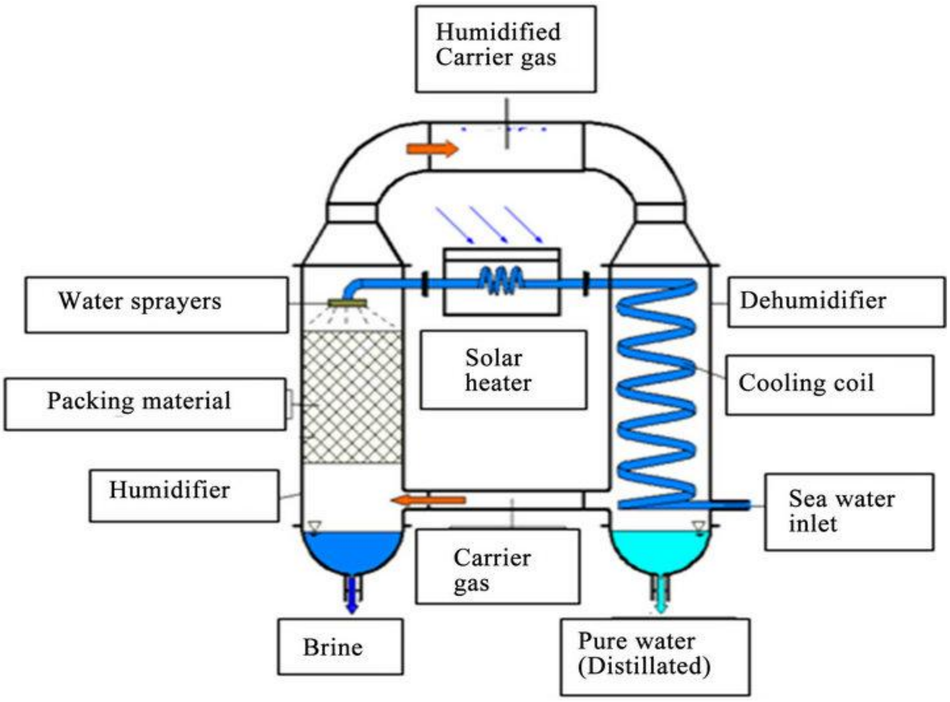


Fig-12: Solar humidification-dehumidification [l]

The solar HDH is a thermal water desalination method. It is based on evaporation of seawater or brackish water and consecutive condensation of the generated humid air, mostly at the ambient pressure. The solar HDH process is also called the multiple-effect humidification-dehumidification process; solar multistage condensation evaporation cycle (SMCEC) or multiple-effect humidification (MEH) is a technique that simulates the natural water cycle on a shorter time frame by evaporating and condensing water to separate it from other substances. The driving force in this process is the solar thermal energy to produce water vapor, which is later condensed in a separate chamber. In sophisticated systems, waste heat is minimized by collecting the heat from the condensing water vapor and pre-heating the incoming water source. This system is effective for small to mid-scale desalination systems in many arid and semi-arid countries because of the relative inexpensiveness of solar collectors. The process of HDH desalination has many advantages such as the simple equipment working under normal pressure, the cost of asset and operation is moderate, the flexible scale, the low-grade energy available, and so on. Therefore, it has a good developing prospect [l].

2.2.6 Solar still Process

Solar Distillation is by far the most reliable, least costly method of 99.9% true purification of most types of contaminated water especially in developing nations where fuel is scarce or too expensive. Solar distillation is used to produce drinking water or to produce pure water for lead acid batteries, laboratories, hospitals and in producing commercial products such as rose water.
Conventional boiling distillation consumes three kilowatts of energy for every gallon of water, while solar distillation uses only the free pure power of the sun. Expensive filtration and de-ionizing systems are even more expensive to purchase and use and will not totally purify the water by removing all contaminants. No additional heat or electrical energy is required in solar still and even after the sun sets, distillation continues at a slower pace into the night.

A single basin solar still has a top cover made of glass, with an interior surface made of a waterproof membrane. This interior surface uses a blackened material to improve absorption of the sun's rays. Water to be cleaned is poured into the still to partially fill the basin. The glass cover allows the solar radiation (short-wave) to pass into the still, which is mostly absorbed by the blackened base. The water begins to heat up and the moisture content of the air trapped between the water surface and the glass cover increases. The base also radiates energy in the infra-red region (long-wave) which is reflected back into the still by the glass cover, trapping the solar energy inside the still (the "greenhouse" effect). The heated water vapor evaporates from the basin and condenses on the inside of the glass cover. In this process, the salts and microbes that were in the original water are left behind. Condensed water trickles down the inclined glass cover to an interior collection trough and out to a storage bottle.

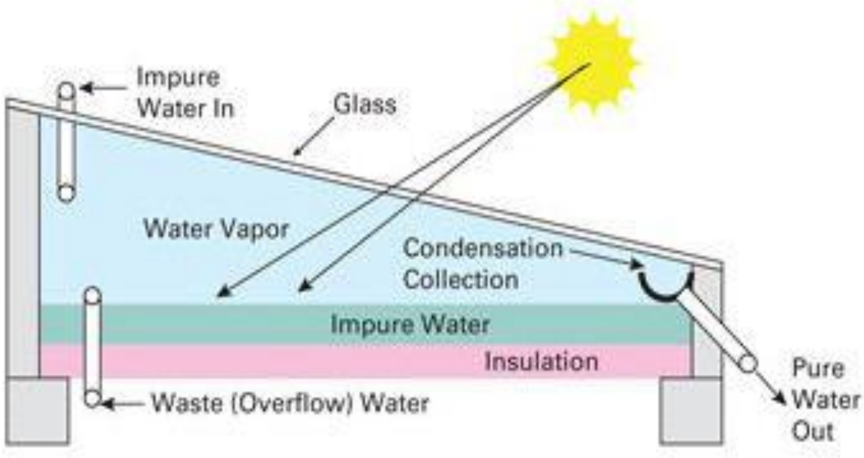


Fig-13: Single slope single basin solar still [m]

Benefits of Distillation:-

Distillation method owing to the following benefits:-
1. It produces water of high quality.
2. Maintenance is almost negligible.
3. Any type of water can be purified into potable water by means of this process
4. The system will not involve any moving parts and will not require electricity to Operate.
5. Wastage of water will be less.

2.2.7 Reverse-Osmosis (RO)

Osmosis is a natural phenomenon by which water from a low salt concentration passes into a more concentrated solution through a semi-permeable membrane. When pressure is applied to the solution with the higher salt concentration solution, the water will flow in a reverse direction through the semi-permeable membrane, leaving the salt behind. This is known as the Reverse Osmosis process or RO process.

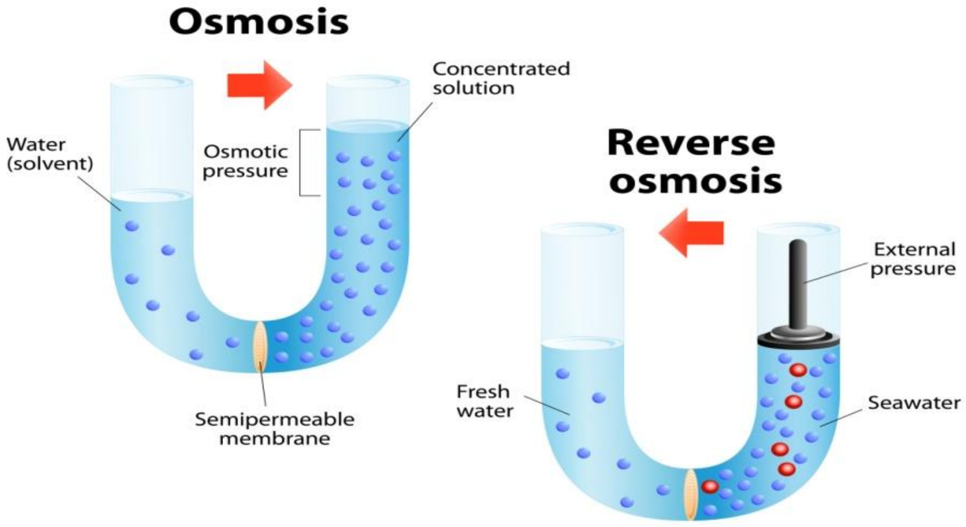


Fig-14: Basic Osmosis and Reverse Osmosis Process [n]

Reverse-Osmosis is one the simplest forms of desalination, it only involves pushing a solution through a filter. Pressure is applied to one side of the system and pushes the seawater through a membrane and the salt is essentially filtered. However, this process is only simple in the idea that drives the process, in order for the process to be successful intricate mathematical calculations must be computed otherwise the system will not function properly. This requires a skilled laborer to operate the Reverse-Osmosis operation. The membranes are also complex polymers that require precise manufacturing [n].

Reverse Osmosis works by using a high pressure pump to increase the pressure on the salt side of the RO and force the water across the semi-permeable RO membrane, leaving almost all (around 95% to 99%) of dissolved salts behind in the reject stream. The amount of pressure required depends on the salt concentration of the feed water. The more concentrated the feed water, the more pressure is required to overcome the osmotic pressure.

The desalinated water that is de-mineralized or de-ionized, is called permeate (or product) water. The water stream that carries the concentrated contaminants that did not pass through the RO membrane is called the reject (or concentrate) stream.

As the feed water enters the RO membrane under pressure (enough pressure to overcome osmotic pressure) the water molecules pass through the semi-permeable membrane and the salts and other contaminants are not allowed to pass and are discharged through the reject stream (also known as the concentrate or brine stream), which goes to drain or can be fed back into the feed water supply in some circumstances to be recycled through the RO system to save water. The water that makes it through the RO membrane is called permeate or product water and usually has around 95% to 99% of the dissolved salts removed from it.

Reverse Osmosis is capable of removing up to 99%+ of the dissolved salts (ions), particles, colloids, organics, bacteria and pyrogens from the feed water (although an RO system should not be relied upon to remove 100% of bacteria and viruses). Reverse Osmosis is very effective in treating brackish, surface and ground water for both large and small applications. Some examples of industries that use RO water include pharmaceutical, boiler feed water, food and beverage, metal finishing and semiconductor manufacturing to name a few.

An RO desalination plant essentially consists of four major systems:

- Pretreatment system
- High-pressure pumps
- Membrane systems
- Post-treatment

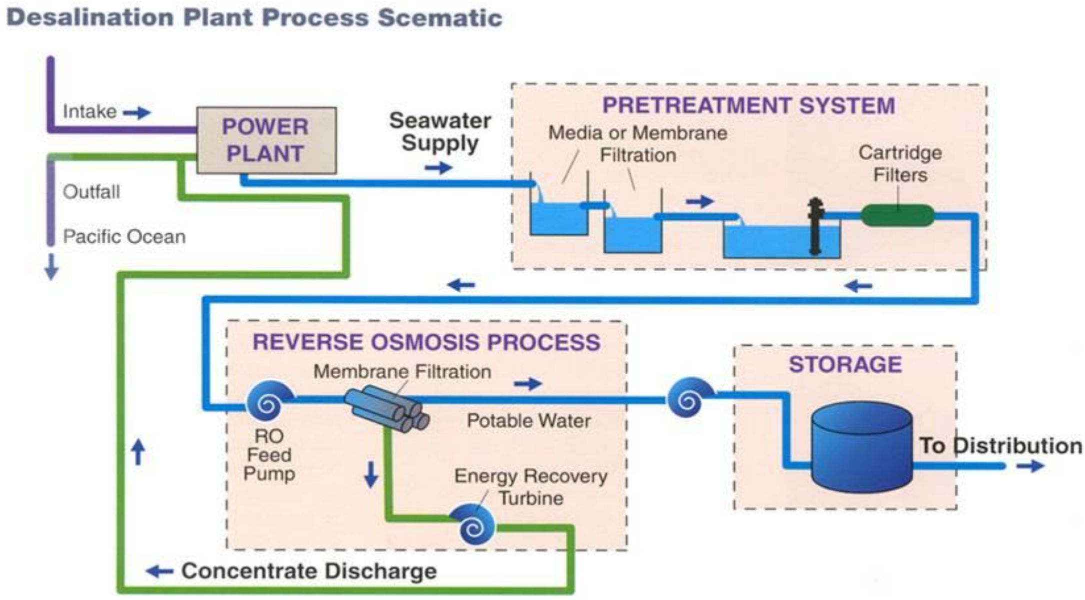


Fig-15: Reverse-Osmosis desalination process [o]

Advantages-

- **RO** can remove 95 -99 percent of total dissolved solids, also known as TDS. RO can also remove fluoride, chlorine, and other impurities.
- RO system can improve the taste of your water for drinking and cooking.
- Reverse Osmosis filtration system consumes absolutely no energy.
- Maintenance is simple.

Here are some disadvantages of Reverse Osmosis:

- If not properly maintained, the tiny pores in an RO system can become clogged.
- Reverse-osmosis process takes some time to processing water.
- Filters needs to replace periodically. Though the RO systems are generally maintenance-free, they should be sterilized and cleaned once every year.

2.2.8 Electro-dialysis (ED)

Electro-dialysis involves running a large amount of electric current through a container of seawater. This creates a salt-poor layer on one side and a salt-rich layer on the other side. This method is very efficient because it does not require a change of state for the water. However, it does require massive amounts of electricity that can get very expensive [p].

An ED system produces fresh water by using a low-voltage direct current (DC) electric field to remove salt ions from the feed water. It consists of two outside electrodes and several hundreds of cell pairs forming chambers separated by membranes that are permeable to either positive (cation) or negative (anion) ions. Feed water moves in parallel paths through all of the cells .When DC is applied, the positive and negative salt ions migrate to the oppositely charged electrode through the appropriate membrane, thus forming compartments of fresh water and highly concentrated water.

Electro-dialysis Reversal (EDR) is an electrochemical charge driven separation process whereby dissolved ions are separated through ion permeable membranes under the influence of an electrical potential created by an anode and a cathode. Ion permeable membranes consist of anion and cation exchange membranes arranged in an alternating mode between the anode and the cathode. The membranes allow opposite charged ions to pass through but reject similar charged ions.

This results in an alternating enriched ions in concentrated compartments and depleted ions in the diluted compartments. The polarity of the electrodes is regularly reversed to minimize the effect of inorganic scaling and fouling by means of freeing accumulated ions on the membrane surface, thus allowing EDR to operate at relatively higher water recoveries and also prolong the membrane life tremendously.

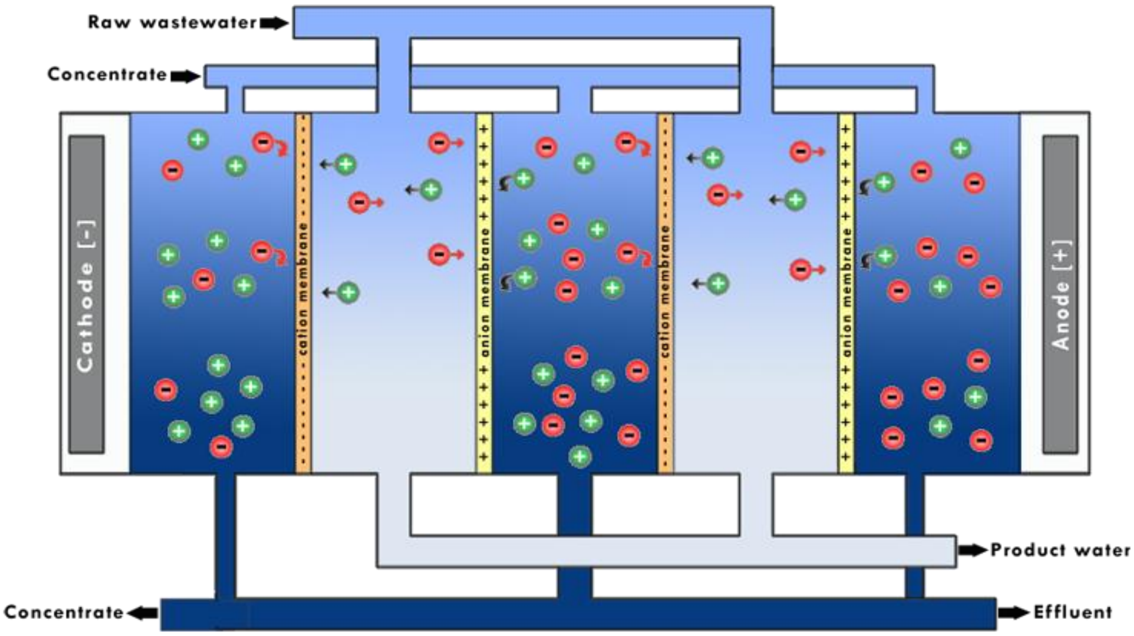


Fig-16: Electro-dialysis desalination process [p]

Advantages- Does not require any of the solution to change its state of matter. Simply separates the solute from the solvent, in this case salt and water respectively.

Disadvantages- Requires massive amounts of electricity to produce the desired effect.

2.2.9 Promising Future Technologies

Carbon nanotubes (CNT), ED-CEDI, solar evaporation, and clathrate formation (freezing) are in a group of alternative technologies that offer a promising future for desalination technology. None are prevalent or commercialized in seawater desalination, and do not bear consideration as a full-scale desalination process at this time. However, although these technologies would not be placed into full-scale service at the proposed Plant in the near future; they could be candidates to consider for testing at it. A brief discussion regarding the status of these technologies is merited.

Integration of carbon nanotubes into a new reverse osmosis membrane manufacturing platform is a relatively new concept; having been initially conceived and developed at the lab-scale in the mid to-late 2000's.One startup company (NanOasis) technology was initially developed at the Lawrence Livermore National Laboratory several years ago based on the observation of extremely high water molecule passage through carbon nanotubes.

A high level of interest and investment money has poured into the development of CNT technology; which is primarily in the pilot testing and early demonstration stages of development. Only one company has commercialized CNT based on the premise that the CNT membrane improves production flow rates and reduces required pressures by 10 to 20-percent compared to traditional SWRO processes. Time will tell if any of the competing nanotube-based processes are successful in gaining a foothold in the industry.

It remains to be seen if nanotube-based process would substantially improve the SWRO process through the reduction of power consumption.

The actual cost-benefit of CNT technology is not highly published nor is readily available based on the infancy of the technology and the limited number of bench and small-scale installations that are in operation. Preliminary estimates place the cost of the technology equal to or greater than SWRO technology.

2.3 Technical and Economic comparison of different desalination processes

The technologies most commonly used commercially are reverse osmosis (RO), multistage flash (MSF), Multi-effect distillations (MED, sometimes called multi-effect evaporation or MEE). Historically, thermal technology dominated the desalination market, especially in the Middle East. The most commonly used thermal technologies are MSF and MED. MSF is still employed in more plants than the newer MED technology, even though MED has lower energy consumption. While both of these technologies require considerable amounts of thermal as well as electric energy to run, MED has a higher upfront investment/ capital expenditure (capex), but lower operational expenditure(OPEX) than MSF [33].

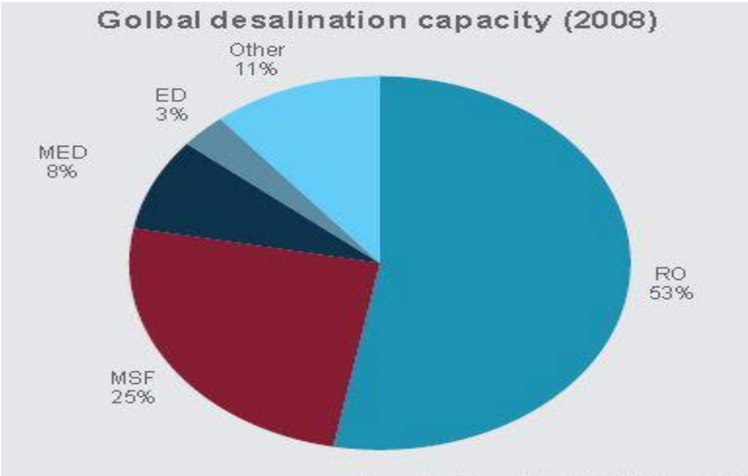


Figure- 17: Global desalination capacity – by Technology (United Nations Economic and Social Commission for Western Asia (ESCWA) 2008)

Distillation processes are a very established technology and are characterized by high-quality product water production, less impacted by the quality of feed seawater, and lower maintenance cost than membrane processes. MSF and MED processes are used in large-capacity distillation plants, whereas VC (TVC and MVC) is used in medium- and small-capacity plants. MSF, MED, and TVC processes require low-pressure and medium-pressure steam, which could be extracted from any heating source such as a fossil fuel boiler, waste heat from a power plant, industrial waste heat, or solar source. In addition, electrical energy is needed to drive the processes of various pumps. MVC requires only electricity. MSF operates at a TBT range from 90^{o}–110^{o}C, whereas MED, MVC, and TVC operate at a lower TBT in the range of 64^{o}–70^{o}C. All thermal distillation processes produce a high-quality permeate, with a salinity of about 10 ppm, which could be achieved by a wire-mesh mist eliminator used to remove brine droplets contained in the evaporated water [33].

Compared to distillation processes, membrane processes have lower capital cost, less energy consumption, higher recovery ratio, higher space-to-production ratio, and less corrosion and scaling due to ambient temperature operation.

RO processes, which use a membrane, are more compact and modular than distillation processes and can be expanded to desalinate a large capacity of water. However, compared to thermal processes, the RO process needs more feed water pre-treatment because of the sensitivity of the membrane to scaling, fouling, and pH of the feed water [34].

For seawater, the power consumption of MSF, MED, and TVC processes are higher than the consumption of MVC and RO. For brackish water, the RO process is more efficient at salinities of more than 5000 ppm compared to the ED process.

Water product cost includes direct, indirect, and annual operating costs and depends on several factors: feed water salinity, plant capacity, site characteristics and design, energy cost, and labor and maintenance cost. Energy is the largest segment of water production cost of all desalination processes. It is around 60% of the total cost of thermal distillation processes and around 45% of the main membrane RO process. Recent advances in the membrane of the RO process have resulted in membranes requiring less pressure, having longer life, and reduced cost; therefore, the water production cost of the SWRO process is lower than other distillation processes. The water cost of the BWRO process is lower than the ED process when TDS is more than 5000 ppm [35].

The water production cost of RE-coupled desalination systems is highly related to the cost of energy produced from these systems, which reflect a high water cost. But with further improvement and more use of RE systems, their capital cost will be reduced and the water production cost of desalination system operated by RE power will also be reduced. Table-6 presents the technology comparison of different processes.

PARAMETERS	Sea water RO	Brackish RO	MED	EDR	MSF	VC
Feed Water salinity(mg\l) TDS	>32,000	2000-10,000	50,000 to 1,50,000	3000-12000	50000 to 1,00,000	10000-50000
Product Water Salinity(mg\l TDS)	<500	<200	<10	<10	<10	<10
Minimum product Water Volume	100L\DAY	100L/ DAY	120KL\ DAY	90 KL\DAY	90KL\ DAY	10KL\ DAY
% Recovery	<35	>90	>80	>90	>80	>70
O & M cost	Up to 30-35 p/l	Up to 5-7 p/l	40 p - `2/l	Up to 5 p/l	50 p - `2/l	Up to 25 p/l
Energy Required	Electric Energy	Electric Energy	Electric + Heat energy	Electric Energy	Electric + Heat energy	Electric + Heat energy
Electrical Energy Consumption	5.8-7 kWh/kl 2.5-4 kWh/kl (with recovery)	Up to 1.5kWh/kl	Up to 4kWh/kl	Up to 6 kWh/kl	Up to 4kWh/kl	Up to 12kWh/kl
Steam Req (Varies with no. of effects/stages)			0.11-0.15unit of steam/ unit of water produced		0.1-0.2 unit of steam/ unit of water produced	Up to 0.05unit of steam/ unit of water produced
Life	5-10 yrs	5-10 yrs	Up to 20 yrs	Up to 20 yrs	Up to 20 yrs	Up to 20 yrs
Replacement	Membranes	Membranes	Tubes	Membranes and electrodes	Tubes	Tubes
Pretreatment Requirement	√	√	x	√	x	x

Table-6: Technological comparison of different desalination processes

The selection of any process depends on many factors, such as salinity and quality of the feed water, plant capacity, site conditions, energy cost, operation and maintenance cost, and the availability of qualified labor. The energy cost is the largest segment of the total water production cost—around 60% of the water cost produced from the distillation plants and about 45% of the water cost produced by the RO plants. The thermal distillation processes have several advantages over the membrane processes. These include better quality of the produced water, less impact with the change of feed water quality, and no membrane replacement. The membrane processes have lower capital cost, better space-to-production ratio, higher recovery ratio, easy to enlarge the plant due to the process modularity, less affected by corrosion and scaling due to low-temperature operation. Normally, the water production cost from the RO process is lower than for any of the distillation processes. But this is not the case in cogeneration plants, where low-pressure steam is extracted from the power plant turbine exhaust. For brackish water of less than 5000 ppm, ED performs better than RO, whereas at TDS above 5000 ppm, RO is the best process. Matching any RE system with desalination processes requires a number of factors to be considered, and the water production cost from these systems is currently very high [35].

Because of this high cost, desalination processes incorporating renewable energy resources are currently economic only in remote areas.

2.4 Renewable Energy applications in water desalination

Desalination processes require thermal and/or electrical energy, which can be supplied by renewable energy (RE) systems. The selection of the appropriate RE technology for water desalination depends on several factors: availability of RE resources, feed water salinity, Permeate water-quality, economics, and plant capacity. If a renewable energy resource is available at a site, experience has shown no significant technical problems in combining RE systems and desalination units. The only current limitation is the economic factor. Solar and geothermal energies could produce low-temperature heat and electricity to drive MSF, MED and TVC and electricity to drive RO, ED, and MVC. Wind energy could provide electricity to drive RO, ED, and MVC.

2.4.1 Solar Thermal Desalination Coupling

Solar thermal energy can be converted to low-temperature heat or electricity to drive desalination units. For medium and large-capacity desalination plants, concentrating solar power (CSP) technologies are the best candidate. CSP technologies could be used to provide energy in the form of low-temperature heat and electricity to desalination plants.

The primary aim of CSP is to produce high-temperature heat to generate electricity, but it can also produce low temperature heat either from the electricity generation turbine exhaust or directly from the CSP through heat exchangers. The parabolic trough CSP system is currently the best candidate for desalination coupling, and two types of desalination processes (MED and RO) are good candidates for this. In a CSP/MED plant, the needed temperature of the supplied heat should be around $70^{o}C$; therefore, there is sufficient energy in the turbine exhaust to provide this heat. In a CSP/RO plant, the CSP system could provide electricity to run the pumps of the RO unit and some low-temperature heat from the turbine exhaust to raise the temperature of the feed water to the unit to improve the performance of the membrane, which results in reducing the RO unit power consumption. Another alternative to operate this system is to use the CSP system to provide low temperature heat to the MED unit for water evaporation and solar photovoltaic (PV) system to produce electricity for the pumps of the MED unit [36–39].

2.4.2 Solar PV Desalination Coupling

Solar PV is a mature technology with systems having a life expectancy of more than 25 years. It could provide both DC and AC electricity to a desalination unit. PV systems are currently used to drive RO and ED units. This type of system could be used without batteries to run only when the solar energy is available, or with batteries for 24-hour operation. PV/RO plants are the most promising system, and many projects of this type have been installed in different parts of the world. Two types of PV/RO systems are currently available in the market. One is used to desalinate brackish water (PV/BWRO system) and the other is to desalinate seawater (PV/SWRO system). The PV/ED system is used to desalinate brackish water. The ED units need only DC electricity for the electrodes, and DC or AC electricity to drive the low-pressure pumps [39–46].

Chapter 3
Solar Powered Water Purification and Desalination

3.1 Solar radiation

Solar radiation is a free and renewable source of energy. The sun is the primary source of solar radiation. It emits radiation at an equivalent black body temperature of about 6000 K with a constant intensity outside the earth's atmosphere [q].

Solar radiation is radiant energy emitted by the sun. About half of the radiation is in the visible short-wave part of the electromagnetic spectrum. The other half is mostly in the near-infrared part, with some in the ultraviolet part of the spectrum. Irradiance is a measure of the rate of energy received per unit area, and has units of Watts per square meter (W/m^2) [r-s].

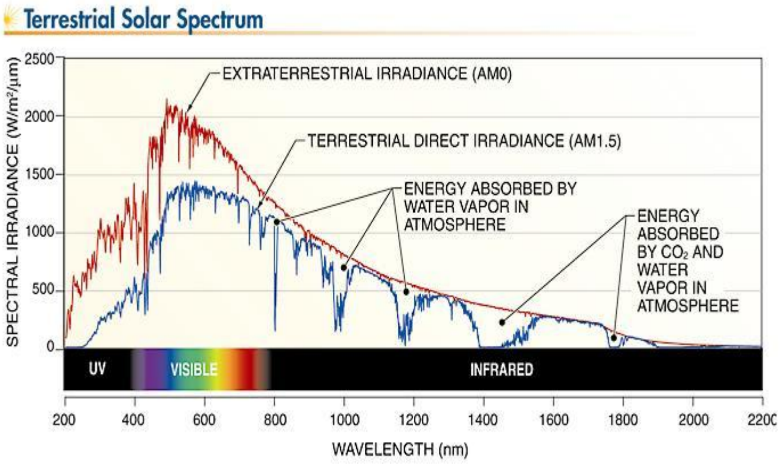


Fig-18: Terrestrial solar Spectrum [s]

3.1.1 Air Mass

Solar radiation must pass through atmosphere to reach Earth's surface. Under clear sky conditions Air Mass is the distance that the sunlight has to travel through the atmosphere [t].

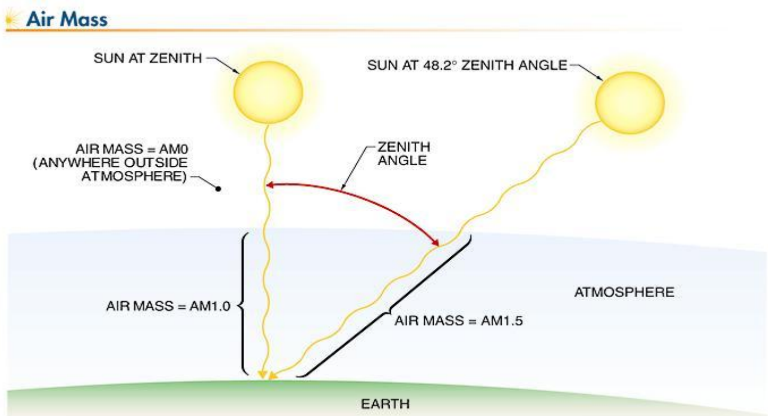


Fig-19: Air Mass [s]

The irradiance of AM1.5 is 827 W/m2. The value of 1000 W/m2 was incorporated to become a standard. The peak power of a photovoltaic system is the power generated under this standard AM1.5 (1000 W/m2) radiation and is expressed in peak watts [r].

3.1.2 Solar constant

Solar constant is the solar radiation level outside the earth's atmosphere, reduced significantly at earth's surface. That Varies with geographical location, time of day, season and weather. The solar constant is the rate of total solar energy at all wavelengths incident on a unit area exposed normally to rays of sun at one astronomical unit outside the atmosphere. It is not a true constant but seems to fluctuate slightly [s].

- The NASA adopted a value of solar constant, $\mathbf{I_{sc}= 1353Wm^{-2}}$ (With error of $\pm 21Wm^{-2}$)
- Frolich and colleagues examined solar constant, $\mathbf{I_{sc}= 1367Wm^{-2}}$ **(**With error of $\pm 1.6Wm^{-2}$)

3.1.3 Available solar radiation

Solar radiation is received at the earth's surface after being subjected to the mechanisms of attenuation, reflection and scattering in the earth's atmosphere. The two major types of radiation reaching the ground are direct radiation and diffuse radiation [t].

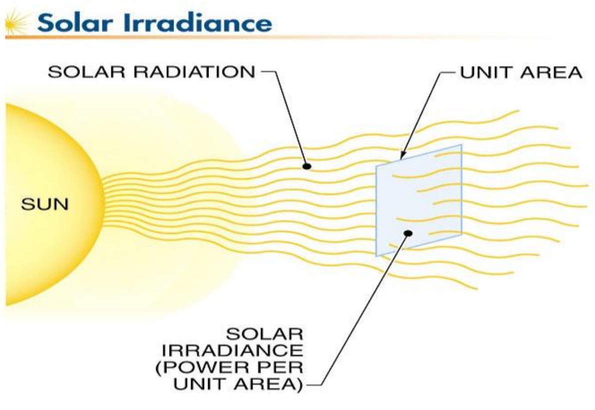
Beam radiation: The solar radiation received from the sun without having been scattered by the atmosphere.

Diffuse radiation: The solar radiation received from the sun after its direction has been changed by scattering by the atmosphere.

Total solar radiation: The sum of the beam and the diffuse radiation on a surface. The most common measurements of solar radiation are total radiation on a horizontal surface often referred to as global radiation.

Irradiance (W/m^2): The rate at which radiant energy is incident on a surface per unit area of surface. *Solar irradiance* is the intensity of solar power. Solar radiation is absorbed, scattered, and reflected by many things in the atmosphere Like carbon dioxide, water vapor, cloud cover, dust storms, air pollution greatly affect solar radiation. The amount of radiation reaching the surface of Earth is greatly reduced.

Solar irradiation ($W/m^2/day$): Solar irradiation equals the total solar irradiance over a time period, typically one day. Solar irradiation is Zero at night, Increases as the sun rises and Decreases as the sun sets.



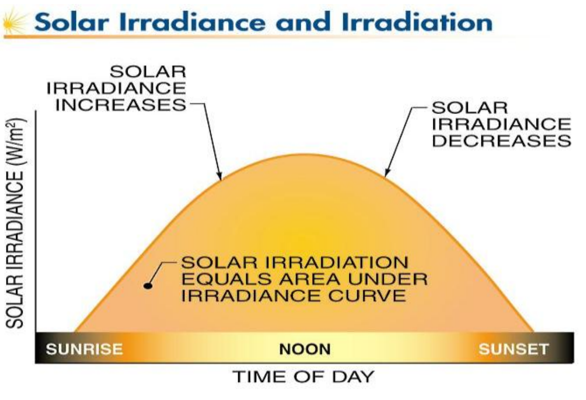


Fig-20: Solar Irradiance and Irradiation [s]

3.1.4 Peak Sun Hours

Peak Sun Hours is the number of hours required for a day's total solar irradiation to accumulate at peak sun condition. An average day may have only one or two actual hours at peak sun condition, but the total irradiation for a day may be expressed in units of peak sun hours by dividing by 1000 W/m^2 (peak sun irradiance) [u].

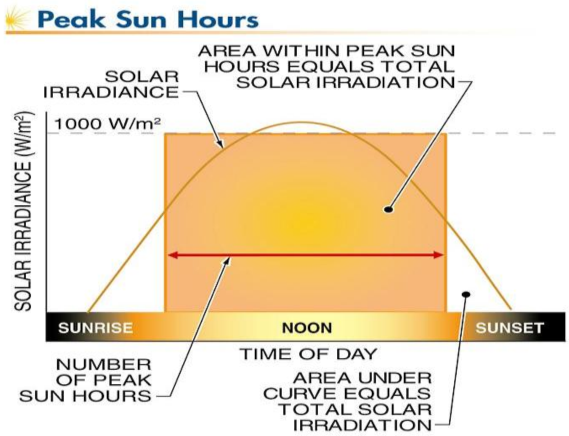


Fig-21: *Peak Sun Hours* [s]

For example, A day with an average irradiance of 600 W/m^2 over 8 hr may only reach peak sun condition for an hour or less around noon. However, the total irradiation of 4800 Wh/m^2 (600 W/m2 × 8 hr = 4800 Wh/m^2) is equivalent to 4.8 peak sun hours (4800 Wh/m^2 ÷ 1000 W/m^2 = 4.8 peak sun hr).

3.1.5 Sunshine duration

Actual duration of bright sunshine hours over a day when solar radiation is equal or above 120 Wm^{-2} known as sunshine duration. The length of time that the ground surface irradiated by direct solar radiation is sunshine duration. This value is equivalent to the level of solar irradiance shortly after sunrise or shortly before sunset in cloud-free conditions. It was determined by comparing the sunshine duration recorded using a Campbell-Stokes sunshine recorder with the actual direct solar irradiance **[u]**.

The figure shows the variation of incident solar radiation received during the study as a function of time. The instantaneous solar radiation received was in the range of 37.5 – 1200 W/m^2. The graph shows that the solar intensity increases with time and reaches a maximum at 12:30 pm in all days and then decreases. Around 6:30 pm the solar intensity reaches a minimum as the sun drops at that time.

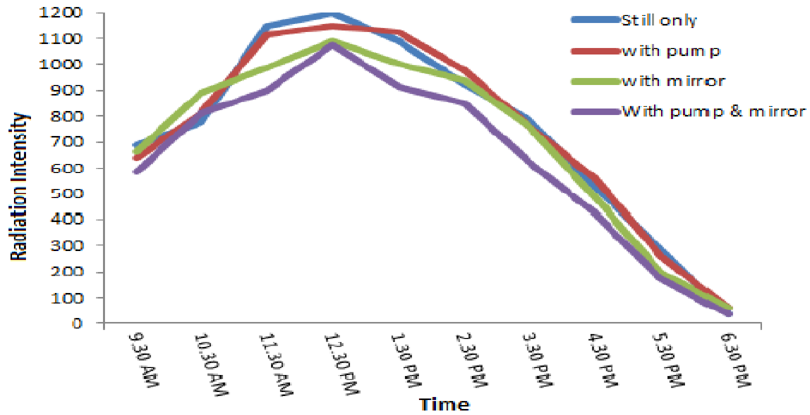


Fig-22: variation of incident solar radiation [u]

3.2 SOLAR ENERGY

Solar energy is radiant light and heat from the Sun that is harnessed using a range of ever-evolving technologies such as solar heating, photovoltaics, solar thermal energy, solar architecture and artificial photosynthesis.

It is an important source of renewable energy and its technologies are broadly characterized as either passive solar or active solar depending on how they capture and distribute solar energy or convert it into solar power. Active solar techniques include the use of photovoltaic systems, concentrated solar power and solar water heating to harness the energy. Passive solar techniques include orienting a building to the Sun, selecting materials with favorable thermal mass or light-dispersing properties, and designing spaces that naturally circulate air.

The Earth receives 174,000 terawatts (TW) of incoming solar radiation at the upper atmosphere. Approximately 30% is reflected back to space while the rest is absorbed by clouds, oceans and land masses. The spectrum of solar light at the Earth's surface is mostly spread across the visible and near-infrared ranges with a small part in the near-ultraviolet. Most of the world's population lived in areas with insolation levels of 150-300 watts/m^2, or 3.5-7.0 kWh/m^2 per day.

The earth receives radiation from sun in the form of electromagnetic radiations. Solar energy is cheap and free from pollution. India receives solar energy equivalent to more than 5000 trillion kWh per year, which is far more than its total annual consumption [s-t].

Solar energy can be used in following applications:-

- Heating and cooling of buildings
- Air conditioning and Refrigeration
- Solar cookers
- Solar water heaters
- Solar water pumping systems

Solar radiation is a general term for the electromagnetic radiation emitted by the sun. This radiation can be captured and converted to useful forms of energy such as heat and electricity, using a variety of technologies.

Solar energy is collected by a device called *Solar Collectors*. Solar Collectors collect radiation and transfer the energy to a fluid passing in contact with it.

The device which converts solar energy into electrical energy is called *Solar Cell.*

3.2.1 Advantages and Limitations of Solar Energy

Renewable energy sources in general, and Solar Energy source in particular, has the potential to provide energy services with zero or almost zero emission. The solar energy is abundant and no other source in renewable energy is like solar energy. Every technology has its own advantages and disadvantages. As the solar insolation and atmospheric conditions vary significantly from place to place, efficiency of solar energy also differs accordingly [s-t].

Advantages

- It is an abundant Renewable Energy
- This technology is Omnipresent and it can be captured for conversion on a daily basis
- It is a Non-polluting technology, which means that it does not release green house gases
- It is a Noiseless technology as there are no moving parts involved in energy generation
- This technology requires Low-maintenance because of lack of moving parts
- It can be installed on modular basis and expanded over a period of time
- Most viable alternative for providing electricity in remote rural areas as it can be installed where the energy demand is high and can be expanded on modular basis.

Limitations

- As the technology is in an *evolving stage*, the efficiency levels of conversion from light to electricity is in the range of 10 to 17%, depending on the technology used.
- The initial investment cost of this technology is high. At present the technology is basically surviving because of subsidy schemes available by the government.
- Solar energy is available only during daytime. Most load profiles indicate peak load in the evening/night time. This necessitates *expensive storage devices* like battery, which need to be replaced every 3 to 5 years. Generally, the cost of the Battery is 30 to 40% of the system cost.
- As the efficiency levels are low, the space required is relatively high. For instance, with the existing levels of technologies, the land required for putting up a 1 MW solar PV power plant is between 6 to 9 acres. However, research is going on to increase the efficiency levels of the cell.
- Solar energy is heavily dependent on atmospheric conditions.
- Solar insolation varies from location to location, so there are certain *geographic limitations* in generating solar power.

3.3 Why we have chosen Solar Powered Desalination?

Solar energy is a very large, inexhaustible source of energy. The power from the sun intercepted by the earth is approximately 1.8×10^{11}MW. Which is many thousands times larger than the present all commercial energy consumption rate on the earth [q]. Thus in principle, solar energy could supply all the present and future energy needs of the world on a continuous basis. This makes it one of the most promising of all the unconventional energy sources. In addition to its size, solar energy has two other factors in its favor.

Firstly, unlike fossil fuels and nuclear power, it is an environmentally clean source of energy. Secondly, it is free and available in adequate quantity.

- Solar Powered Distillation is one method of desalination. Distillation has the advantage of using thermal energy, such as sunlight, thus saving electricity costs.

- With technology constantly improving, and current prices of conventional fuel sources increasing, it can be safe to say that solar-assisted desalination will be one of the most efficient and affordable options in the near future.

- Desalination powered by renewable energy: environmentally friendly and de-centralized solution for sustainable water supply.

- Solar distillation is a relatively simple treatment of brackish water supplies. This process removes salts and other impurities.

Generally, solar stills are used in areas where piped or well water is impractical. Such areas include remote locations or during power outages. One of the main setbacks for solar desalination plant is the low thermal efficiency and productivity. In areas that frequently loss power, Solar stills can provide an alternate source of clean water.

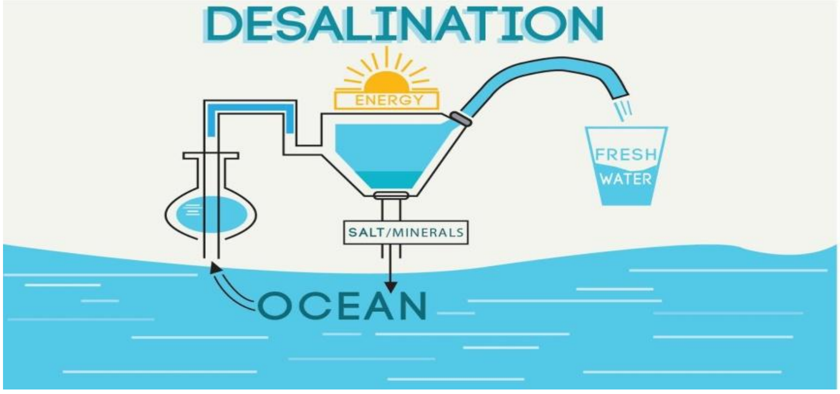


Fig-23: Desalination process [r]

Main benefits of solar desalination are-

- Solar energy = untapped resources
- Every year, energy the demand is increasing. It uses solar energy to distill the water
- A solar still is a simple way of distilling water. Solar still water is affordable
- Solar distillation is efficient and practical
- It removes impurities such as salt and other microbiological organisms
- Easy to operate

3.4 Funding opportunity

Due to the impending global water scarcity crisis, many human rights organizations are funding research on desalination in order to provide people with adequate drinking water.

1) Red cross
2) UNICEF (United Nations International Children's Emergency Fund)
3) WV (World Vision)
4) Climate Change Fund
5) UGC
6) NGO
7) Government

3.5 Current Desalination Research and Activities in other countries

As fresh water scarcity concerns have risen, research and development in desalination has increased. A large portion of the research is being done in the United States, the Middle East, and Japan. The most commonly used desalination method is multi-flash distillation and the most commonly used solar powered desalination method is passive evaporation.

Boehner discusses solar powered distillation desalination using large scale plants using a low technology intensive system. His system is 100% powered by the sun but is an example of passive distillation.

El-Nashar is a researcher in the UAE working on a solar assisted vacuum freezing ejector adsorption system with a million gallon a day capacity. This is an example of a system in which solar power can only supply a portion of the energy requirements needed. [47]

Purification of saline water involves chemical separation processes for removing dissolved ions from water. These processes are more energy intensive than the standard treatment processes for freshwater supplies. In many settings where fresh water resources or water supply infrastructure are inadequate, fossil energy costs may be high whereas solar energy is abundant. Such locations include sub-Saharan Africa and southern India. In the industrialized world, particularly the European Union, government policies increasingly emphasize the replacement of fossil energy by renewable, low-carbon energy, and so water-scarce regions such as Spain or the southwestern United States are considering solar-driven desalination systems as a supplement to existing fresh water supplies. Even in regions where petroleum resources are copious, such as the Arabian or Persian Gulf, solar-driven desalination is attractive as a means of conserving fossil fuel resources and limiting the carbon footprint of desalination. Finally, in settings that are remote and "off the-grid," a solar-driven desalination system may be more economical than alternatives such as trucked-in water or desalination driven by diesel-generated electricity.

Currently about 15,000 desalination units are operating world-wide with a total capacity of over 32 millions m^3/d. The desalination capacity contracted annually on average is 1 million m^3/d, which is equivalent to some $ 2,000 millions.

3.6 Basic Concept of Solar Water Distillation

Desalination is one of the most important methods of getting potable water from brackish and sea water by using the free energy supply from the sun. In nature, solar desalination produces rain when solar radiation is absorbed by the sea and causes water to evaporate. The evaporated water rises above the earth's surface and is moved by the wind. Once this vapor cools down to its dew point, condensation occurs, and the fresh water comes down as rain. The same principle is used in all manmade distillation systems using alternative sources of heating and cooling. Working of solar still is based on the simple scientific principle of evaporation and condensation. There are several types of solar stills, the simplest of which is the single basin still. Different still designs have been used in different regions globally, where high quality drinking water supplies are scarce and the solar option is viable. The operation of solar still is very simple and no special skill is required for its operation and maintenance [48].

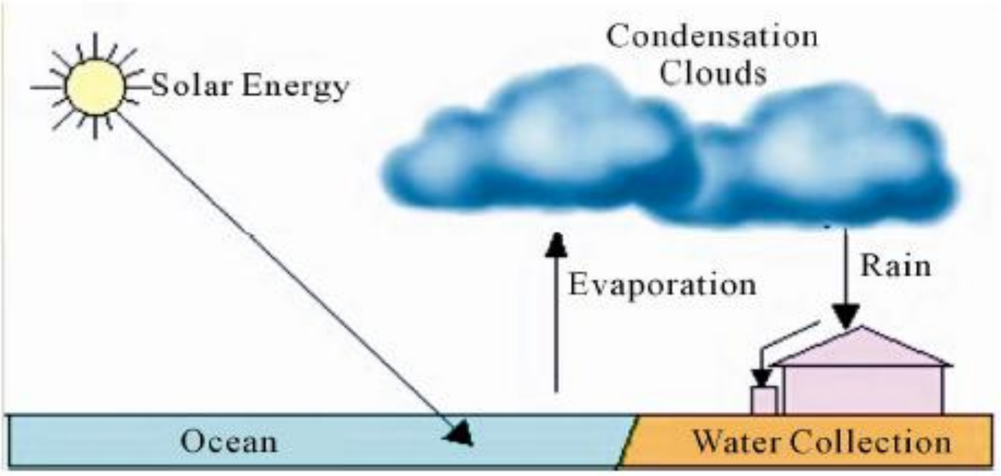


Fig-24: Principle of desalination [48]

The Basic principles of solar water distillation are simple yet effective, as distillation replicates the way nature makes rain. The sun's energy heats water to the point of evaporation. As the water evaporates, water vapor rises, condensing on the glass surface for collection. This process removes impurities such as salts and heavy metals as well as eliminates microbiological organisms. The end result is water cleaner than the purest rainwater. The Sol Aqua still is a passive solar distiller that only needs sunshine to operate. There are no moving parts to wear out.

The distilled water from a Sol Aqua still does not acquire the "flat" taste of commercially distilled water since the water is not boiled (which lowers pH). Solar stills use natural evaporation and condensation, which is the rainwater process. This allows for natural pH buffering that produces excellent taste as compared to steam distillation [v].

Solar stills can easily provide enough water for family drinking and cooking needs. Solar distillers can be used to effectively remove many impurities ranging from salts to microorganisms and are even used to make drinking water from seawater. Sol Aqua stills have been well received by many users, both rural and urban, from around the globe. Sol Aqua solar distillers can be successfully used anywhere the sun shines [v].

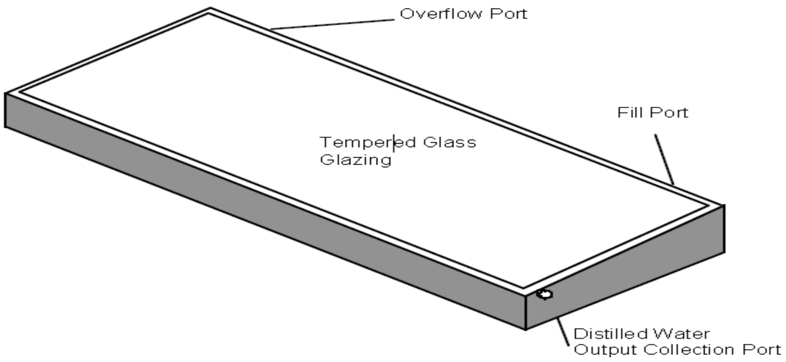


Fig-25: Sol Aqua solar still [v]

The Sol Aqua solar stills are simple and have no moving parts. They are made of quality materials designed to stand-up to the harsh conditions produced by water and sunlight. Operation is simple: water should be added (either manually or automatically) once a day through the still's supply fill port. Excess water will drain out of the overflow port and this will keep salts from building up in the basin. Purified drinking water is collected from the output collection port [v].

Supply Fill Port: Water should be added to the still via this port. Water can be added either manually or automatically. Normally, water is added once a day. Care should be taken to add the water at a slow enough flow rate to prevent splashing onto the interior of the still glazing or overflowing into the collection trough.

Overflow Port: Once the still basin has filled, excess water will flow out of this port. Sol Aqua recommends three times daily distilled water production to be allowed to overflow from the still on a daily basis to prevent salt build-up in the basin. If your still produced 2 gallons of product water then you should add 6 gallons of fresh feed water through the fill port. If flushed on a daily basis, the overflow water can be used for other uses as appropriate for your feed water.

Distilled Output Collection Port: Purified water is collected from this port. Stills that are mounted on the roof can have the distillate output piped directly to an interior collection container. For a newly installed still, allow the collection trough to be self-cleaned by producing water for a couple of days before using the distillate output.

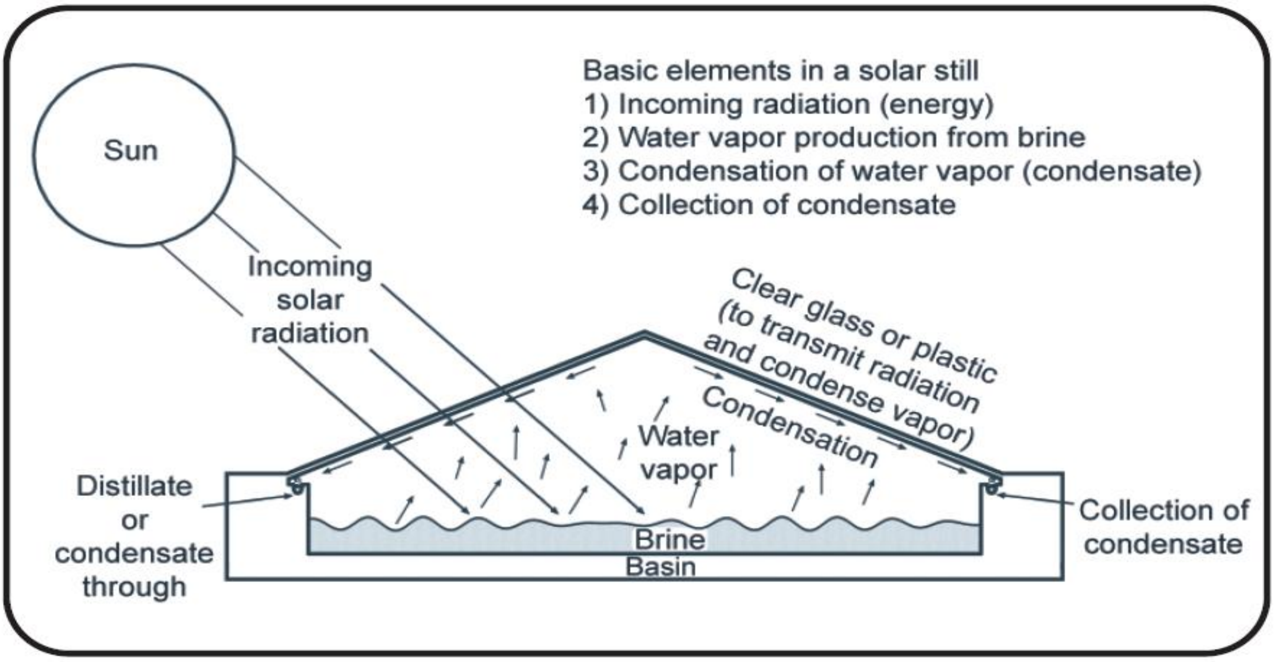


Fig-26: Basic concept of Solar Water Distillation [49]

3.6.1 Working of Solar Still

Solar stills are called stills because they distill, or purify water. A solar still operates on the same principle as rainwater: evaporation and condensation. The water from the oceans evaporates, only to cool, condense, and return to earth as rain. When the water evaporates, it removes only pure water and leaves all contaminants behind. Solar stills mimic this natural process.

A solar still has a top cover made of glass, with an interior surface made of a waterproof membrane. This interior surface uses a blackened material to improve absorption of the sun's rays. Water to be cleaned is poured into the still to partially fill the basin. The glass cover allows the solar radiation (short-wave) to pass into the still, which is mostly absorbed by the blackened base. The water begins to heat up and the moisture content of the air trapped between the water surface and the glass cover increases. The base also radiates energy in the infra-red region (long-wave) which is reflected back into the still by the glass cover, trapping the solar energy inside the still (the "greenhouse" effect). The heated water vapor evaporates from the basin and condenses on the inside of the glass cover. In this process, the salts and microbes that were in the original water are left behind. Condensed water trickles down the inclined glass cover to an interior collection trough and out to a storage bottle. There are no moving parts in Solar still and only the sun's energy is required for operation.

The still is filled each morning or evening, and the total water production for the day is collected at that time. The still will continue to produce distillate after sundown until the water temperature cools down. Feed water should be added each day that roughly exceeds the distillate production to provide proper flushing of the basin water and to clean out excess salts left behind during the evaporation process.

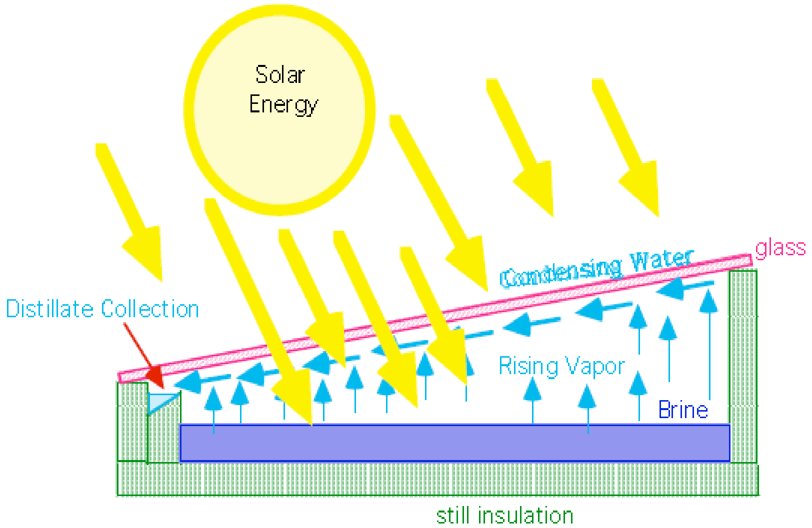


Fig-27: Working of Solar Still [49]

The most important elements of the design are the sealing of the base with black

3.6.2 Classification of Distillation Systems

Solar stills are classified in a number of ways. As per one category of classification which is based on the expected life span and application, the solar stills are classified into "permanent" (e.g. glass covered), "semi-permanent" (e.g. plastic covered) and "expandable" (e.g. double tube and floating type) type solar stills. However, one of the most commonly used classifications is based on the novelty of their design, and has been used here also. Following this, the simple solar stills are organized as given below [50]:

- Single basin solar stills
- Inclined solar stills
- Multi-basin solar stills

Single basin solar stills

The single basin solar still represents one of the earliest designs used for distillation of water using solar energy directly. Its main advantage lies in its easy construction and simplicity of operation and maintenance. Basically, it consists of an airtight assembly enclosed at the top by a cover which is transparent to solar radiation, but opaque to the long wavelength radiation. The assembly is partially filled with the saline or brackish water. The absorption of solar radiation by the basin liner and water causes evaporation of water. The air-vapor mixture therefore attains higher temperature and lower density at the water surface. It moves upwards by the convection currents established because of the density gradient so created. When air-vapor mixture comes in contact with the top cover which is at a lower temperature as compared to the water surface, it cools down to saturation resulting in the condensation of water. The condensed water trickles down the inner surface of the top cover and is collected as distilled water in the troughs provided along lower edges of the top cover.

Several configurations have been developed for single basin solar stills using different designs of basic structure and materials of construction. Figure 1 shows a deep basin solar still, designed by Lof et al. (1961).

Single basin solar stills are again classified according to the shape of the top transparent cover. They are

- Single slope type
- V type solar still
- Inverted V type solar still
- Hemispherical type solar still

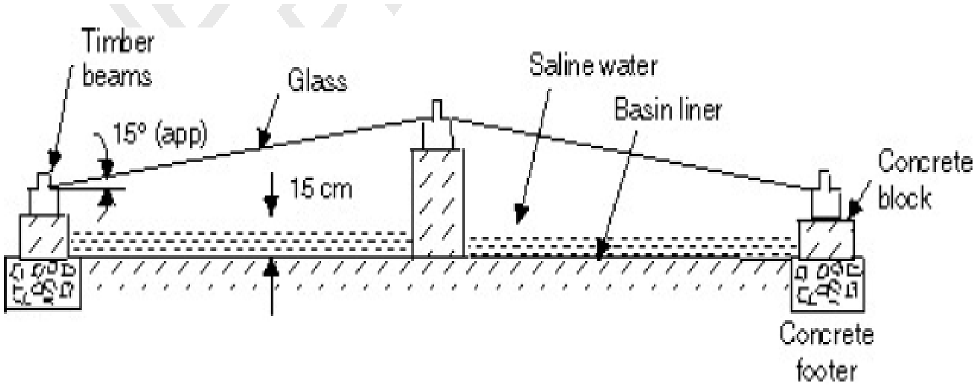


Fig-28: Deep basin solar still [50]

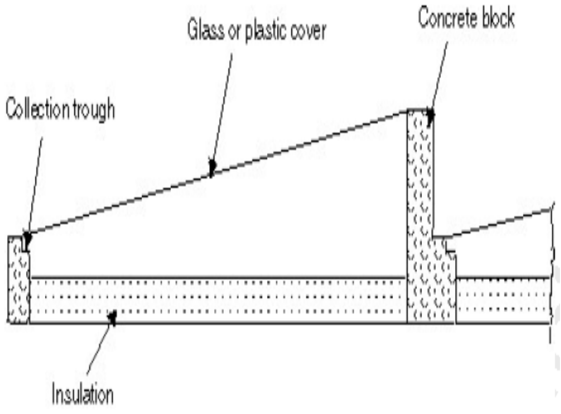


Fig-29: Single slope type solar still [50]

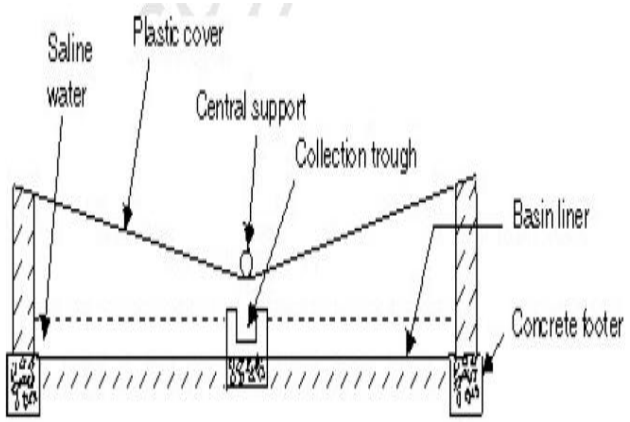


Fig- 30: V type solar still [50]

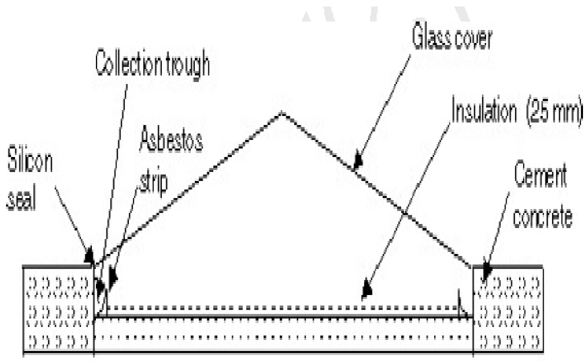


Fig-31: Inverted V type solar still [50]

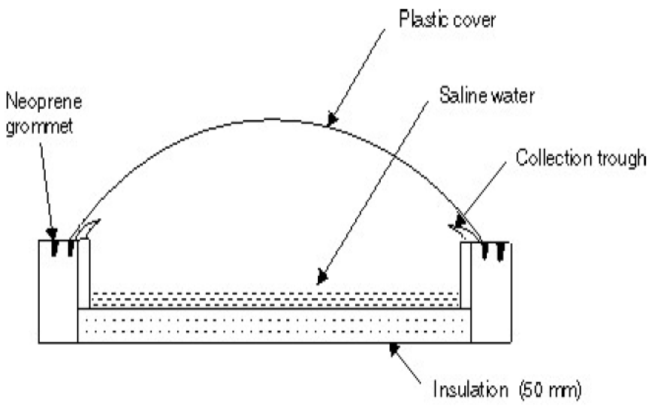


Fig-32: Hemispherical type solar still [50]

Inclined solar stills

As the name suggest the basin of this type of still is inclined at some angle to the horizontal. By making this type of stills, the distillate output is increased. Figure 7 shows the inclined solar still.

Multi-basin solar stills

In this type of solar still, the basin is divided in to more than one chamber. Both chambers is filled with brackish water.

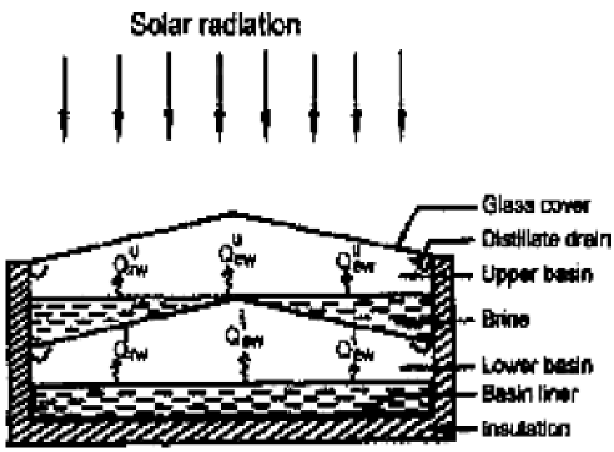


Fig-33: Multi basin solar still [50]

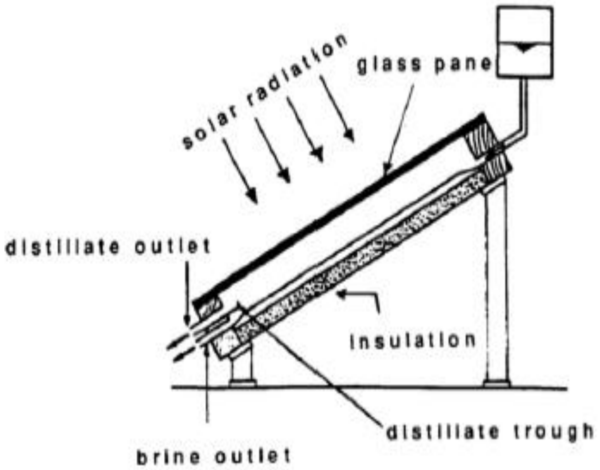


Fig-34: Inclined solar still [50]

3.6.3 Parts of the Solar Still

The major parts of a solar still are given below.

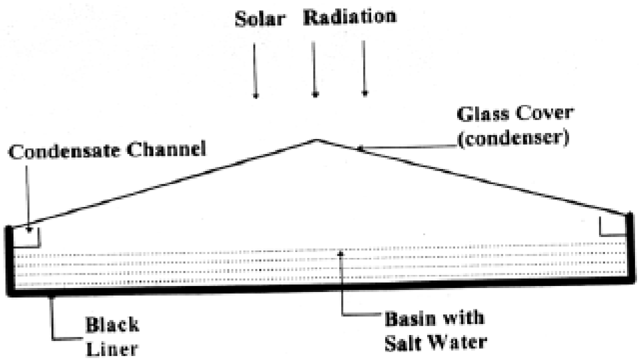


Fig-35: Parts of a solar still [50]

Transparent Cover- Transparent cover should have high transmittance for solar radiation, opaque to thermal radiation, resistance to abrasion, long life, low cost, high wet ability for water, lightweight, easy to handle and apply, and universal availability. This cover transfer solar radiation in to the still and also helps to condensate the vapor. The Materials used for transparent cover are glass or treated plastic.

Black Liner- A black liner is used in the basin of the solar still to absorb more solar radiation. The liner should be durable, water tight, easily cleanable, low cost, and should be able to withstand temperature around 100^0C. The materials used for making liner are asphalt matt, black rubber, black polyethylene etc.

Sealant- A sealant is used in the solar still to prevent the vapor leakages through the sides of the transparent cover. The sealant material should remain resilient at very low temperatures, low cost, durable and easily applicable. Materials used as sealant are putty, tars, tapes silicon etc.

Basin Tray- The salt/brackish water is initially stored in the basin tray of the solar still. The materials used for basins should have long life, high resistance to corrosion and low cost. The commonly used materials are wood, iron, steel, aluminium, asbestos cement, masonry bricks, concrete, etc.

Condensate Channel- The vapor generated inside the solar still is condensed on the inner surface of the transparent cover and the water droplets move downwards through the transparent cover. This fresh water is collected through the condensate channel fitted inside the solar still. The materials used for the condensate channel are Aluminium, galvanized iron, concrete, plastic materials, etc.

Insulation- The solar stills are thermally insulated to prevent the heat loss through the side walls and the basin. Vapor leakage is prevented by the sealant. All the energy received from the sun should be kept inside the still to vaporize water. The side walls and basin bottom are insulated by a low thermal conductivity material. The materials commonly used are saw dust, thermocole, glass wool etc. The better insulation will improve the performance of the still.

Water Supply System- Brackish or salt water should be supplied into the still continuously. In case of nocturnal production stills, water is fed once in a day [2][8]. In case of wick type systems, the feed rate of water should be kept equal to the evaporation rate of water from the still. Generally the water supply system includes an overhead tank, pipes to carry water into the still and regulatory valves.

3.7 Design of Solar Still

3.7.1 Design objectives for an efficient solar still

For high efficiency the solar still should maintain:-

- A high feed (un-distilled) water temperature
- A large temperature difference between feed water and condensing surface
- Low vapour leakage

A high feed water temperature can be achieved if:-

- A high proportion of incoming radiation is absorbed by the feed water as heat. Hence low absorption glazing and a good radiation absorbing surface are required
- Heat losses from the floor and walls are kept low
- The water is shallow so there is not so much to heat.

A large temperature difference can be achieved if:-

- The condensing surface absorbs little or none of the incoming radiation
- Condensing water dissipates heat which must be removed rapidly from the condensing surface by, for example, a second flow of water or air, or by condensing at night.

3.7.2Design Considerations

Different designs of solar still have emerged. The single effect solar still is a relatively simple device to construct and operate. However, the low productivity of the Solar still triggered the initiatives to look for ways to improve its productivity and Efficiency.

These may be classified into passive and active methods.

Passive methods include the use of dye or charcoal to increase the solar absorbtivity of water, applying good insulation, lowering the water depth in the basin to lower its thermal capacity, ensuring vapor tightness, using black gravel and rubber, using floating perforated black plate, and using reflective side walls.

Active methods include the use of solar collector or waste heat to heat the basin water, the use of internal] and external condensers or applying vacuum inside the solar still to enhance the evaporation/condensation processes, and cooling the glass cover to increase the temperature difference between the glass and the water in the basin and hence increases the rate of evaporation.

Single-basin stills have been much studied and their behavior is well understood. The efficiency of solar stills which are well-constructed and maintained is about 50% although typical efficiencies can be 25%. Daily output as a function of solar irradiation is greatest in the early evening when the feed water is still hot but when outside temperatures are falling. At very high air temperatures such as over 45ºC, the plate can become too warm and condensation on it can become problematic, leading to loss of efficiency.

3.7.3 Some problems with solar stills which would reduce their efficiency include

- Poor fitting and joints, which increase colder air flow from outside into the still
- Cracking, breakage or scratches on glass, which reduce solar transmission or let in air
- Growth of algae and deposition of dust, bird droppings, etc. To avoid this the stills need to be cleaned regularly every few days
- Damage over time to the blackened absorbing surface.
- Accumulation of salt on the bottom, which needs to be removed periodically
- The saline water in the still is too deep, or dries out. The depth needs to be maintained at around 20mm

3.7.4 Concepts for making a Good Solar still

The cover can be either glass or plastic. Glass is preferable to plastic because most plastic degrades in the long term due to ultra violet light from sunlight and because it is more difficult for water to condense onto it. Tempered low-iron glass is the best material to use because it is highly transparent and not easily damaged (Scharl & Harrs, 1993). However, if this is too expensive or unavailable, normal window glass can be used. This has to be 4mm think or more to reduce breakages. Plastic (such as polyethylene) can be used for short-term use. Stills with a single sloping cover with the back made from an insulating material do not suffer from a very low angle cover plate at the back reflecting sunlight and thus reducing efficiency.

It is important for greater efficiency that the water condenses on the plate as a film rather than as droplets, which tend to drop back into the saline water. For this reason the plate is set at an angle of 10 to 20º. The condensate film is then likely to run down the plate and into the run off channel.
Brick, sand concrete or waterproofed concrete can be used for the basin of a long-life still if it is to be manufactured on-site, but for factory-manufactured stills, prefabricated Ferro-concrete can be used. Moulding of stills from fiber glass was tried in Botswana but in this case was more expensive than a brick still and more difficult to insulate sufficiently, but has the advantage of the stills being transportable.

By placing a fan in the still it is possible to increase evaporation rates. However, the increase is not large and there is also the extra cost and complication of including and powering a fan in what is essentially quite a simple piece of equipment. Fan assisted solar desalination would only really be useful if a particular level of output is needed but the area occupied by the stills is restricted, as fan assistance can enable the area occupied by a still to be reduced for a given output.

Sufficient Insulations of wool, Thermocol, sealants etc. are provided inside the Basin in order to prevent loss of heat.

3.7.5 Design types and their performance

Single-basin stills have been much studied and their behavior is well understood. Efficiencies of 25% are typical. Daily output as a function of solar irradiation is greatest in the early evening when the feed water is still hot but when outside temperatures are falling.

Multiple-effect basin stills have two or more compartments. The condensing surface of the lower compartment is the floor of the upper compartment. The heat given off by the condensing vapour provides energy to vaporize the feed water above. Efficiency is therefore greater than for a single-basin still typically being 35% or more but the cost and complexity are correspondingly higher.

In a **wick still**, the feed water flows slowly through a porous, radiation-absorbing pad (the wick). Two advantages are claimed over basin stills. First, the wick can be tilted so that the feed water presents a better angle to the sun (reducing reflection and presenting a large effective area). Second, less feed water is in the still at any time and so the water is heated more quickly and to a higher temperature.
Simple wick stills are more efficient than basin stills and some designs are claimed to cost less than a basin still of the same output.

Emergency still - To provide emergency drinking water on land, a very simple still can be made. It makes use of the moisture in the earth. All that is required is a plastic cover, a bowl or bucket, and a pebble.

Hybrid designs - There are a number of ways in which solar stills can usefully be combined with another function of technology. Three examples are given:

a) Rainwater collection:-By adding an external gutter, the still cover can be used for rainwater collection to supplement the solar still output.

b) Greenhouse-solar still:-The roof of a greenhouse can be used as the cover of a still.

c) Supplementary heating: - Waste heat from an engine or the condenser of a refrigerator can be used as an additional energy input.

After going through the various existing designs of solar stills there are a few facts that come to picture:
1. The efficiency of single stage still is around 25%.
2. The efficiency of multistage stills is higher than 35%.
3. Mostly people use three staged stills because for more stages the cost outweighs the utility.
4. Most of the losses can be attributed to heat transfer losses.
5. Thermal losses are mostly in form of conduction and convection and very little by radiation – owing to low temperatures. So we can assume radiative losses to be negligible.

Also the cost of a solar still which produces reasonable amount of purified water is high.
The cost of water produced by the still is high. This fact attributes to almost negligible penetration of solar stills.

3.7.6 The equations governing the heat transfer rates

A. Conduction- **Q = - k A dT / dx**

B. Convection- **Q = h A (T**surface **- T**ambient **)**

Both the losses are greatly dependant on the area and temperature difference between the medium i.e., water and ambient. Hence if we can reduce temperature of the whole system we can reduce the heat loss and hence improve the efficiency.

But reducing operating temperature will come at the cost of lower rated of evaporation and consequently lower rated of condensation leading to slower distillation. So now the problem boils down to increasing the rated of evaporation at lower temperature.

(Mass loss rate) / (Unit area) = (Vapor Pressure - Ambient Partial Pressure) * sqrt ((Molecular Weight)/(2*pi*R*T))

The Vapor Pressure of a liquid at a given temperature is a characteristic property of that liquid. Vapor pressure of a liquid is intimately connected to boiling point.

Vapor Pressures are influenced by Temperature logarithmically and this relationship is defined with the **Clausius-Clapyron Equation:**

Log P2 / P1 = Delta H vaporization **[1 / T1 - 1/T2] / 2.303 (R)**

Where,

R = universal gas law constant = 8.31 J/mol-K = 8.31 X 10-3 Kj / mol-K

P1 and P2 = vapor pressure at T1 and T2

T1 and T2 = Kelvin Temperature at the initial state and final state

At 373K the pressure is 1 atm.

We all know that boiling takes place when the ambient temperature equals that of the vapor pressure of the liquid. This means that we can increase the rate of evaporation by reducing the pressure of the vessel. This will ensure higher rates of evaporation even at low temperatures.

3.7.7 Estimation of the Quantity of Output Water

Empirical relationship given by Schumacher Center For Technology & Development, UK

$$Q = \frac{A.E.G}{2.3}$$

Where,

A = Aperture area of the still in m^2

E = Efficiency of the still usually taken as 50%

G = Global radiation energy in MJ/m^2 (Approx. 18 MJ/m^2)

Estimate: *3.91 liters/m^2 /day.*

3.7.8 Material Requirements of Basin Still

The materials used for this type of still should have the following characteristics:

- Materials should have a long life under exposed conditions or be inexpensive enough to be replaced upon degradation.
- They should be sturdy enough to resist wind damage and slight earth movements.
- They should be nontoxic and not emit vapors or instill an unpleasant taste to the water under elevated temperatures.
- They should be able to resist corrosion from saline water and distilled water.
- They should be of a size and weight that can be conveniently packaged, and carried by local transportation.
- They should be easy to handle in the field.

Although local materials should be used whenever possible to lower initial costs and to facilitate any necessary repairs, keep in mind that solar stills made with cheap, unsturdy materials will not last as long as those built with more costly, high quality material.

3.7.9 Material Used

1. The side and bottom walls need to be insulated. This can be achieved by using multilayered insulator. Glass wool will be sand-witched between two metallic plates.
2. The main frame is composed of steel owing to its corrosion resistance, low weight, long life and easy clean ability.
3. The outside of the complete distiller is coated with carbon black to increase absorption of radiation.
4. The cover on the top is made of tempered glass so that the birds can"t see their reflection and hence avoid nuisance.

3.7.10 Assembling and manufacture

Fabrication of the whole unit is pretty straight forward and involves metal cutting, welding, glass cutting, sealing, painting and drilling. All these processes can be done at any local workshop using simple machines – lathe, drill, welding, milling etc.

The steps in the process of assembling are outlined as follows:

1. The outer box will be fabricated first. It will be made of double wall and will be filled with glass wool to provide insulation.
2. The stages will be fabricated second the collector holes will be made at the time of fabrication. Finally the stages will be assembled inside the outer covering.
3. The collector tubes are then made and attached to the lowermost stage.
4. The holes are provided for Collecting distilled water and Transporting saline water
5. The whole system is sealed using sealant to prevent the air from leaking in from the atmosphere.

3.7.11 Design of an practical solar still

The photograph of the modified single slope solar still are shown in figure. The still mainly consists of the basin and absorber plate carrying the saline water, the cover, and the support structure as shown in Fig. The basin of the still (tray) and absorber plate, and the collector were all fabricated using Galvanized Iron. The basin contains the absorber aluminium plate which has a surface area of 1×1 m_2. A hole with diameter of approximately 30 mm was drilled into the tray to provide accessibility of saline water into the basin during initial filling and bottom section of basin was insulated to reduce thermal losses to the surroundings. The absorber was coated with black paint to maximize absorption of the incident solar radiation on the basin. The two different condensing covers, located on the top of the solar still unit, was made of two different material (a) A glass cover and (b) A transparent PVC sheet. The side walls are made of using two 5 mm thick glass plates separated by 2 cm air gap. The side walls are made of glass to capture more diffuse radiation and the air gap is provided to minimize heat loss from sides. The distillate output from the still was frequently collected using a plastic container placed under the nozzle outlet part of the collector.

Fig-36: Photograph of the modified design single slope solar still

Constructing a solar water distiller using available utensils like plastic for casing, aluminum for absorption of heat, glass and the thermocol for insulation, Got the temperature of water up to 60 degrees and 1000 ml of distilled water in 4 hours.

Surface area: 1 m^2.

Output: After 4 hours under the sun an output of 500 ml of pure distilled water

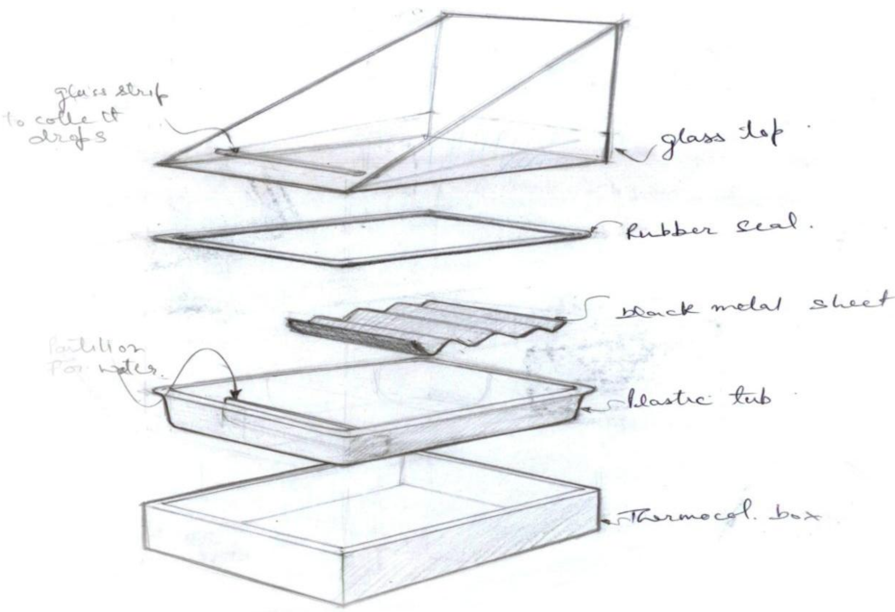


Fig-37: Components of Solar Still

3.8 Solar PV Panel

3.8.1 Solar Panel

A solar panel is a packaged connected assembly of photovoltaic cells. The solar panel can be used as a component of a larger photovoltaic system to generate and supply electricity in commercial and residential applications. Each panel is rated by its DC output power under standard test conditions, and typically ranges from 100 to 320 watts. The efficiency of a panel determines the area of a panel given the same rated output – an 8% efficient 230 watt panel will have twice the area of a 16% efficient 230 watt panel. Because a single solar panel can produce only a limited amount of power, most installations contain multiple panels.

A photovoltaic system typically includes an array of solar panels, an inverter, and sometimes a battery and or solar tracker and interconnection wiring.

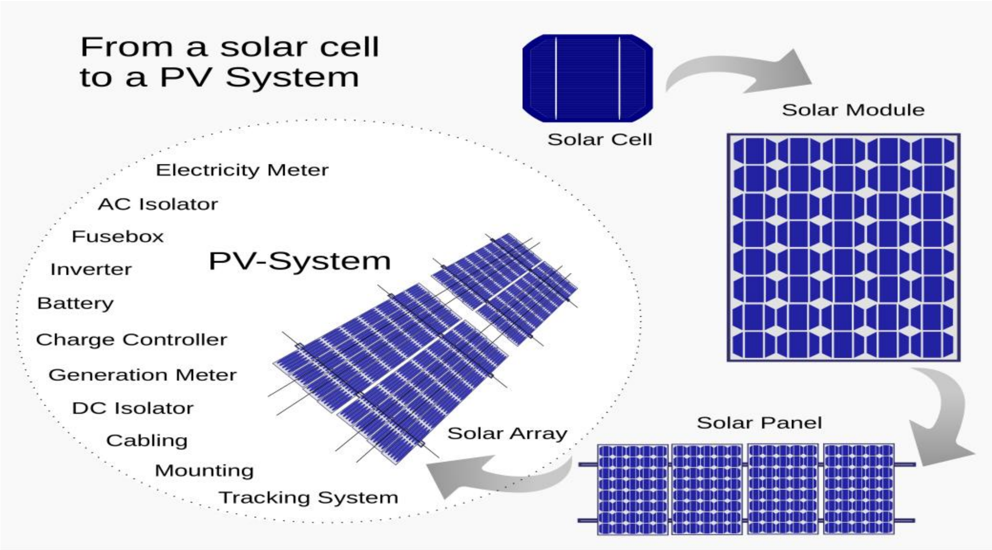


Fig-38: Solar cell to PV system [w]

A solar panel is made up numerous series and parallel combinations of identical individual cells to generate the desired power output (current and voltage). Panels are assigned a power rating in watts based on the maximum power they can produce under ideal sun and temperature conditions. The rated power output is used to help determine how many panels are needed to meet the electrical load demands. Multiple panels combined together are called solar arrays. In a typical SHS household one solar panel of less than 120w is usually utilized. There is a linear relationship between solar panel cost and output power.

Electrical connections are made in series to achieve a desired output voltage and/or in parallel to provide a desired current capability. The conducting wires that take the current off the panels may contain silver, copper or other non-magnetic conductive transition metals. The cells must be connected electrically to one another and to the rest of the system. Externally, popular terrestrial usage photovoltaic panels use MC3 (older) or MC4 connectors to facilitate easy weatherproof connections to the rest of the system.

Bypass diodes may be incorporated or used externally, in case of partial panel shading, to maximize the output of panel sections still illuminated. The p-n junctions of mono-crystalline silicon cells may have adequate reverse voltage characteristics to prevent damaging panel section reverse current. Reverse currents could lead to overheating of shaded cells. Solar cells become less efficient at higher temperatures and installers try to provide good ventilation behind solar panels.

3.8.2 Basic Construction, Characteristics and Assembling

Solar Cell

Solar Cell converts solar energy into electrical energy. Solar cell converts photons in Solar rays to direct-current (DC) and voltage. The associated technology is called Solar Photovoltaic. A typical silicon PV cell is a thin wafer consisting of a very thin layer of phosphorous-doped (N-type) silicon on top of a thicker layer of boron-doped (P-type) silicon. An electrical field is created near the top surface of the cell where these two materials are in contact (the P-N junction). When the sunlight hits the semiconductor surface, an electron springs up and is attracted towards the N-type semiconductor material. This will cause more negatives in the n-type and more positives in the P-type semiconductors, generating a higher flow of electricity. This is known as Photovoltaic effect.

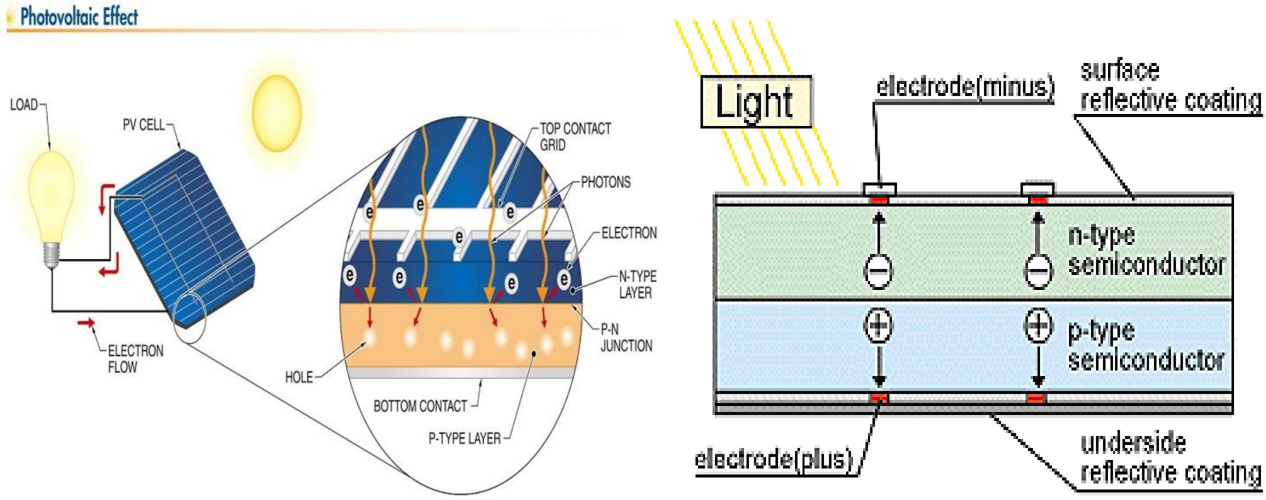


Fig-39: Photovoltaic effect, Silicon Solar Cell and its working mechanism [x]

The amount of current generated by a PV cell depends on its efficiency, its size and the intensity of sunlight. There are three main types of solar cells: mono-crystalline silicon, poly-crystalline silicon, and thin film materials. The different cell technologies represent different energy conversion efficiencies and manufacturing approaches in trying to reduce the cost of energy production.

Module

A *module* is a PV device consisting of a number of individual cells connected electrically, laminated, encapsulated, and packaged into a frame. PV Module is basic building block of a PV power system. One silicon solar cell produces 0.5V to 0.6V. Usually 36 cells are connected together to make a module. Such one module has enough voltage to charge 12 volt batteries and Run pumps and motors. Modules are constructed from PV cells surrounded by several layers of protective materials.

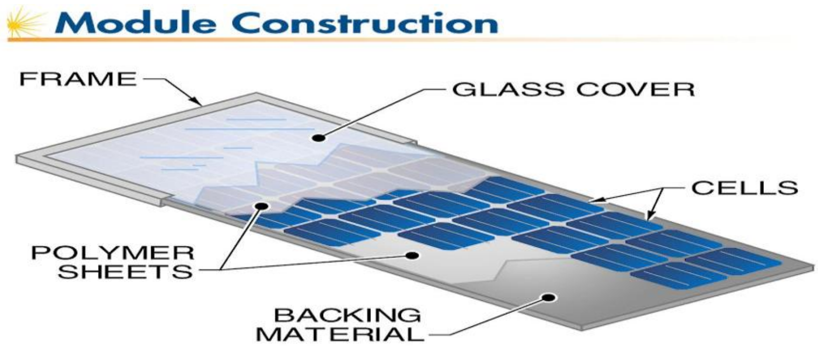


Fig-40: A PV Module Construction [y]

Current-Voltage (I-V Curve)

A I-V curve (performance curve) shows the electrical current and voltage output of a PV device. Short circuit current (**I_{sc}**) occurs when the module is shorted, the voltage then is zero. Open circuit voltage (**V_{oc}**) occurs when there is a break in the circuit. Typically 70-80% of the V_{oc} and 90% of the I_{sc} .

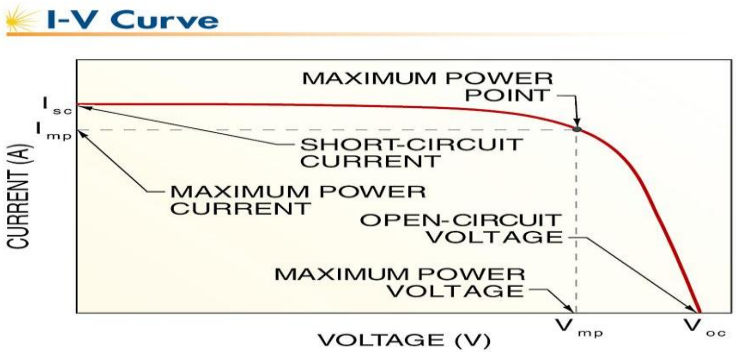


Fig-41: I-V characteristics [y]

When voltage is plotted against current for all the operating points, it forms a curve.

An *I-V curve* is the graphic representation of all possible voltage and current operating points for a PV device (Cell, Module, Array) at a specific operating condition. As voltage increases, the current begins at its maximum and decreases gradually until the knee of the curve is reached. After the knee, small increases in voltage are associated with larger reductions in current, until the current reaches zero and the device is at maximum voltage

Junction box

A junction box on the back of a module provides a protected location for electrical connections and diodes. All modules include some means for making inter-module electrical connections, through the use of either pre-wired connectors or a junction box. The junction box may also include bypass diodes and the ability to change the series or parallel configuration of the module cells.

Nameplates

Module nameplates must include performance ratings for the module and may include other information used to design a PV system. Standard performance ratings for modules are referred to as nameplate ratings, and they are required by the NEC® to be clearly labeled on every module. At a minimum, each module must be marked with polarity identification, maximum over current device rating, and ratings at specified conditions for key I-V curve parameters, including open-circuit voltage, maximum permissible system voltage, maximum power current, short-circuit current and maximum power. Additional information may include product listings and certifications, design qualifications, fire class ratings, ratings at other temperatures, and allowable wire sizes.

Fig-42: Junction Box and Name Plate [y]

Chapter 4
Design and fabrication

4.1 Design of Solar Powered Desalination Device

Design of my solar desalination model is very simple. One aim of the calculation is to find out how much distilled water will get per day from one square feet area and how much total area is required to fulfill the requirement.

- ***Latent heat of water evaporation***-2260 kj/kg (heat required to change water from liquid to steam phase)
- ***Efficiency of solar still***-0.25 (25 percent ,can be different depending on the design)
- ***Average daily solar radiation on a given location***-4.5 kwh/m^2-day (data varies from one location to another and one season to another)

Step-1: Finding Out Useful Solar Radiation

Useful Solar Radiation (which is actually converting radiation heat energy to distilled water)
=**Daily Solar Radiation X Solar Distill Efficiency**

Step-2: Litres of distilled water produced per day per square metre

Latent heat of water evaporation- 2260 KJ/kg
Number of Litres of distilled water produced per square metre per day=

$$\frac{\textbf{Useful Solar Radiation}}{\textbf{Latent heat of water evaporation}}$$

Step-3: Total area of the solar distill to fulfill the requirement

Total areas of the solar distill to fulfill family requirement =

$$\frac{\textbf{Total Daily Requirement}}{\textbf{Number of Litres produced per day per square metre}}$$

Alternatively, the total solar distill area required to fulfill daily requirement can be calculated using following formula

$$\mathbf{A} = \frac{\mathbf{Q \times 2.26}}{\mathbf{G \times E}}$$

Where,

A = Total distill area requirement
Q = Total distilled water required pre day
G = Daily solar radiation in MJ/m^2-day
E = Efficiency of solar distill in decimal

The formula should be used for any volume of water. In this design, We just tried to stand up a new model using heater. We used 1feet X 1feet size because our task was to make a sample of our thinking and proposed model. Volume of the device was 1 cubic feet.

4.2 Experimental Model

- The experimental model is the combination of solar powered heater and a single basin solar still. The basic construction is same as we use normally in simple single basin solar still except that it has conjunction with solar powered dc heaters.

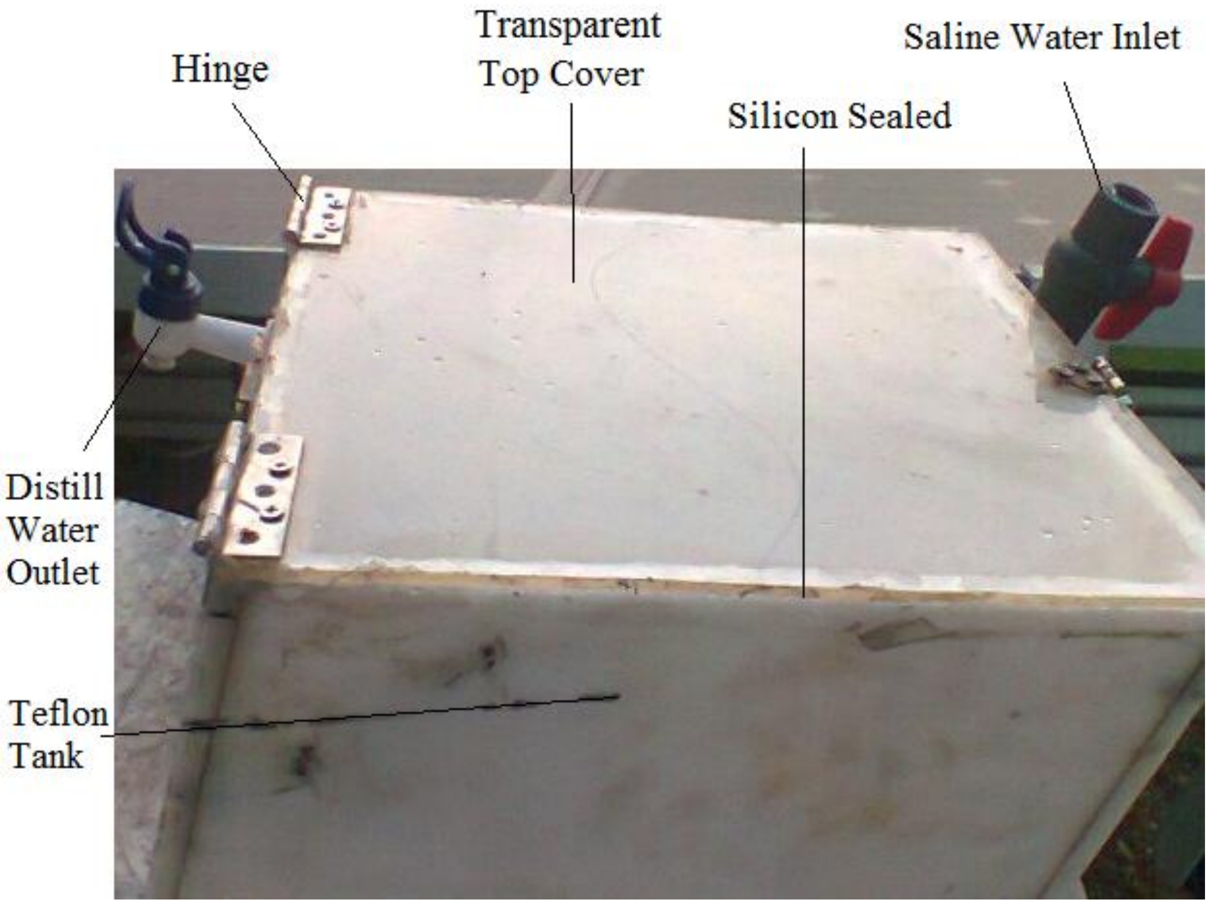


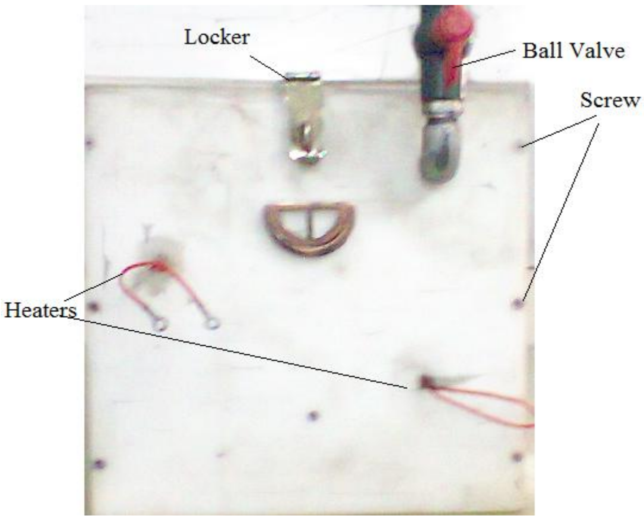
Fig-43: Designed model for better desalination.

4.2.1 Basic Construction

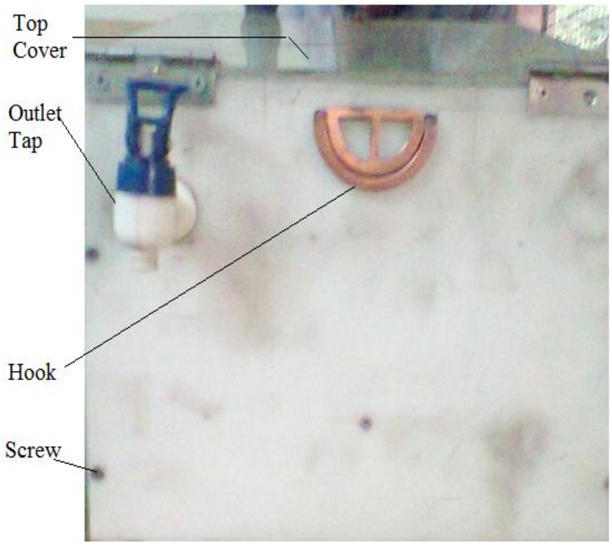
Container of saline water should be insulated at side wall and bottom. Heat proof teflon is used for this reason. They are pasted with silicon sealant to prevent heat losses. To transmit solar energy high transmittive material and heavy tempered glass has been used. To absorb the heat from sun and heater quickly we used metallic surface of aluminium at bottom. The side wall is kept white to use the reflected beam for providing supporting heating action. A stainless steel condensate is used to collect droplets of water. A storage pot is used for storing the distill water.

4.2.2 System Components

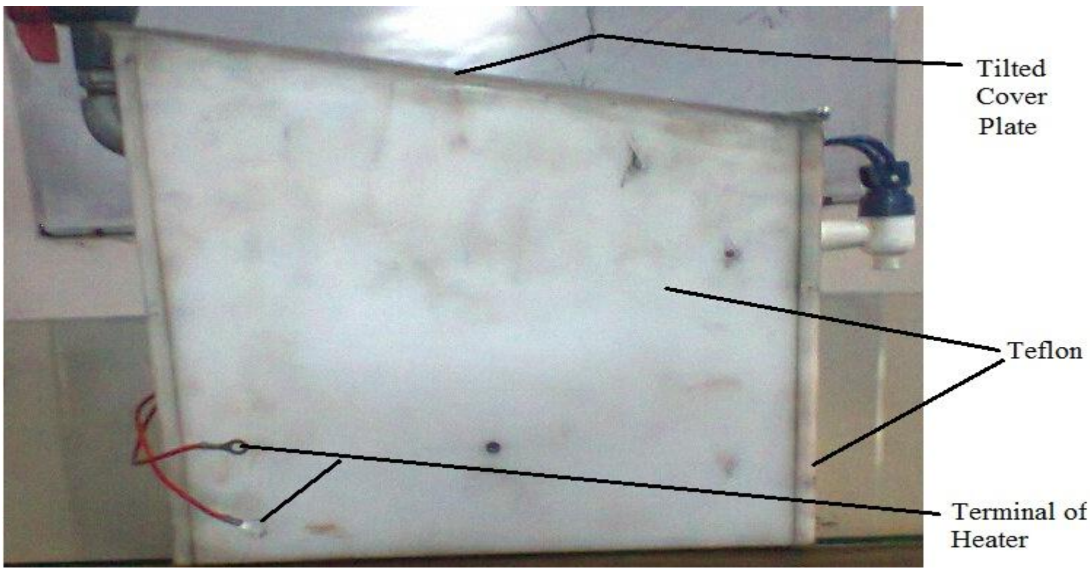
(a) **Water Basin** : Heat Proof Plastic (Teflon)
(b) **Insulation** : Silicon sealant
(c) **Transparent cover** : Tempered Glass
(d) **Absorber** : Aluminium Sheet(0.5 mm)
(e) **Condensate Channel** : Stainless Steel (SS)
(f) **Storage pot** : PET Glass (used for soft drinks normally)
(g) **DC heater for upper heat** : Nicrome Heater2 pcs. (Made in England,200W ,24V)
(h) **DC heater for bottom** : U shaped Heater1 pcs (Made in England,200W,24V)
(i) **Screw** : Stainless Steel (SS)
(j) **Locker** : MS Steel (Mild Steel)
(k) **Water Inlet** : Ball Valve
(l) **Water Outlet** : Simple Tap



(A)Back View



(B) Front View



(C) Side view

Fig-44: Ins and Outs of Dual Mode Solar powered desalination device.

4.2.3 Working Principle of Some Instruments

Pyranometer: Basically the pyranometer consists of a black surface which heats up when exposed to solar radiation. Its temperature increases until its rate of heat loss by convection, conduction and re-radiation. The hot junctions of a thermopile are attached to the black surface, while the cold junctions are located in such a way that does not receive the radiation. As a result an e.m.f is generated. This e.m.f which is usually in the range of 0 to 10mV. The detector is covered by two concentric hemispherical optical glass covers. The output of thermopile is unaffected by detector orientation. The outer precision-ground hemisphere can be either optically clear glass or one of several filter glasses. Measurements of diffuse radiation can be made with pyranometers by shading the instrument from beam radiation. The ring is used to allow continuous recording of diffuse radiation without the necessity of continuous positioning of smaller shading devices; adjustments need to be made for changing declination only and can be made every few days. The ring shades the pyranometer from part of diffuse radiation and a correction for this shading must be estimated and applied to the observed diffuse radiation.

Fig-45: Pyranometer

DC immersion heater: DC immersion heater is a device which is installed in a tank or container to heat a liquid. These heaters are available with heating elements made of copper, steel, stainless steel, cast iron, Incoloy, titanium, and PFA coated. They are constructed of one or more heater elements brazed or welded into various types of mounting fittings. A wide selection of kilowatt ratings, shapes are available to suit many different types of applications. DC immersion heater is a environmentally friendly technology, ease of heating element with high power consumption and the risk of electrical shock.

Fig-46: DC Heaters used in the device

4.2.4 PV module size

We have no other power supply except solar energy. We all know solar energy is a renewable source of energy. The dc heaters used here were powered by solar PV modules. So, we had to connect the terminal with solar panel. Before connecting, we measured and matched the appropriate values needed. We used multi-meter for that purpose.

The rating of each Panel:-
Short circuit current, I_{SC}=8A
Open circuit Voltage, V_{OC}=36.7V

Combination of the three 200w, 24V panels in parallel gave the output below:
Output (Peak) power = 600W

Fig-47: Solar panels on the roof top

Fig-48: Measurement of Module power output

4.3 Operation

1) A certain amount of saline water was taken as input through the ball valve.

Fig-49: Saline Water Input

2) The initial temperature of saline water was measured.
3) Then, heaters were connected to solar panel.
4) When vapor starts to create droplet, the temperature was measured again.

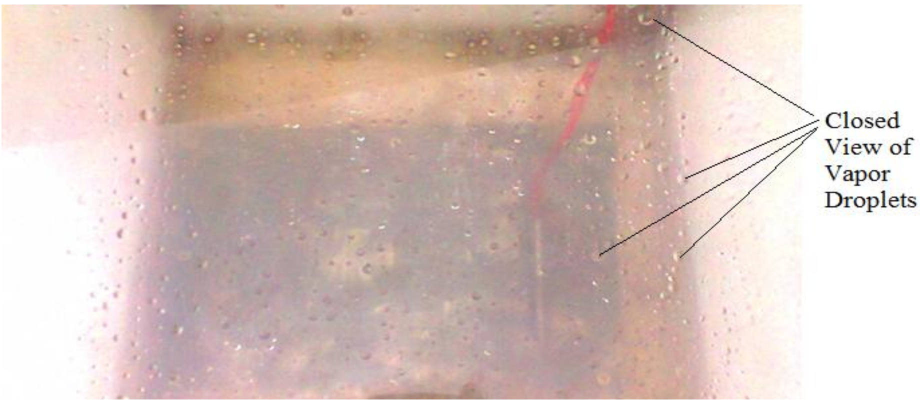


Fig-50: Saline Water creating bubbles.

5) The droplet continued to turn into larger size and moved toward the condensate.
6) The distill water was collected through the output tap.

Fig-51: Collection of Distill Water

4.4 Economics of Solar Powered Desalination

4.4.1 Cost for Construction

A short description of construction cost of the device below.

Four pc's Heat resistive Teflon sheet (1ftX1ft) = 800tkX4 = 3200 tk	
Bottom Al sheet (0.5 mm) =	400 tk
Heater (3pcs) = (250+200+200) =	650 tk
Top cover plate =	350 tk
Ball Valve =	100 tk
Output Tap=	60 tk
Condensate =	200 tk
Others =	1040 tk
Total =	6,000 tk (approximate)

Total water production cost will be high enough if we add power production cost from PV panel. This seems to be very costly in a poor country like Bangladesh. But when the production will start in huge amount, the cost will be lower due to averaging.

4.4.2 Time to Recovery

Daily Distill water production for one square feet area = 1.3 Litre/day (7 hour working)
Cost of manufacturing of solar distill for one square feet area=6,000 tk
Solar Electricity facility cost (per year) = 6,000 tk
Total cost to produce water = 6,000+6,000= 12,000 tk
Distill water production per year = 1.3 X 365 = 474.5 L
Price of distill water in the market = 20 tk/litre
Price of distill water produced per year = 474.5 X 20 = 9490 tk
The number of years required to recover the cost = 12,000/9490=1.2 years

Distill water can be used for homeopathy, animal vaccine, juice mixer, herbal syrup, rose water, battery etc. Depending on requirements, solar insolation payback period may become lesser.

4.4.3 Cumulative Heat Balance on a Solar Still

Heat Absorbed/Lost	**Percentage (%)**
Heat energy for evaporation	38.4%
Heat Loss by convection in still	3.7%
Heat Loss by radiation in still	12.2%
Heat loss by reflection from glass cover	10.0%
Heat absorbed by cover	10.0%
Heat loss by conduction through bottom	16.0%
Unaccounted heat loss such as vapor Leakage and side losses	9.7%
	Total =100%

Table-7: *Heat Balance table*

The values mentioned above are approximated from the characteristics of device components and device structure.

4.4.4 Energy required for solar desalination

The energy required to evaporate water is the latent heat of vaporization of water. *The latent heat is the heat that is required by a substance to change its phase, from solid to liquid or liquid to gas or vice versa.*

The latent heat of evaporation of water is about 2260 kilojoules per kilogram. This implies that in order to produce 1litre of water through distillation, heat input of 2260KJ is required (assuming water density as 1Kg per litre)

In practice, one has to supply much higher amount of heat energy because the efficiency of the still will not be 100%.

Chapter 5
Measurement and Performance Testing

5.1 Experimental Data

Observation No: 1

Date of experiment: 20-06-16 (Monday)

Mode of Operation : Dual Mode (Using Heaters and Sunshine)
Amount of Saline water : 5 Litres
Initial Temperature of saline water : 30.2 ^{O}C
Temperature Rise (until evaporation started): 69.5^{O}C
Pyranometer Model : CM11
Sensitivity Factor : $5.02 \times 10^{-6} V / Wm^{-2}$
Starting Time : 09:00 AM
Ending Time : 4:00 PM
Total operating Time : 7 hours

Time (AM/PM)	Panel Voltage (At Load) Volts	Pyranometer Reading (mV)	Solar radiation (W/m^2)
09:00	14.1	2.9	577.69
09:30	14.1	3	597.61
10:00	13.9	2.7	537.85
10:30	15.8	3.3	657.37
11:00	18.7	3.6	717.13
11:30	19.6	3.8	756.97
12:00	20.2	3.9	776.89
12:30	19.8	3.8	756.97
01:00	15.9	3.4	677.29
01:30	9.9	2.1	418.33
02:00	13.5	2.5	498.01
02:30	12.1	2.4	478.09
03:00	10	2.2	438.25
03:30	8	2	398.41
04:00	5	1.3	258.97
Total= 7 Hours		Average Solar Radiation = **541.17** W/m^2	

Table-8: *Experimental Data table- **1***

From 5 litres of saline water, 1300mL distill water has been produced.
So, the distill water produced per litre (in 7 hours) = 260 mL (based on above irradiance)

Observation No: 2

Date of experiment: 26-06-16 (Sunday)

Mode of Operation : Single Mode (Using only Sunshine)
Amount of Saline water : 1Litre
Initial Temperature of saline water : 28.6 ^{O}C
Temperature Rise (until evaporation started): 70 ^{O}C
Pyranometer Model : CM11
Sensitivity Factor : $5.02\times10^{-6} V / Wm^{-2}$
Starting Time : 09:00 AM
Ending Time : 04:00 PM
Total operating Time : 7 hours

Time (AM/PM)	**Pyranometer Reading (mV)**	**Solar radiation (W/m^2)**
09:00	2.2	438.25
09:30	2.7	537.85
10:00	2.5	498.01
10:30	3.0	597.61
11:00	3.1	617.53
12:00	2.9	577.69
12:30	2.9	577.69
01:00	2.2	438.25
01:30	2.5	498.01
02:00	2.1	418.33
02:30	2.2	438.25
03:00	2.7	537.85
03:30	2.5	498.01
04:00	2.2	438.25
Total=7 Hours	Average Solar Radiation = **519.92 W/m^2**	

Table-9: *Experimental Data table- **2***

From 1litre saline water, 35 mL distill water has been produced.
So, the distill water produced per litre (in 7 hours) = 35 mL(based on above irradiance)

Observation No: 3

Date of experiment: 29-06-16 (Wednesday)

Mode of Operation : Single Mode (Using only Heaters without sunshine)
Amount of Saline water : 2.5Litres
Initial Temperature of saline water : $28^{O}C$
Temperature Rise (until evaporation started): $69^{O}C$
Pyranometer Model : CM11
Sensitivity Factor : $5.02\times10^{-6} V/Wm^{-2}$
Starting Time : 09:00 AM
Ending Time : 04:00 PM
Total operating Time : 7 hours

Time (AM/PM)	Panel Voltage (At Load) Volts	Pyranometer Reading (mV)	Solar radiation (W/m^2)
09:00	12	2	398.41
09:30	13.7	2.5	498.01
10:00	12.9	2.2	438.25
10:30	7.5	1.2	239.04
11:00	12.1	2.4	478.09
11:30	12.5	2.1	418.33
12:00	13	2.3	458.17
12:30	13.5	2.5	498.01
01:00	12.5	2.1	418.33
01:30	13.7	2.5	498.01
02:00	8.9	1.6	318.73
02:30	6.7	1.1	219.12
03:00	12.5	2.1	418.33
03:30	8.9	1.6	318.73
04:00	6.7	1.1	219.12
Total= 7Hours		Average Solar Radiation =	**373.51 w/m^2**

Table-10: *Experimental Data table- **3***

From 2.5litres of saline water, 540 mL distill water has been produced.
So, the distill water produced per litre (in 7 hours) = 216 mL(based on above irradiance)

5.2 Efficiency Calculation

Efficiency of solar still with heater (From observation: 1)

From observation no-1, we have:

m_s = Saline water used (litre) =5litre (≈5kg)
S = Specific heat (heat capacity) of sea water = 3.93 X 10^3J/kg-^{0}C
θ_1 = Standard room temperature before solar energy being applied = 30.2^{0}C
θ_2 = Saline water heated before evaporation up to = 69.5^{0}C
$\Delta\theta$ = Change of Heat into saline water = θ_2-θ_1= (69.5-30.2)^{0}C =39.3^{0}C
m_d = Mass of distill water (litre) = 1300ml = 1.3litre (≈1.3kg)
l_v = Latent heat for vaporization = 2.26 X 10^3J/kg
I_r = Solar radiation = 541.17 W/m^2
A = Area of the surface = 1ft X 1ft = 0.3048m X 0.3048m = 0.093m^2
t = Operating Time = 7 hours = (7 X 3600) = 25200 Sec
P = Power from the panel for heaters = (I_rX 600)/1000 = (541.17 X 600)/1000 = 324.702 W (since, the panel gives 600Watt peak power)

►Total Heat Input, H = Heat produced by solar radiation + Heat produced by heaters **=I_rAt + Pt**

►Heat absorption by water to evaporate, **$Q = m_sS\Delta\theta + m_dl_v$**

∴ Efficiency, η= **(Q/H) X 100 %**

$$= \left[\frac{m_sS\Delta\theta + m_dl_v}{I_rAt + Pt} \right] \text{X } 100\ \%$$

$$= \left[\frac{\{5 \text{ X } (3.93\text{X}10^3) \text{ X } 39.3\} + \{1.3 \text{ X } (2260\text{X}10^3)\}}{\{(541.17\text{X}0.093\text{X}25200) + (324.702\text{X}2500)\}} \right] \text{X } 100\ \%$$

=39.53 %

≈ 40 %

Efficiency of solar still without heater (From observation: 2)

From observation no-2, we have:

m_s = Saline water used (litre) =1litre (≈1kg)
S = Specific heat (heat capacity) of sea water = 3.93 X 10^3J/kg-^{0}C
θ_1 = Standard room temperature before solar energy being applied = 28.6^{0}C
θ_2 = Saline water heated before evaporation up to = 70^{0}C
$\Delta\theta$ = Change of Heat into saline water = θ_2-θ_1= (70-28.6)^{0}C = 41.4^{0}C
m_d = Mass of distill water (litre) = 35ml = 0.035litre (≈0.035kg)
l_v = Latent heat for vaporization = 2.26 X 10^3J/kg
I_r = Solar radiation = 519.92 W/m^2
A = Area of the surface = 1ft X 1ft = 0.3048m X 0.3048m = 0.093m^2
t = Operating Time = 7 hours = (7 X 3600) = 25200 Sec

►Total Heat Input, H = Heat produced by solar radiation =$\mathbf{I_rAt}$

►Heat absorption by water to evaporate, $\mathbf{Q = m_sS\Delta\theta + m_dl_v}$

∴Efficiency, η= **(Q/H) X 100 %**

$$= \left[\frac{m_sS\Delta\theta + m_dl_v}{I_rAt}\right] \times 100\ \%$$

$$=\left[\frac{\{1 X (3.93X10^3) X 41.4\}+ \{0.035 X (2260X10^3)\}}{(519.92X0.093X25200)}\right] X\ 100\ \%$$

=19.84 %
≈ 20 %

Efficiency of solar still using only heaters without sunrays (From observation: 3)

From observation no-3, we have:

m_s = Saline water used (litre) =2.5litre (≈2.5kg)
S = Specific heat (heat capacity) of sea water = 3.93 X 10^3J/kg-^{0}C
θ_1 = Standard room temperature before solar energy being applied = 28^{0}C
θ_2 = Saline water heated before evaporation up to = 69^{0}C
$\Delta\theta$ = Change of Heat into saline water = θ_2-θ_1= (69-28)^{0}C = 41^{0}C
m_d = Mass of distill water (litre) = 540ml = 0.540litre (≈0.540kg)
l_v = Latent heat for vaporization = 2.26 X 10^3J/kg
I_r = Solar radiation = 373.51 W/m^2
P = Power from the panel for heaters = (I_rX 600)/1000 = (373.51 X 600)/1000 = 224.106 W (since, the panel gives 600Watt peak power)
t = Operating Time = 7 hours = (7 X 3600) = 25200 Sec

►Total Heat Input, H = Heat produced by heaters =**Pt**

►Heat absorption by water to evaporate, $\mathbf{Q = m_sS\Delta\theta + m_dl_v}$

∴Efficiency, η= **(Q/H) X 100 %**

$$= \left[\frac{m_sS\Delta\theta + m_dl_v}{Pt}\right] X\ 100\ \%$$

$$= \left[\frac{\{2.5 X (3.93X10^3) X 41\} + \{0.540 X (2260X10^3)\}}{(224.106 X 25200)}\right] X\ 100\ \%$$

=28.74 %
≈ 29 %

5.3 Parameters that affecting the solar still performance

The performance of solar still is governed by many parameters such as climatic condition, design parameters and operating parameters. The climatic parameters consist of the amount solar insulation, ambient air temperature, wind speed, sky condition etc. The design parameters consist of orientation of the still, thermo-physical properties of materials used in the still, tilt angle of glass cover, insulation at the base, etc. And, the operating parameters consist of water depth in the basin, water salinity, initial water temperature, etc.

Effects of some major parameters are discussed here:

Solar insolation available: The solar still output is a strong function of the amount of solar radiation falling on a given location. For a given temperature, higher solar radiation results in higher amount of distill water. Thus more the solar insolation, more is the output of solar still.

Wind Velocity: Higher wind speed would cause higher heat losses from the still, which will result in lower efficiency, meaning less distilled water. Thus lesser the wind speed, more is the output of the solar still.

Ambient air temperature: Increase in ambient temperature will increase the output of solar still because heat losses will decrease. Thus more the ambient air temperature, more is the output of solar still.

Brine depth: As brine depth increases, the solar still productivity decreases. Thus lesser the brine depth, more is the output of solar still.

Slope of the glass cover: Lower glass cover increases the output but for practical reason it should be more than 10^0 because for much smaller angle the water droplets will fall in the basin. Thus, slope of solar still must be $20\text{-}30^0$ with horizontal

Glass material and angle: The slope of the cover must be sufficient to ensure that the condensed water runs smoothly through the condensate channel without reflecting too much solar energy and without forming large droplets. The glass should be low absorption glazing type.

To sum up,
For greater performance of solar still I need:

- More solar Radiation
- Lesser wind speed
- Higher ambient temperature
- Lesser brine depth
- Smaller tilt angle of slope
- Low absorbing glazing type glass

Chapter 6

Result, Discussion and Conclusion

6.1 Result

In the experimental setup, we found about 23% energy from sunrays and about 77% energy from heaters. From the observations, we got the following results:

Obs. No	Date	Mode of Operation	Operating Time	Daily Average Solar Radiation (W/m^2)	Input Saline Water (Litre)	Distill Water Produced (mL)	Distill Water From per litre Saline Water (mL)	Efficiency η
1	20-06-16	**Dual Mode** (Using Heaters and Sunshine)	7 hours	**541.17**	**5**	**1300**	**260**	**40%**
2	26-06-16	**Single Mode** (Using only sunshine)	7 hours	**519.92**	**1**	**35**	**35**	**20%**
3	29-06-16	**Single Mode** (Using Only Heaters Without sunshine)	7 hours	**373.51**	**2.5**	**540**	**216**	**29%**

Table-11: Result table

Heat could be lost due to conduction, convection and radiation. Other possible heat loss paths in solar still are vapor leakage, heat loss at the bottom and sidewalls, heat loss from the glass cover, heat absorbed by the cover etc. The overall heat loss could be 50-70%.Based on this information, the efficiency of solar distill could vary in the range 20-25%.

Generally, in a simple single basin solar still efficiency is about 20-30%.In that dual thermal solar energy model, the efficiency increases up to 40%.So, the best performance is achieved when we used dual mode (using solar powered heaters and sunshine).

The efficiency comparison for three different modes can be shown in figure below-

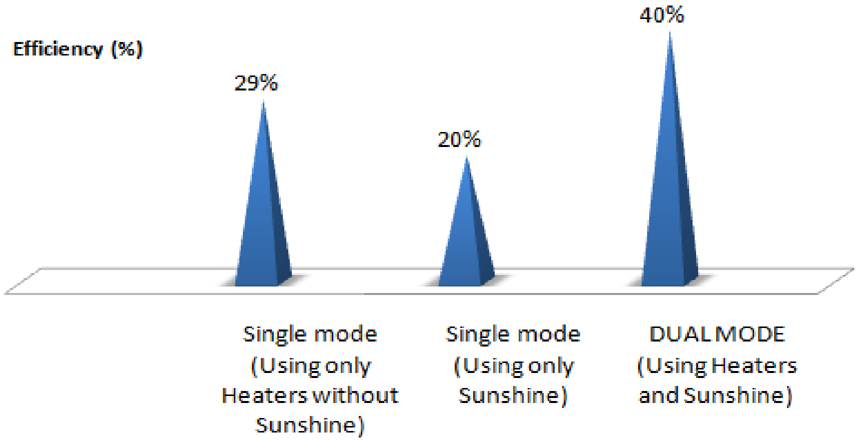


Fig-52: Efficiency comparison between Modes of operation.

6.2 Maintenance and Troubleshooting

Some precautions must be taken for the good performance of the still. They are as follows:

1. **Cleaning the basin and flushing:** As water evaporates from the still basin, salts and other contaminations are left behind. Overtime, these salts can build to the point of saturation if the still is not properly maintained and flushed on a regular basis.
2. **Cleaning the glass:** The glass cover must be cleaned periodically to remove dust from cover, which otherwise absorbs some part of the solar radiation reducing the efficiency of the solar still. Glass can be cleaned with distillate itself or any other available cleanable solution.
3. **Cleaning the condensate channel:** Condensate channel also must be cleaned periodically while draining out the basin water.
4. **Care about Breakage of Glass:** Care must be taken to avoid the breakage of glass which may lead vapor leak.

6.3 Advantages

- Our Device can be used for the purpose of Cooking, Water heating, Water disinfection, Water detoxification, Salt separation and Fresh water for human consumption.
- This system is run by renewable energy resource and we are able to use solar module for passive heating.
- The device is a portable system that can be used in remote locations and the system is durable enough for outdoor condition.
- The device needs less time than single basin still.
- No skilled manpower is required to operate.
- Maintenance cost is less.

6.4 Drawbacks

1. Due to the unavailability of sea water, we used saline water. It was a mixture of salt and fresh water. It may not properly contain all elements as we find in sea water. It also changes the specific gravity of saline water.

2. A controlling device and temperature sensor might make the device more efficient and automated. For simplicity we haven't used these devices.

3. Since the main source of heat was solar PV powered heater, We put less concentration on direct absorption of heat from sun.

4. The top cover of tempered glass should be tilted according to sun tracking path. Only 15-30^0tilting will be enough for satisfactory performance.

6.5 Discussion and Conclusion

Availability of solar radiation is very good in Bangladesh. The use of solar powered desalination is already in practice in the many countries of the world. In Bangladesh the use of solar desalination is still remain unexplored. In this work, we have attempted to find the usability of solar powered desalination for Bangladesh environment.

To attain workable solar desalination, temperature rising is very important. In order to achieve it, heat is essential. Addition of solar powered heating system can act as complementary for the heat generation. In this experiment, we have included PV powered heater as well as direct solar radiation as a dual power source. The world is turning towards renewable energy. For a country like Bangladesh, dual mode solar water desalination process will be useful both in domestic and commercial sectors.

In this work, we also studied some desalination techniques. Among them, we fixed our target to develop the beneficial and cost-effective design of solar water desalination and which is easy to build. So, we planned to make a device on solar powered water desalination device by considering simple solar still. We learned the idea of its construction and tried our best to make the device as efficient as possible.

We have found some observations in the field performance of device. Although there were some difference between my assumption and field performance, the purpose of our work was fruitful due to good collection of distill water from our designed system. The overall efficiency is obtained 40% but there are scopes to improve it further.

The quantity of purified water could be increased if we used proper tank and devices up to the international level. In this design, we used a small tank .But if large tank is used then 5Litre-10Litre water can be produced. Cost of devices will also have some price benefit for larger system.

If we get financial assistance, then it would be more helpful for us to develop an improved device. Therefore, we may conclude that our research work is satisfactory.

Abbreviation

DC-Direct Current
DNA- Deoxyribo Nucleic Acid
ED- electrodialysis
e.m.f- Electro Motive Force
HDH-Humidification-dehumidification
MEB- Multiple effect boiling
MEH-multiple-effect humidification
MS-Mild steel
MSF- multi-stage flash
NGO-Non Governmental Organization
PET-Polyethylene Terephthalate
PFA-Perfluoroalkoxy
Ppm- parts per million
PV -photovoltaics
RO- reverse osmosis
SS-Stainless Steel
SMCEC-Solar Multistage Condensation Evaporation Cycle
TDS - Total dissolved solids
UGC-University Grants Commission
UNICEF -United Nations International Children's Emergency Fund
UV -Ultraviolet
VC - vapour compression
WV - World Vision

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