Water desalination technologies utilizing conventional and renewable energy sources

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Abstract

Water is one of the earth's most abundant resources, covering about three-quarters of the planet's surface. Yet, there is an acute shortage of potable water in many countries, especially in Africa and the Middle East region. The reason for this apparent contradiction is, of course, that ~97.5% of the earth's water is salt water in the oceans and only 2.5% is fresh water in ground water, lakes and rivers and this supplies most human and animal needs. Tackling the water scarcity problem must involve better and more economic ways of desalinating seawater. This article presents a comprehensive review of water desalination systems, whether operated by conventional energy or renewable energy, to convert saline water into fresh water. These systems comprise the thermal phase change and membrane processes, in addition to some alternative processes. Thermal processes include the multistage flash, multiple effects boiling and vapour compression, cogeneration and solar distillation, while the membrane processes include reverse osmosis, electrodialysis and membrane distillation. It also covers the integration into desalination systems of potential renewable energy resources, including solar energy, wind and geothermal energy. Such systems are increasingly attractive in the Middle East and Africa, areas suffering from shortages of fresh water but where solar energy is plentiful and where operational and maintenance costs are low. The advantages and disadvantages, including the economic and environmental aspects, of these desalination systems are presented.

Keywords: desalination; thermal process; membrane process; renewable energy

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1 INTRODUCTION

Water is essential for life. Many countries around the world, especially developing countries and countries in the Middle East region, suffer from a shortage of fresh water. The United Nations (UN) Environment Programme stated that one-third of the world's population lives in countries with insufficient freshwater to support the population [1]. Consequently, drinking water of acceptable quality has become a scarce commodity. The total global water reserves are ~1.4 billion km^3, of which around 97.5% is in the oceans and the remaining 2.5% is fresh water present in the atmosphere, ice mountains and ground water. Of the total, only ~0.014% is directly available for human beings and other organisms [2]. Thus, tremendous efforts are now required to make available new water resources in order to reduce the water deficit in countries which have shortages [3]. According to World Health Organization (WHO) guidelines, the permissible limit of salinity in drinking water is 500 ppm and for special cases up to 1000 ppm [4]. Most of the water available on the earth has a 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 [5]. Desalination is a process in which saline water is separated into two parts, one that has a low concentration of dissolved salts, which is called fresh water, and the other which has a much higher concentration of dissolved salts than the original feed water, which is usually referred to as brine concentrate [6]. The desalination of seawater has become one of the most important commercial processes to provide fresh water for many communities and industrial sectors which play a crucial role in socio-economic development in a number of developing countries, especially in Africa and some countries in the Middle East region, which suffer from a scarcity of fresh water. There is extensive R&D activity, especially in the field of renewable energy technologies, to find new and feasible methods to produce drinking water [7, 8]. Currently, there are more than 7500

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desalination plants in operation worldwide producing several billion gallons of water per day. Fifty-seven per cent are in the Middle East [9] where large-scale conventional heat and power plants are among the region's most important commercial processes, they play a crucial role in providing fresh water for many communal and industrial sectors, especially in areas with a high density of population. However, since they are operated with fossil fuel, they are becoming very expensive to run and the environmental pollution they produce is increasingly recognized as very harmful to the globe. Moreover, such plants are not economically viable in remote areas, even near a coast where seawater is abundant. Many such areas often also experience a shortage of fossil fuels and an inadequate electricity supply. The development of compact, small-scale systems for water desalination is imperative for the population in such areas [7, 8]. Thermal solar energy water desalination is known to be a viable method of producing fresh water from saline water [10] in remote locations; conventional basin solar stills with a relatively large footprint are an example of such simple technology. And using a clean natural energy resource in water desalination processes will significantly reduce the pollution that causes global warming. This article aims to present a review of the published literature on the various desalination technologies and their advantages and disadvantages in addition to their economics.

2 OVERVIEW OF DESALINATION PROCESSES

Various desalination processes have been developed, some of which are currently under research and development. The most widely applied and commercially proven technologies can be divided into two types: phase change thermal processes and membrane processes, and, as shown in Figure 1, both encompass a number of different processes. In addition, there are the alternative technologies of freezing and ion exchange which are not widely used. All are operated by either a conventional energy or renewable energy to produce fresh water.

2.1 Thermal desalination processes

Thermal desalination, often called distillation, is one of the most ancient ways of treating seawater and brackish water to convert them into potable water. It is based on the principles of boiling or evaporation and condensation. Water is heated until it reaches the evaporation state. The salt is left behind while the vapour is condensed to produce fresh water [11]. In modern times, the required thermal energy is produced in steam generators, waste heat boilers or by the extraction of back-pressure steam from turbines in power stations [12]. The most common thermal desalination processes are:

- multi-stage flash distillation (MSF),
- Multiple-effect distillation (MED),
- vapour-compression evaporation (VC),
- cogeneration,
- solar water desalination.

2.1.1 *Multi-stage flash distillation*

Water distillation in a vessel operating at a reduced pressure, and thus providing a lower boiling point for water, has been used for well over a century. In the 1950s, Weirs of Cathcart in

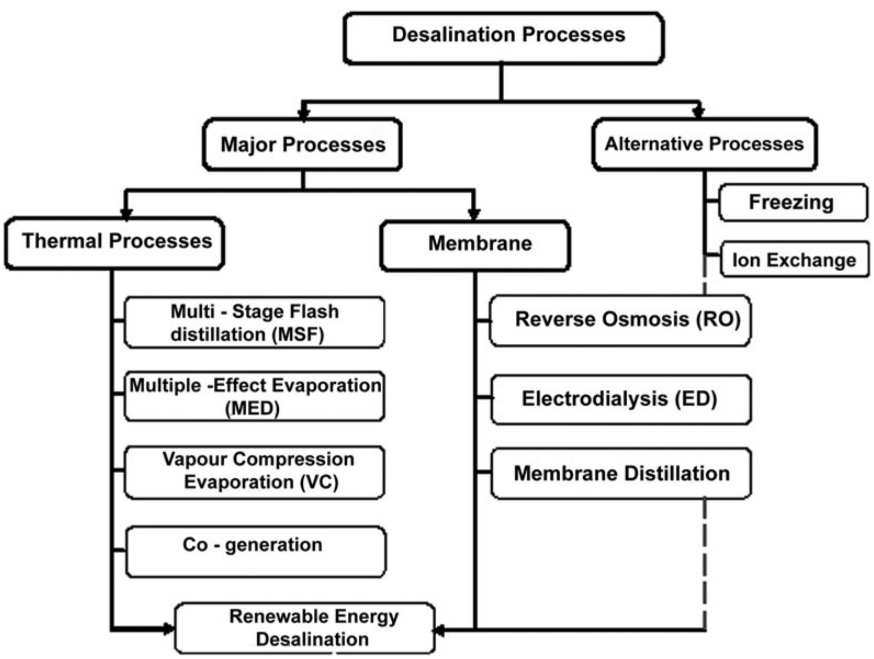

Figure 1. *Classification of water desalination technologies.*

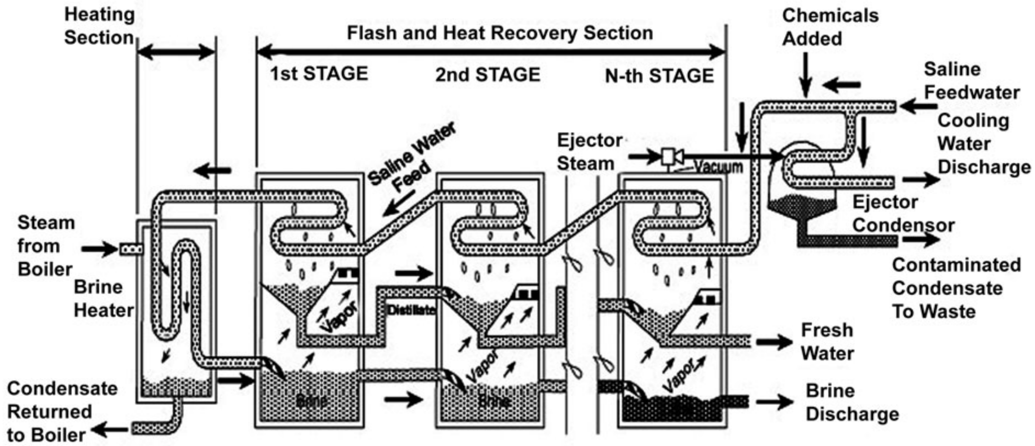

Figure 2. *Multi-stage flashing process—MSF [8].*

Scotland used this concept to invent the MSF process and it had significant development and wide application throughout the 1960s due to both to its economical scale and its ability to operate on low-grade steam [13]. MSF is currently producing around 64% of the total world production of desalinated water. Most of the MSF plants are located in the Arab region. Although the MSF process is the most reliable source for the production of fresh water from seawater, it is considered as an energy intensive process, which requires both thermal and mechanical energy [14].

In the MSF process, illustrated in Figure 2, feed water (saline water) is heated in a vessel called the brine heater until it reaches a temperature below the saturation boiling temperature. The heated seawater flows through a series of vessels, in sequence, where the lower ambient pressure causes the water to boil rapidly and vaporize. This sudden introduction of heated water into the reduced-pressure chamber is referred to as the ‘flashing effect’ [15] because the water almost flashes into steam.

A small percentage of this water is converted into water vapour; the percentage is mainly dependent on the pressure inside the stage, since boiling continues until the water cools and vaporization stops. The vapour steam generated by flashing is converted to fresh water by being condensed on the tubes of heat exchangers (condenser) that run through each stage. The incoming feed water going to the brine heater cools the tubes. This, in turn, heats up the feed water and increases the thermal efficiency by reducing the amount of thermal energy required in the brine heater to raise the temperature of the seawater.

An MSF unit that used a series of stages set at increasingly lower atmospheric pressures was developed so that the feed water which was passed from one stage to another was boiled repeatedly without adding more heat. Typically, an MSF plant contains between 15 and 25 stages [6]. Distillation processes produce ~50% of the worldwide desalination capacity, and 84% of this is produced by MSF technology. Most MSF plants have been built in the Middle East, where energy resources have been plentiful and inexpensive [16].

Advantages and disadvantages of MSF.

- MSF plants are relatively simple to construct and operate [15].
- They have no moving parts, other than conventional pumps, and incorporate only a small amount of connection tubing [15].
- The quality of water effluent contains 2–10 ppm dissolved solids, a high level of purification. Therefore, it is re-mineralized in the post-treatment process [17].
- The quality of the feed water is not as important as it is in the reverse osmosis (RO) system technology [6].
- Operating plants at higher temperatures (over 115°C) improves their efficiency but causes scaling problems where the salts such as calcium sulphate precipitate on the tubes surfaces and create thermal and mechanical problems like tube clogging [6].
- It is considered as an energy intensive process, which requires both thermal and mechanical energy, but it can be overcome by the cogeneration system [14].
- Adding more stages improves the efficiency and increases water production, but it increases the capital cost and operational complexity [6].

2.1.2 *Multi-effect distillation*

The MED process is the oldest large-scale distillation method used for seawater desalination. At present, ~3.5% of the world’s desalted water is produced by MED plants [18]. High distilled water quality, high unit capacity and high heat efficiency are its most obvious characteristics [18, 19]. In addition, MED has traditionally been used in the industrial distillation sector for the evaporation of juice from sugarcane in the production of sugar and in the production of salt using the evaporative process. The MED process, like MSF, takes place in a series of vessels or evaporators called effects, and it also uses the principle of evaporation and condensation by reducing the

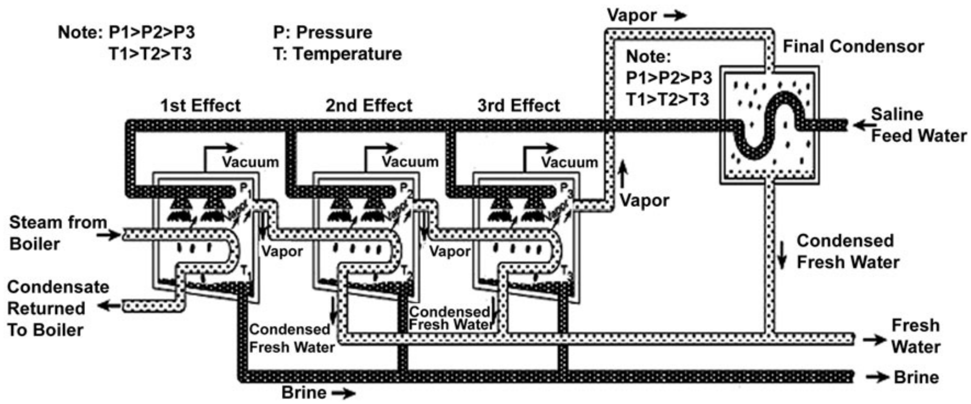

Figure 3. *Multi-effect distillation plant [30].*

ambient pressure in the various effects. This process permits the seawater feed to undergo multiple boiling without supplying additional heat after the first effect. The seawater enters the first effect and is raised to the boiling point after being preheated in tubes. The seawater is sprayed onto the surface of the evaporator tubes to promote rapid evaporation. The evaporator tubes are heated by externally supplied steam, normally from a dual-purpose power plant. The steam is condensed on the opposite side of the tubes, and the steam condensate is recycled to the power plant for its boiler feed water as shown in Figure 3.

The MED plant's steam economy is proportional to the number of effects. The total number of effects is limited by the total temperature range available and the minimum allowable temperature difference between one effect and the next effect. Only a portion of the seawater applied to the tubes in the first effect is evaporated. The remaining feed water is fed to the second effect, where it is again applied to a tube bundle. These tubes are in turn heated by the vapours created in the first effect. This vapour is condensed to form the fresh water product, while giving up heat to evaporate a portion of the remaining seawater feed in the next effect.

The process of evaporation and condensation is repeated from effect to effect, each at a successively lower pressure and temperature. This continues for, typically, 4–21 effects and a performance ratio between 10 and 18 is found in large plants [20].

Advantages and disadvantages of MED. The MED process is designed to operate at lower temperatures of ~70°C (158°F). This minimizes tube corrosion and the potential of scale formation around the tube surfaces [6].

- The quality of the feed water is not as important as in the RO system technology. Hence, the pre-treatment and operational costs of MED are low.
- The power consumption of MED is lower than that of the MSF plant [15].
- The performance efficiency in MED plants is higher than that in MSF plants; therefore, the MED process is more efficient than the MSF process in terms of heat transfer and fresh water production cost [21].

2.1.3 *Vapour-compression evaporation*

The vapour compression distillation process is used in combination with other process like MED and single-effect vapour compression. In this process, the heat for evaporating the seawater comes from the compression of vapour. VC plants take advantage of the principle of reducing the boiling point temperature by reducing the pressure. Two devices, a mechanical compressor (mechanical vapour compression) and a steam jet (thermal vapour compression), are used to condense the water vapour to produce sufficient heat to evaporate incoming seawater, as illustrated in Figure 4.

The mechanical compressor is usually electrically or diesel-driven. VC units have been built in a variety of configurations to promote the exchange of heat to evaporate the seawater. The compressor creates a vacuum in the evaporator and then compresses the vapour taken from the evaporator and condenses it inside a tube bundle. Seawater is sprayed on the outside of the heated tube bundle where it boils and partially evaporates, producing more vapour. With the steam-jet type of VC distillation unit, called a thermo compressor, a venturi orifice at the steam jet creates and extracts water vapour from the evaporator, creating a lower ambient pressure. The extracted water vapour is compressed by the steam jet. This mixture is condensed on the tube walls to provide the thermal energy (heat of condensation) to evaporate the seawater being applied on the other side of the tube walls in the evaporator.

Advantages and disadvantages of VC.

- The simplicity and reliability of plant operation make it attractive unit for small-scale desalination units. They are usually built up to a capacity of 3000 m^3/day and are often

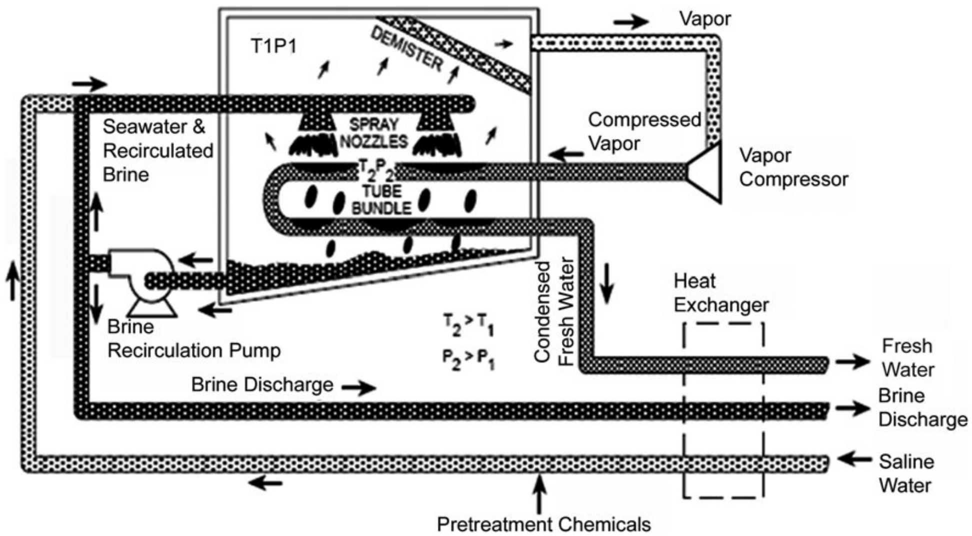

Figure 4. *Vapour-compression evaporation [6].*

used for resorts, industries and drilling sites where fresh water is not readily available [6].

- The low operating temperature of VC distillation makes it a simple and efficient process in terms of power requirement.
- The low operating temperatures (below 70°C) reduces the potential for scale formation and tube corrosion.

2.1.4 *Cogeneration system for power and water desalination*

It is possible to use energy in a dual use or cogeneration systems in which the energy sources can perform several different functions such as electric power generation and water desalination. Most of the desalinated potable water and electricity in the Arabian Gulf countries, and North Africa are produced by cogeneration plants associated with multi-stage flash desalination units operating on seawater [6]. Although other distillation processes such as thermal vapour compression and MED are starting to find their way into the market, the MSF process is still considered as the workhorse of the desalination industry. This process has proven its reliability and flexibility over almost 50 years of plant design and operation. For large desalination capacity, the MSF process can be considered as the only candidate commercially. However, on the cogeneration plant side, the situation is different in that several alternatives are commercially available to provide the required electrical power and steam for desalination [22]. In cogeneration plants, the electricity is produced with high-pressure steam to operate the turbines; the steam produced by boilers at temperatures up to 540°C. As this steam expands in turbines, its temperature and energy level are reduced. As previously stated, distillation plants need steam with temperatures lower than 120°C and this can be obtained easily at the end of the turbine after much of its energy has been utilized in electric power generation. This steam is used in the desalination process and the condensate from the steam is then returned to the boiler to be reheated again for use in the turbine. The main advantage of this system is that it uses much less fuel than each plant operating separately and energy costs are a crucial factor in any desalination process. In contrast, one of the disadvantages is the permanent coupling between the desalination plant and the power plant which can create a problem in water production when the demand for electricity is reduced or when the turbine or generator is down for repair. The size of the desalination plant can be efficiently integrated with a power cogeneration plant, so that the ratio of desalted water to power production is consistent with water and power requirements of the community it serves. Cogeneration plants have also reduced power costs. Meanwhile, other types of cogeneration plants have achieved lower costs by benefiting from heat recovery systems on gas turbines, heat pumps and other industrial processes such as burning solid wastes in an incinerator [7].

2.2 Membrane processes

Synthetic membranes were first introduced in separation processes in the 1960s, but they began to play an increasingly crucial role in water desalination in the 1980s. Originally, membrane applications were limited to municipal water treatment such as microfiltration and desalination but, with the development of new membrane types, uses have expanded to cover not only the water industry but also high return processes such as chemical separations, enzyme concentration and beverage purification. This technology uses a relatively permeable membrane to move either water or salt to induce two zones of differing concentrations to produce fresh water. These processes are also useful in municipal water treatment; RO and electrodialysis (ED) are replacing phase change desalting technologies for supplying water to coastal and island communities all over the world. RO, in particular, is becoming an

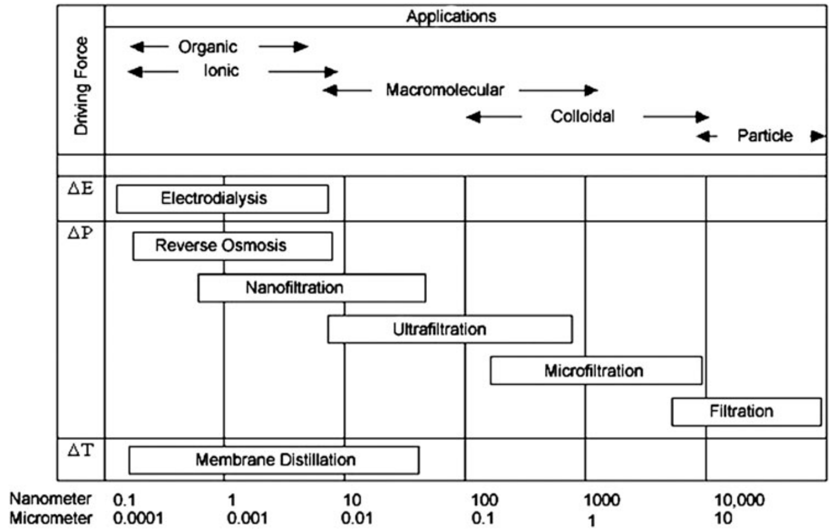

Figure 5. *Effective range of membrane processes and applications [23].*

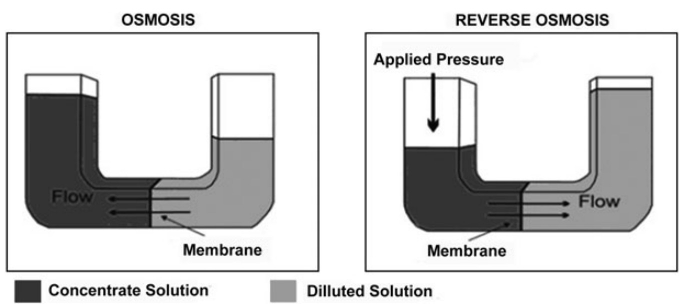

Figure 6. *Osmosis and RO processes [66].*

economical alternative to the traditional water softening processes [23]. Membrane technology includes several processes, but the principal difference between them lies in the size of the entities, ions, molecules and suspended particles that are retained or allowed to pass through the membranes. Typical separation processes are nano-filtration, ultra-filtration, micro-filtration and filtration used in the pre-treatment stages of desalination to remove large particles, bacteria, ions and for water softening [15]. Figure 5 shows the effective range of membrane processes and applications.

This section looks at the following process

- reverse osmosis,
- electrodialysis,
- membrane distillation (MD).

2.2.1 *Reverse osmosis*

The RO process is relatively new in comparison to other technologies and was introduced as a successful commercialized technology in water desalination in the early 1970s. RO is a membrane separation process in which the water from a pressurized saline solution is separated from the solutes (the dissolved material) by flowing through a membrane without the need for heating or phase change. The major energy required is for pressurizing the feed water [6]. It can also be described as a process of forcing a solvent from a region of high solute concentration through a membrane to a region of low solute concentration by applying a pressure in excess of the osmotic pressure, as shown in Figure 6. Thus, water flows in the reverse direction to the natural flow across the membrane, leaving the dissolved salts behind with an increase in salt concentration [24].

A typical large saline water RO plant consists of five major components, a saline water supply system, a feed water pre-treatment system, high-pressure pumping, RO modules (membrane separation) and post-treatment system [25]. In the recent years, the largest RO desalination plants have been built in the Middle East and particularly in Saudi Arabia. A plant in Jeddah produces 15 million gallon per day (MGD), while the Al Jubail and Yanbu RO plants have capacities of 24 and 33.8 MGD, respectively [25, 26].

Seawater supply system. An open intake channel supplies the plant with raw seawater which is pumped through trash racks and travelling screens to remove debris [27].

Pre-treatment. Pre-treatment is very important in the RO process because it protects membrane surfaces from fouling and also provides protection to the high-pressure pumps and the RO section of the plant. The nature of the pre-treatment depends largely on the feed water characteristics, the membrane type and configuration, the recovery ratio and the required product water quality. In this stage, the seawater is treated against debris, particles and suspended solids by a multimedia gravity filter that removes particles larger than 10 μm. The water is biologically disinfected by injecting

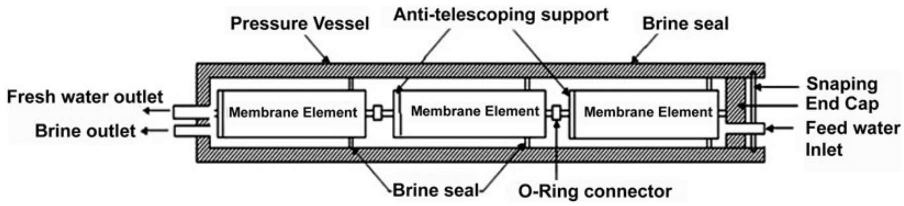

Figure 7. *Cross-section of a pressure vessel with three membrane elements [6].*

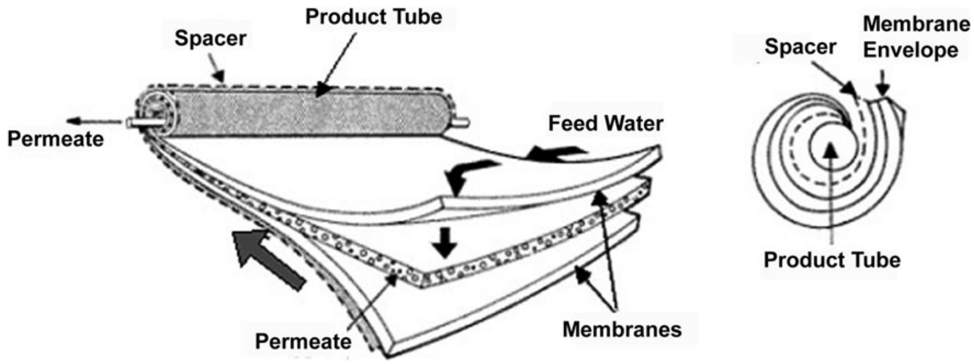

Figure 8. *Cutaway view of a spiral wound membrane element [30].*

chemicals like sodium hypochlorite to remove algae and bacteria and to prevent microorganism growth. Also added are ferric chloride as a flocculant and sulphuric acid to adjust pH and control scale formation [25].

High-pressure pumping. The high-pressure pump supplies the appropriate pressure needed to enable the water to pass through the membrane where the semi-permeable membrane restricts the passage of dissolved salts while permitting water to pass through. Then, the concentrated brine water is discharged into the sea. This pressure ranges from 15 to 25 bar for brackish water and from 54 to 80 bar for sea water [6, 20].

RO modules (membrane separation). The membrane must be strong enough to withstand the drop of the entire pressure across it. A relatively small amount of salts passes through the membrane and appears in the permeate [6]. In principle, RO membranes should be semi-permeable, possessing a high degree of water permeability but presenting an impenetrable barrier to salts. A membrane should have a large surface area to allow maximum flow. There are membranes available which are suitable for pump operation up to 84 kg/cm^2 discharge pressure. This pressure ranges from 54 to 80 bars for seawater, depending on its salt content. Most RO applications require two or more modules arranged to operate in series [28] as shown in Figure 7.

RO membranes are made in a variety of configurations. Two of the most commercially successful membranes are spiral wound and hollow fine fibre (HFF) and both of these are used to desalt brackish water and seawater [29].

Spiral wound membrane: This type of membrane element is most commonly manufactured as a flat sheet of either a cellulose diacetate and triacetate blend or a thin film composite usually made from polyamide, polysulphone or polyurea polymers. The configuration is illustrated in Figure 8 [30].

HFF membrane: HFF is a U-shaped fibre bundle housed in a pressure vessel. The membrane materials are based on cellulose triacetate and polyamide and its arrangement allows the highest specific surface area of all the module configurations, resulting in compact plants. Figure 9 illustrates the HFF formation [30].

Post-treatment. The post-treatment generally stabilizes the water and might include pH adjustment by adding lime to meet the potable water specifications, and the removal of dissolved gases such as hydrogen sulphide and carbon dioxide [20].

Advantages and disadvantages of RO process.

- Material corrosion problems are significantly less compared with MSF and MED processes due to the ambient temperature conditions.
- Polymeric materials are utilized as much as possible rather than the use of metal alloys [20].
- Two developments have also helped to reduce the operating cost of RO plants during the past decade.
  - The development of operational membranes with high durability and lower prices.
  - The use of energy recovery devices that are connected to the concentrated stream as it leaves the pressure vessel.

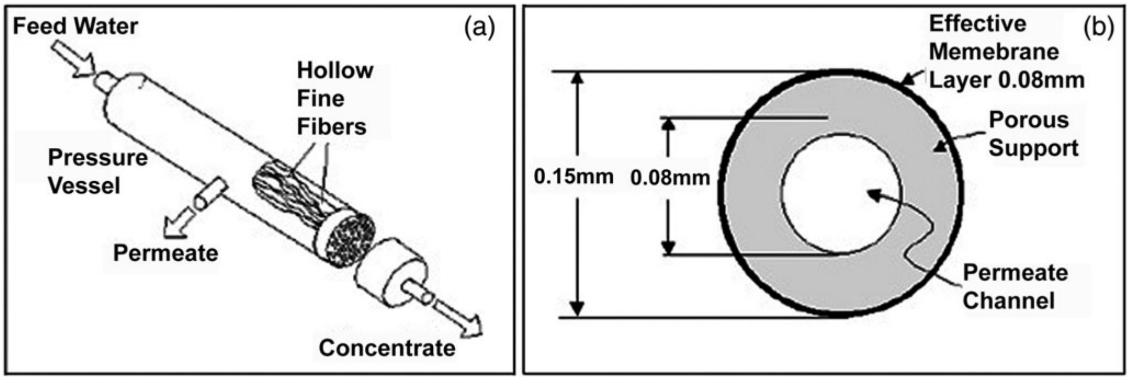

Figure 9. *Hollow fine fiber membrane module [30].*

The concentrated brine loses only ~1–4 bar relative to the applied pressure from the high-pressure pump. The devices are mechanical and generally consist of turbines or pumps that can convert a pressure difference into rotating energy that can be used to reduce energy costs.

- RO units sold for residential water filtration require very large quantities of water since they recover only 5–15% of the feed water that enters the filter. In seawater systems, for every 5 gallons of usable water, 40–90 gallons of water are sent to the wastewater system [6].
- Membrane scaling caused by the precipitation of salts is a common problem in the RO process, but it is less than in MSF.
- Membranes are liable to be fouled (plugged) by large particles, but this can be avoided by pre-filtering the feed water through a 5–10 μm cartage micro-filter. Biological fouling can be caused by the formation of micro-organism colonies and by entrapping dead and live organisms. Colloidal fouling is caused by the settlement on membrane surfaces of colloids from an accumulation of aluminium silicate and clays and from soap detergents and organic materials [15].

2.2.2 *Electrodialysis*

ED was commercially introduced in the early 1960s, about 10 years before RO. It provided a cost-effective way to desalt brackish water and spurred considerable interest in the whole field of using desalting technologies to produce potable water for municipal use [6]. It also has many other applications in the environmental and biochemical industries as well as in the production of table salt [15, 31].

ED is an electrochemical separation process that employs electrically charged ion exchange membranes with an electrical potential difference as a driving force. It depends on the fact that most salts dissolved in water are ionic, being either positively (cationic) or negatively (anionic) charged and they migrate towards electrodes with an opposite electric charge. Membranes can be constructed to permit the selective passage of either cations or anions. A schematic diagram of the process is illustrated in Figure 10.

Advantages and disadvantages of ED.

- It has the capability of high recovery in terms of more fresh water product and less brine [6].
- ED is feasible for brackish water with a salinity of <6 g/l of dissolved solids, but not suitable for water with dissolved solids of <0.4 g/l.
- The desalination of water with concentrations of dissolved solids higher than 30 g/l, like seawater, is possible, but it is not economically viable [32].
- The major energy requirement is the direct current to separate the ionic substances in the membrane.
- Energy usage is proportional to the salts removed.
- It can treat feed water with a higher level of suspended solids than RO.
- Chemical usage for pre-treatment is low [6].

2.2.3 *Membrane distillation*

MD was first studied at the end of 1960s [33], but developed commercially on a small scale in the 1980s [15]. This technology is a thermally driven, membrane-based process combines the use of distillation and membranes and is, essentially, an evaporation process. It takes advantage of the temperature difference between a supply solution, coming in contact with the surface, on one side, of the readily selected micro-porous membrane, and the space, on the other side of the membrane as shown in Figure 11. This temperature difference results in a vapour pressure difference, leading to the transfer of the produced vapour, through the membrane, to the condensation surface. The overall process is based on the use of hydrophobic membranes, permeable by vapour only, thus excluding transition of liquid phase and potential dissolved particles [34]. After the vapour passes through the membrane, it is condensed on a cooler surface to produce fresh water. In the liquid form, the fresh water cannot pass back through the membrane, so it is collected as the fresh water product [6]. Although MD has not achieved great commercial success at the beginning, while the most recent research and development proved a promising

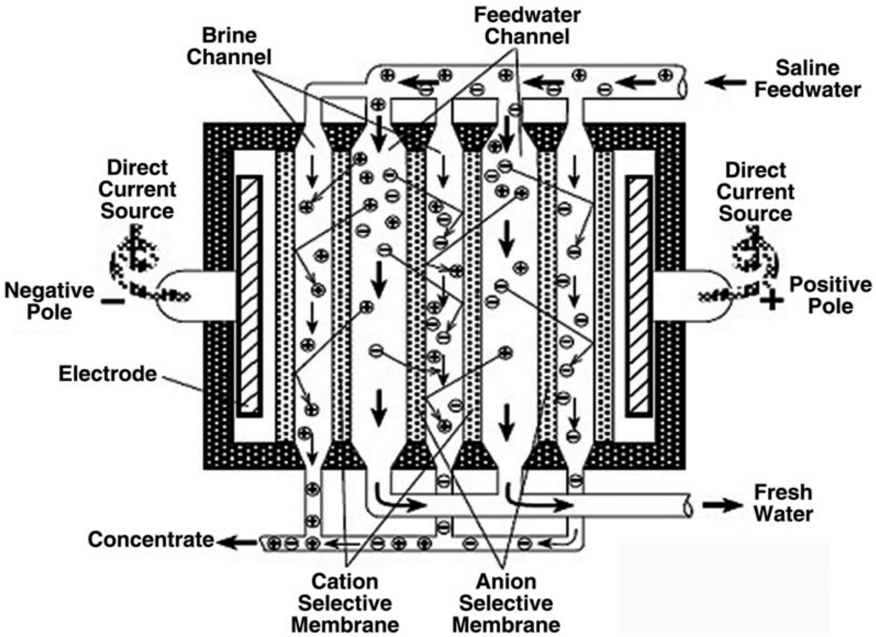

Figure 10. *Movement of ions in the ED process—adapted from [6].*

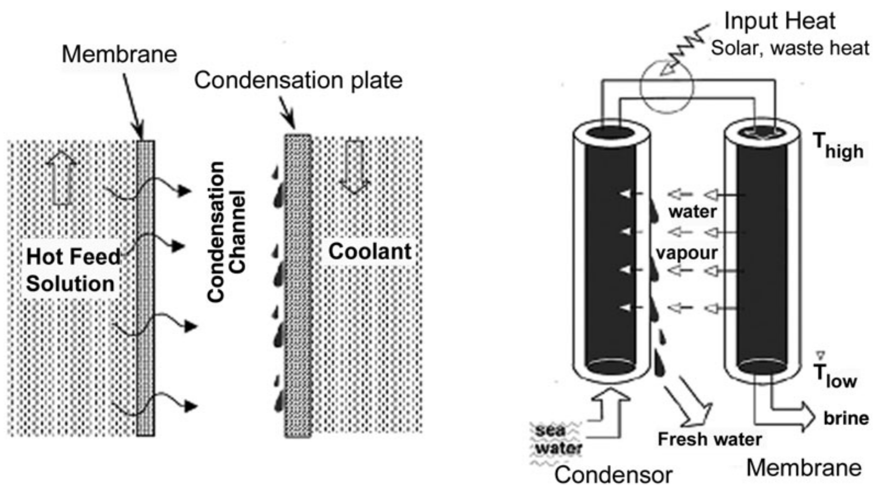

Figure 11. *Schematic diagram of the MD system [34].*

success for small-scale MD desalination systems combined with solar energy.

Advantages and disadvantages of MD.

- The main advantages are its simplicity and the low operating temperature rise it requires to operate. These facilitate and make utilizing the waste heat as a preferable energy source possible, such as by coupling the MD units with solar energy sources, which is attractive [6, 15].
- It requires a lower operating pressure than pressure-driven membrane processes, and reduced vapour space compared with conventional distillation [35].
- MD requires more space than other membrane processes; however, the recent R&D will reduce the size [6].
- Energy consumption is approximately the same as that of MSF and MED plants [6, 15].
- The MD process requires that the feed water should be free of organic pollutants; this explains the limited use of this method [15].

2.3 Alternative processes

A number of other processes have been used in water desalination, but none has achieved as high a productive performance or reached the same level of commercial success as the MSF, ED and RO processes. They may prove valuable under special circumstances or after further research and development.

2.3.1 *Freezing*

Extensive commercial research was done during the 1950s and 1960s to improve the performance of the freezing process. The basic principles of freezing desalination are simple. During the process of freezing, dissolved salts are excluded during the formation of ice crystals. Seawater can be desalinated by cooling the water to form crystals under controlled conditions. Before the entire mass of water has been frozen, the mixture is usually washed and rinsed to remove the salts in the remaining water or adhering to the ice crystals. The ice is then melted to produce fresh water [6]. The main heat transfer processes, that is freezing and melting, are regenerative, resulting in very high-energy efficiency [36]. A small number of plants have been built over the past 40 years, but the process has not been a commercial success in the production of fresh water for municipal purposes. The most recent significant example of desalting by freezing was an experimental solar-powered unit constructed in Saudi Arabia in the late 1980s, but that plant has been disassembled. At present, freezing technology probably has better applications in the treatment of industrial wastes than in the production of municipal drinking water [6, 20].

Advantages and disadvantages.

- The advantages include a lower theoretical energy requirement, minimal potential for corrosion and little scaling or salt precipitation.
- It can produce very pure potable water, and it has special advantages to produce water for irrigation [36].
- The disadvantage is that it involves handling ice and water mixtures that are mechanically complicated to move and process [6].

2.3.2 *Ion exchange: solvent process*

In the last 50 years, ion exchange membranes have been moved from a laboratory tool to industrial products with a significant technical and commercial impact. Today, ion exchange membranes are receiving considerable attention and are successfully applied in the desalination of sea and brackish water and in treating industrial effluents. They are efficient tools for the concentration or separation of food and pharmaceutical products containing ionic species as well as in the manufacture of basic chemical products [37]. Ion exchangers are organic or inorganic solids that are capable of exchanging one type of cation (or anion) immobilized in the solid for another type of cation (or anion) in solution. For example, Na^+ ions in solution can be replaced with H^+ by a cation exchanger and Cl^- can subsequently be replaced with OH^- by an anion exchanger resulting in the complete 'demineralization' of a NaCl solution. The process can be reversed by regenerating the cation exchanger with an acid, and the anion exchanger with a base. In practice, ion exchange is a useful process for completely demineralizing water in applications where high purity is required, as in high-pressure boilers. Unfortunately, it is not suited to treat and desalinate brackish or sea water, simply because its costs are prohibitive [38, 39].

3 RENEWABLE ENERGY WATER DESALINATION

The potential use of renewable energy as a clean friendly source of energy to operate small-scale desalination units in remote communities has received increasing attention in recent years [40]. The coupling of renewable energy sources and desalination such as solar, wind and geothermal energy with desalination systems holds great promise for tackling water shortage and is a potential for viable solution of climate change and water scarcity [41].

An effective integration of these technologies will allow countries to address water shortage problems with a domestic energy source that does not produce air pollution or contribute to the global problem of climate change due to lower conventional energy consumption and lower gas emissions. Meanwhile, the cost of desalination and renewable energy systems are steadily decreasing, while fossil fuel prices are rising and its supplies are depleting. The desalination units powered by renewable energy systems are uniquely suited to provide water and electricity in remote areas where water and electricity infrastructures are currently lacking [42]. The rapid increase in demand for energy is making the world focus on alternative sustainable sources. In 2008, 10% of the generated electricity worldwide was produced by renewable energy sources (hydropower, biomass, biofuels, wind, geothermal and solar). A recent assessment conducted by the US Energy information administration forecasts that by 2035, consumption of renewable energy will be ∼14% of total world energy consumption, which shows strongest growth in global electric generating capacity as illustrated in Figure 12 [43].

The majority of desalination systems that use a renewable energy source can be divided into three categories: wind, solar [photovoltaics (PVs) or solar collectors] and those that use geothermal energy. These renewable energy sources can be coupled with thermal distillation or membrane desalination systems as shown in Figure 13 to produce water. In some cases [34, 44], these systems are connected with a conventional source of energy (e.g. local electricity grid) in order to minimize the variations in the level of energy production and consequently water production [45]. When renewable energy sources are used to operate the RO plants, the cost was found to dramatically increase (10.32 $/m^3) due to high cost of desalination unit capital cost [46].

It has become obvious that the solar energy is the most widely used among other renewable energies as illustrated

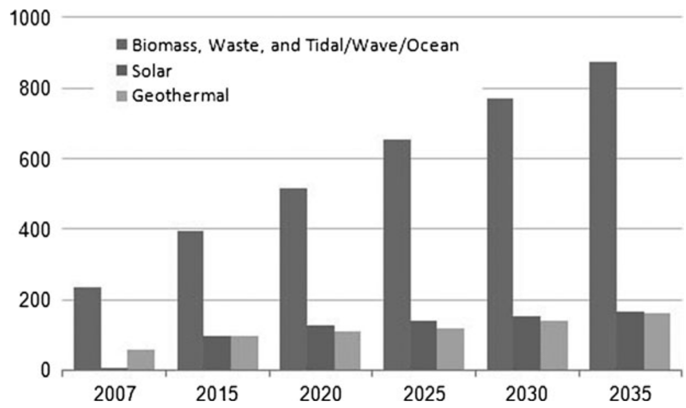

Figure 12. *World renewable electricity generation forecast [43].*

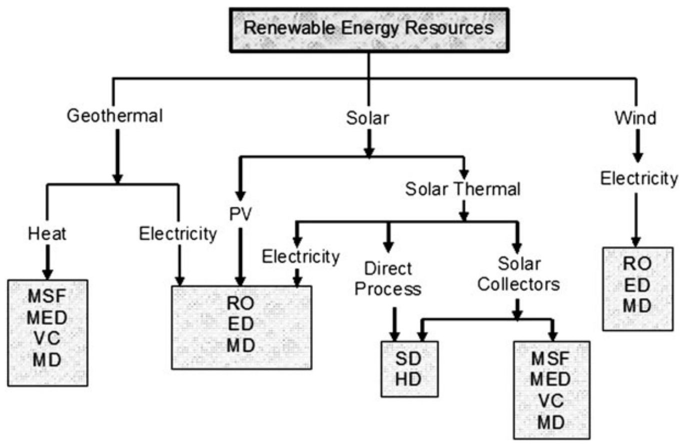

Figure 13. *Combinations of renewable energy resources with water desalination technologies.*

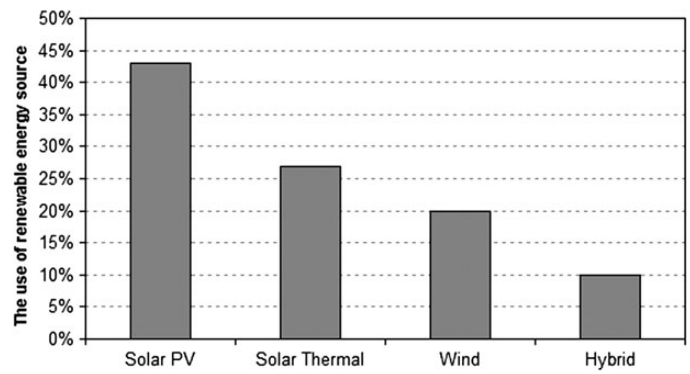

Figure 14. *Renewable energy sources for desalination.*

in Figure 14. For the relative distribution between desalination processes using renewable energy sources, see Quteishat *et al.* [47].

3.1 Solar-powered water desalination

3.1.1 *Introduction to solar energy*

The sun was adored by many ancient civilizations as a powerful God and solar energy is the oldest energy source used by human beings. The first known practical application was in drying for food preservation. Scientists have long looked at solar radiation as a source of energy, trying to convert it into a useful form for direct utilization. Archimedes, the Greek mathematician and philosopher (287–212 BC), used the sun's reflected heat to burn the Roman fleet in the Bay of Syracuse [32]. During the eighteenth century, the French naturalist Boufon experimented with various solar energy devices which he called 'hot mirrors burning at long distance' [48]. Most forms of energy are solar in origin. Oil, coal, natural gas and wood were originally produced by photosynthetic processes [49]. Even wind and tide energy have a solar origin, since they are caused by differences in temperature in various regions of the earth. The great advantages of solar energy, compared with other forms of energy, are that it is clean, sustainable and can be used without any environmental pollution. Solar energy is used to heat and cool buildings, to heat water for domestic and industrial uses, to heat swimming pools, to power refrigerators, to operate engines and pumps, to desalinate water for drinking purposes, to generate electricity, in chemistry applications and for many more functions. The decision about which source of energy to use should be made on the basis of economic, environmental and safety considerations. Because of its desirable environmental and safety advantages, it is widely believed that, where possible, solar energy should be utilized instead of energy derived from fossil fuels, even when the costs involved are slightly higher [50]. This section focuses on the desalination of saline water by using solar energy.

3.1.2 *Water desalination using solar power*

Solar water desalination has a long history. The first documented use of solar stills was in the sixteenth century and, in 1872, the Swedish engineer, Carlos Wilson, built a large-scale solar still to supply a mining community in Chile with drinking water [51]. Solar desalination using humidification and dehumidification is a promising technique for producing fresh water, especially in remote and sunny regions. It has the potential to make a significant contribution to providing humans with fresh water using a renewable, free and environmentally friendly energy source [52]. Solar energy can be used to convert saline water into fresh water with simple, low cost and economical technology and thus it is suitable for small communities, rural areas and areas where the income level is very low [53]. Recent developments have demonstrated that solar-powered desalination processes are better than the alternatives, including ED, RO and freezing, for fresh water provision in remote rural areas [54]. Solar-powered desalination processes are generally divided into two categories, direct and indirect systems.

Direct systems. The direct systems are those where the heat gaining and desalination processes take place naturally in the same device. The basin solar still represents its simplest application, the still working as a trap for solar radiation that passes through a transparent cover.

Solar still: Solar still distillation represents a natural hydrologic cycle on a small scale. The basic design of a solar still, which is similar to a greenhouse, is shown in Figure 15. Solar energy enters the device through a sloping transparent glass or plastic panel and heats a basin of salt water. The basin is generally black to absorb energy more efficiently. The heated water evaporates and then condenses on the cooler glass panels. The condensed droplets run down the panels and are collected for use as fresh water. Experience proves that $\sim$1 m^2 of ground will produce 3–4 l/day of freshwater. Because of this low production, it is important to minimize capital costs by using very inexpensive construction materials. Efforts have been made by various researchers to increase the efficiency of solar stills by changing the design, by using additional effects such as multi-stage evacuated stills and by adding wicking material, etc. and these modifications have increased production per unit area [6]. In the simple solar still shown in Figure 15, the latent heat

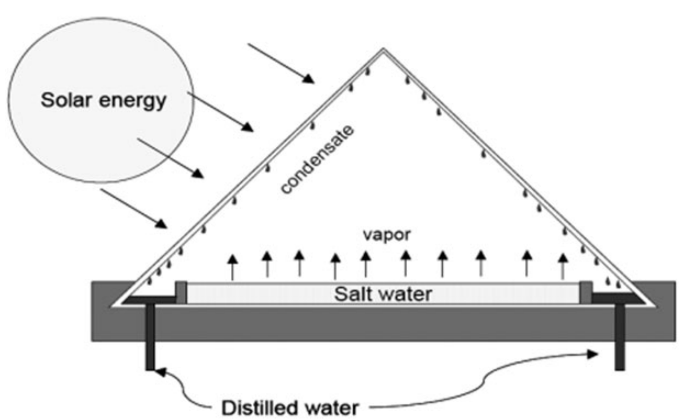

Figure 15. *Solar still unit [38].*

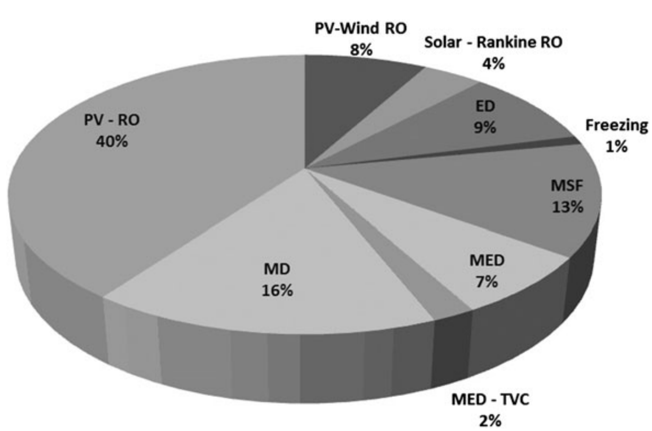

Figure 16. *Water desalination technologies coupled with solar power sources installed worldwide [44].*

of condensation is dissipated to the environment. However, the latent heat of condensation can be used to preheat the feed water, and this obviously leads to an improvement in the still efficiency.

Advantages and disadvantages of the solar still: Solar still technology requires a large area for solar collection so it is not viable for large-scale production, especially near a city where land is scarce and expensive. The comparative installation costs tend to be considerably higher than those for other systems. They are also vulnerable to damage by weather. Labour costs are likely to be high for routine maintenance to prevent scale formation and to repair vapour leaks and damage to the still's glass [6, 38]. However, they can be economically viable for small-scale production for households and small communities, especially where solar energy and low cost labour are abundant [6, 53].

Indirect systems. In these systems, the plant is separated into two subsystems, a solar collector and a desalination unit. The solar collector can be a flat plate, evacuated tube or solar concentrator and it can be coupled with any of the distillation unit types described previously which use the evaporation and condensation principle, such as MSF, VOC, MED and MD for possible combinations of thermal desalination with solar energy. Systems that use PV devices tend to generate electricity to operate RO and ED desalination processes [38]. Figure 16 shows the worldwide use of the various desalination technologies using solar power sources [55].

Factors for the selection of solar collectors: There are many factors that influence the selection of solar collectors for desalination processes. The flat plate and evacuated tube solar collectors are appropriate for low-temperature processes which use heat to evaporate the saline water, often utilizing low-pressure conditions created with vacuum pumps. Evacuated tube collectors ensure some energy even on cloudy days, and their efficiency at high-operating temperatures or low insolation is significantly better than that of flat-plate collectors. Cylindrical tracking collectors can be more efficient than evacuated tube collectors, but they have almost no output on cloudy days and collect only a small fraction of the diffuse radiation. Parabolic concentrating collectors require very accurate two-axis tracking mechanisms, but they can produce temperatures of more than 120°C, which is higher than the temperature needed for solar desalination [56]. The selection of the most appropriate solar desalination technology is affected by many factors, including plant size, feed water salinity, remoteness, availability of grid electricity, technical infrastructure and the type of solar technology available.

There are several possible combinations of desalination and solar energy technologies that could have more promising water production in terms of economic and technological feasibility than others. Some combinations are better suited for large-size plants, whereas some others are better suited for small-scale applications. Prior to any process selection, the water resources should be investigated. Brackish water is the most economical as its salinity is normally much lower (<10 000 ppm), and the energy requirement would be lower as explained earlier in the literature.

Solar still coupled with solar collectors: In order to increase still productivity, many researchers have experimented with coupling a single still or multi-effect stills with solar collectors, as shown in Figures 17 and 18, respectively. Coupling more than one solar still with such solar collector panels produces an increase in efficiency through utilizing the latent heat of condensation in each effect to deliver heat to the next stage.

Solar humidification and dehumidification: Potable water may be obtained from saline water through a humidification–dehumidification cycle. In this process, saline water is evaporated by thermal energy and the subsequent condensation of the generated humid air, usually at atmospheric pressure, produces freshwater [57]. Air has the capability to hold large quantities of water vapour and its vapour carrying capability increases with temperature [58]. Many studies on desalination using humidification–dehumidification have been conducted with a variety of fabricated devices [59]. The principle of this desalination process is based on the evaporation of water and the condensation of steam from humid air. The humid air flows in a clockwise circuit driven by natural convection between the condenser and the evaporator, as shown in Figure 19. In this example, the evaporator and condenser are located in the same thermally insulated box. Seawater is heated in the evaporator and distributed slowly as it trickles downwards. The air moves in a countercurrent flow to the brine through the evaporator and becomes saturated with humidity. Partial evaporation cools the brine that is left in the evaporation unit and it now has a higher salt concentration, while the saturated air condenses on a flat-plate heat exchanger.

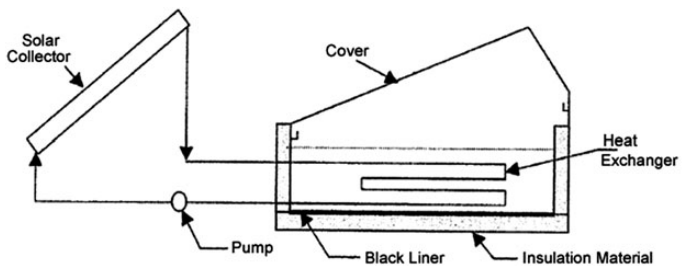

Figure 17. *Schematic diagram of a single solar still coupled with a solar collector [2].*

The distillate runs down the plates and trickles into a collecting basin. The heat of condensation is mainly transferred to the cold seawater flowing upwards inside the flat-plate heat exchanger. Thus, the temperature of the brine in the condenser rises from 40°C to ~75°C. In the next step, the brine is heated to the evaporator inlet temperature, which is between 80 and 90°C. The salt content of the brine as well as the condenser inlet temperature can be increased by a partial reflux from the evaporator outlet to the brine storage tank [60]. Then, distillate can be collected in a vessel and the brine goes also to saline water tank to recover a portion of the heat.

Water desalination powered by solar PV: Solar PV systems for generating electricity have become more popular due to the recent introduction by governments of Feed in Tariffs system, which enable their owners to sell some or all of the electricity they generate, thus reducing the payback period and increasing the attractiveness of this technology [61]. Solar PV systems directly convert sunlight into electricity by using solar cells made from silicon or other semiconductor materials. Usually, a number of solar cells are connected together to form a PV module, which supplies the power required by the needed

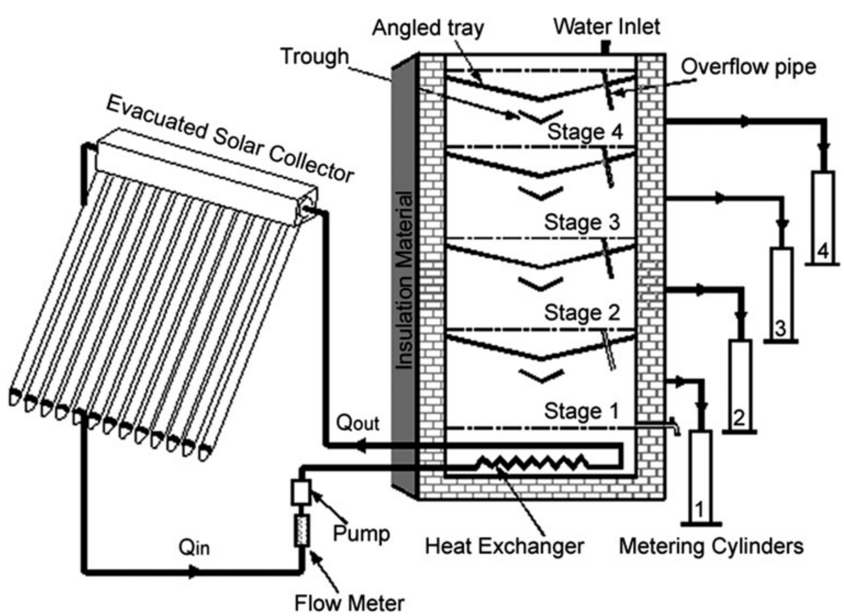

Figure 18. *Schematic diagram of multi-effect solar still coupled with a solar collector [80].*

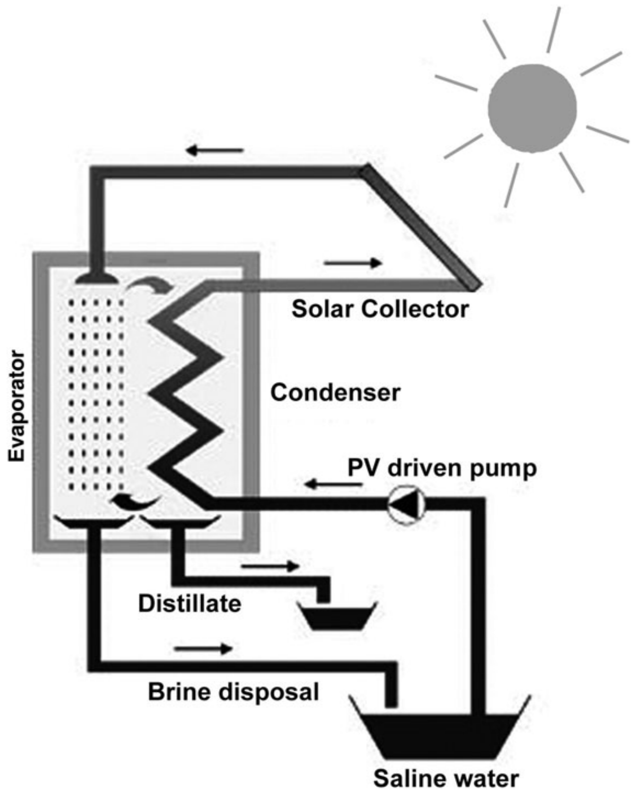

Figure 19. *Schematic diagram of the distillation system—adapted from [60].*

load. In addition to the PV module, power-adapting equipment (e.g. charge controller, inverters and energy storage equipment), such as batteries, might be required to supply energy to a desalination plant. Charge controllers are used for the protection of the battery from overcharging. Inverters are used to convert the direct current from the PV modules system to alternating current to the loads. The rapid development of PV technology and the dramatic recent decrease in the PV cell prices in the market have made several desalination technologies more affordable, especially for remote and poor areas in developing countries. Currently (November 2011), the lowest retail price for a multicrystalline silicon PV module is $1.31 (£0.85) per watt from a US retailer or $1.28 (£0.83) per watt from an Asian retailer. However, at this price, of the cost of the PV module represents only 40% of the total cost of a solar PV system. The total current cost, including the necessary power adapting equipment, is shown in Table 1 [62].

The PV generator can be connected either with RO or ED water desalination technology as described previously [63]. Figure 20 shows the assembly of an RO desalination plant coupled with a PV generator with multi-PV modules to produce electricity, a charge controller to protect the battery block from deep discharge and overcharge, a set of battery blocks to stabilize the energy input to the RO unit and to compensate for solar radiation variations and an RO unit to desalinate the water.

Table 1. *PV solar system elements and cost adapted from [62].*

S/N	Solar PV system elements	Prices in US$	Prices in GBP £
1	PV Module per Wp	1.28	0.83
2	Inverter per Wp	0.714	0.462
3	Battery per Wp	0.213	0.138
	Subtotal	2.207	1.43
4	Charge controller 10% of total system cost	0.22	0.143
	Total	2.427	1.573

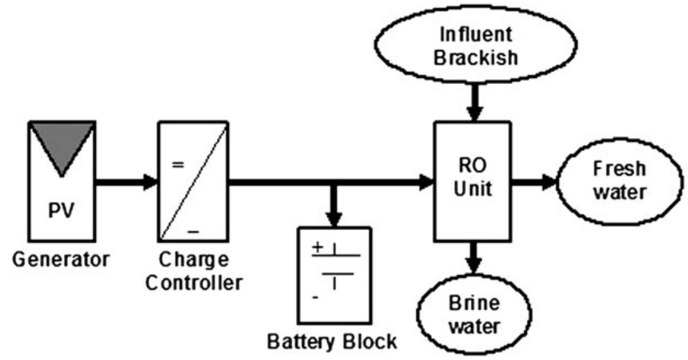

Figure 20. *Schematic diagram of RO desalination unit coupled with a PV generator.*

4 ECONOMICS AND PERFORMANCE OF DESALINATION PROCESSES

Phase change water desalination processes, which use conventional sources of fuel and energy and which usually have large production capacities, are more expensive than membrane plants because of the large quantities of fuel required to vaporize salt water. Membrane methods are also more economical for brackish water desalination [45]. A detailed cost comparison is illustrated in the next section.

4.1 Economics of thermal desalination processes

Thermal process desalination plants are mostly operated by fossil fuel, which jeopardizes a high cost of desalination per unit cost. In the case of multi-effect distillation (MED), the cost for large systems with a daily production from 91 000 to 320 000 m^3 ranges between 0.52 and 1.01 $/$m^3$. These costs refer to examples of plants built between 1999 and 2009 with the most recent having lower costs and the older installations being the most expensive [45]. For medium-sized systems, with a daily production from 12 000 to 55 000 m^3, the cost ranges between 0.95 and 1.5 $/$m^3$. For small systems with a daily capacity around 100 m^3, the cost varies between 2.50 and 10 $/$m^3$. For the MSF method, the cost can vary between 0.52 and 1.75 $/$m^3$ for systems with a daily production of 23 000 to 528 000 m^3. The cost is reduced when MSF is coupled with electric power generation in a cogeneration plant.

VC is used mainly for small systems with production of around 1000 m^3/day, and a cost that ranges between and 2.01 and 2.66 US$/m^3 [64, 65]. Table 2 shows the water unit cost for various thermal desalination processes.

4.2 Economics of water desalination using membrane processes

The cost of membrane desalination technology has steadily decreased from its commercial introduction in 1970s until today, despite rising energy prices. Recent developments in membrane materials, pumping and energy recovery systems have dramatically reduced the energy consumption in RO desalination processes as shown in Figures 21 and 22, respectively [66, 67].

Table 2. *Cost of desalinated water in thermal processes.*

Desalination process	Capacity of desalination plant (m^3/day)	Desalination cost per m^3 (US$)
Multi-effect distillation, MED	<100	2.5–10
	12 000–55 000	0.95–1.95
	>91 000	0.52–1.01
Multi-stage flash, MSF	23 000–528 000	0.52–1.75
Vapour compression	1000–1200	2.01–2.66

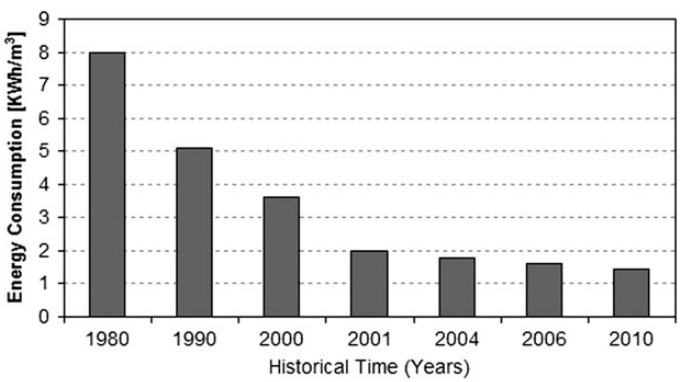

Figure 21. *Development of achievable energy consumption in RO desalination processes.*

The cost of water desalination in membrane processes varies according to the type and composition of the feed water. Large-scale RO plants can use brackish water containing total dissolved solids (TDS) of from 2000 to 10 000 ppm [68], but, as TDS concentrations increase, the unit cost of the desalinated water also increases as shown in Figure 22 [69]. The cost of brackish water desalination in the Middle East with a TDS concentration of 2300 ppm is 0.26 $/m^3 while in Florida, for brackish water with a TDS of 5000 ppm, it is 0.27 $/m^3 [70]. In small-scale RO units, the costs are greater. For example, the cost of a desalination unit of 1000 m^3/day ranges from 0.78 to 1.23 $/m^3 [71, 72] or even 1.33 $/m^3 [73]. For the desalination of seawater, the RO method has been used more and more in recent years, as the cost of membranes has fallen, but it is still slightly costly [74]. For instance, the estimated water production cost for the world's largest RO seawater desalination plant at Ashkelon in Israel with a capacity of 320 000 m^3/day is 0.52US$/m^3 [75] and costs at an RO plant with a capacity of 94 600 m^3/day in Tampa Bay in USA was reported to be at $0.56/m^3 [76]. Table 3 shows typical costs for RO desalination of brackish water and seawater [45].

4.3 Summary of water desalination economics

To sum up, the desalination systems can be operated by the use of conventional and renewable energy sources and the vast majority of desalination plants over the world are currently operated by fossil fuel instead of renewable energy due to technical and economical barriers. From the literature, it has been concluded that the cost of water produced from desalination systems using a conventional source of energy is much lower than those powered by renewable energy sources. Generally, water desalination prices have been decreased over the recent years due to technical improvements and research advancements in technologies. In conventional systems, the cost for seawater desalination ranges from 0.35 Euro/m^3 to more than

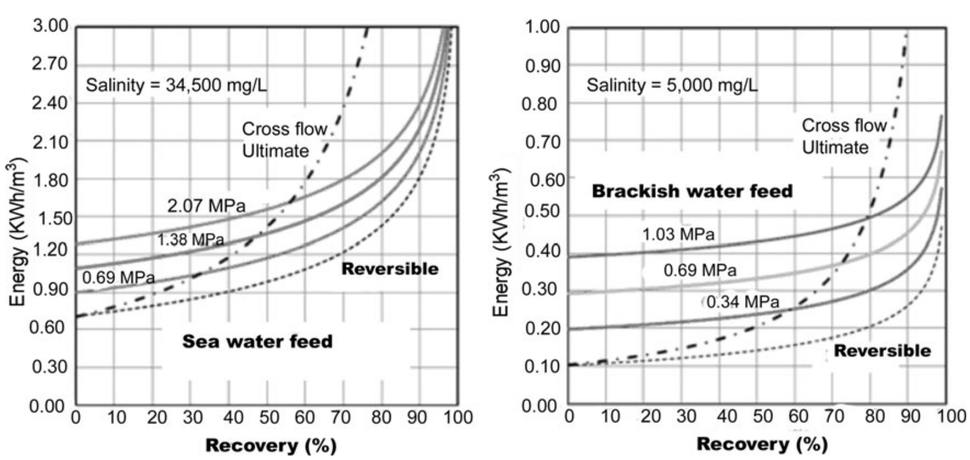

Figure 22. *Energy requirement for RO desalination (Sea and Brackish Water Feed).*

Table 3. *Cost of desalinated water in membrane (RO) plants.*

Type of feed water	Capacity of desalination plant (m^3/day)	Desalination cost per m^3 (US$)
Brackish water	<20	5.63–12.9
	20–1200	0.78–1.33
	40 000–46 000	0.26–0.54
Seawater	<100	1.5–18.75
	250–1000	1.25–3.93
	15 000–60 000	0.48–1.62
	100 000–320 000	0.45–0.66

Table 4. *Type of energy supplied and water production cost [45].*

Type of feed water	Type of energy	Water cost (Euro/m^3)
Brackish water	Conventional fuel	0.21–1.06
	Photovoltaic cells	4.5–10.32
	Geothermal	2
Sea water	Conventional fuel	0.35–2.70
	Wind energy	1.0–5.0
	Photovoltaic cells	3.14–9.0
	Solar collectors	3.5–8.0

2.7 Euro/m^3, while for brackish water desalination, the cost is almost half. When renewable energy sources are used, the cost is much higher, and in some cases can reach even 10.32 Euro/m^3, due to most expensive energy supply systems. However, this cost is counter balanced by the environmental benefits. Table 4 summarizes the cost of fresh water when the desalination system is powered by conventional and renewable energy sources.

RO methods, which become dominant in the desalination of brackish and seawater, have the lowest cost, mainly due to much lower energy consumption and the recent technological advances that have been achieved in membranes and energy recovery systems. Therefore, the potential of coupling solar energy sources with desalination systems are cost promising, especially in the Middle East and areas of plentiful sun availability. Table 5 illustrates the performance and cost of various solar desalination plants.

5 HEALTH AND ENVIRONMENTAL ASPECTS

The number of desalination plants worldwide is growing rapidly, and as the need for fresh water supplies grows more acute, desalination technologies improve and unit costs are reduced. Desalination processes should aim to be environmentally sustainable. Most drinking water applications use WHO drinking water guidelines as water quality specifications. ‘WHO Guidelines for Drinking-water Quality’ cover a broad spectrum of contaminants, including inorganic and synthetic organic chemicals, disinfection by-products, microbial

Table 5. *Performance and cost of various solar desalination plants adapted from [45, 81].*

Technology	Feed water type	Specific energy consumption (kWh/m^3)	Recovery ratio (%)	Water cost (US$/$m^3$)
MSF	Seawater, brackish water	81–144 (thermal)	0.6–6	1–5
MED	Seawater, brackish water	50–194 (thermal)	6–38	2–9
MD	Seawater, brackish water	100–600 (thermal)	3–5	13–18
RO	Seawater, brackish water	1.2–19 (electric)	10–51	3–27
ED	Brackish water	0.6–1 (electric)	25–50	3–16

indicators and radionuclides, and are aimed at typical drinking water sources and technologies. Currently, WHO says that existing guidelines may not fully cover the unique factors that can be encountered during the intake, production and distribution of desalinated water. Hence, it imposes stringent guidelines not only for drinking water quality but also for environmental protection issues. This is in order to assist with the optimization of both proposed and existing desalination facilities, and to ensure that nations and consumers will be able to enjoy the benefits of the expanded access to desalinated water with the assurance of quality, safety and environmental protection [77]. Obviously, the intake and pre-treatment of seawater, as well as the discharge of the concentrate reject water produced, have to be adapted to the specific conditions at the site of each desalination plant. Hence, it is necessary to consider and evaluate the criteria that help to select the best available technology and the optimal solution for the intake and outfall system at each plant. These environmental aspects are just as important as the commercial details and must be considered in the design and construction phases and during plant operation. Important elements regarding the environmental impact requirements that should be considered for different options are [77, 78].

- Concentrate discharge standards and locations
- Wastewater discharge standards
- Air pollution control requirements
- Noise control standards
- Land use
- Public services and utilities
- Aesthetics light and glare

6 CONCLUSIONS AND OUTLOOK

The desalination of brackish water and seawater is proving to be a reliable source of fresh water and is contributing to tackling the world’s water shortage problems. This article has reviewed a number of thermal and membrane water desalination processes developed during recent decades. The advantages and disadvantages, including economic, for each desalination technology have also been covered. In recent years, there have been considerable developments in membrane desalination processes, especially in terms of the design of membrane module, energy recovery and pre-treatment methods which have made it cost competitive with thermal processes. The use of renewable energies for desalination becomes a reasonable and technically mature alternative to the emerging and stressing energy situation and a sustainable solution for water scarcity. Currently, coupling desalination plants with clean environment-friendly energy resources is a pressing issue due to the dramatic increase in fossil fuel prices and the harmful impacts of burning fossil fuels, such as environmental pollution and climate change.

The scarcity of drinking water limits the socio-economic development in many areas, where solar resources are abundant. Hence, the use of solar energy for water desalination in countries in Africa and the Middle East region which have plenty of solar energy is a promising issue for meeting water demand and would definitely contribute both towards solving water scarcity problems and reducing carbon dioxide emissions by means of an environmentally friendly process.

Collective research and development programmes involving all the stakeholders—governments, industries, universities and research institutions—are required to improve and develop seawater desalination technologies to make them affordable worldwide, and especially in countries lacking conventional forms of energy and suffering shortages of water. Accordingly, various water desalination systems require extensive research and analysis for evaluating their potentials of development, applications and performance. The most mature technologies of renewable energy application in desalination are wind and PV-driven membrane processes and direct and indirect solar distillation. The connection of RO membrane technology would be considered the most cost-competitive solar desalination technologies approaching conventional desalination water costs. Hence the linkage of photovoltaic cells and membrane water desalination processes could be also considered the second most competitive alternative for brackish water desalination because of low water cost as presented in El-Nashar [79] in addition to the current rapid decrease in PV modules prices in the market. However, solar distillation may be advantageous for seawater desalination, as solar-MED is recommended for large-scale solar desalination, other renewable energy resources have to be taken into account such as wind and geothermal energy, which could be suitable for different desalination processes at viable costs. Moreover, the coupling of renewable energy and desalination systems has to be optimized and further technical research development of renewable energy augmented desalination technologies that require little maintenance and waste heat source are recommended which are uniquely suited to provide fresh water in remote areas where water and electricity infrastructure are currently lacking.

REFERENCES

[1] United Nations Environment Programme. http://www.unep.org/themes/freshwater.html (10 April 2008).
[2] Al-Kharabsheh S. Theoretical and experimental analysis of water desalination system using low grade solar heat. PhD dissertation. University of Florida, 2003.
[3] Colombo D, De Gerloni M, Reali M. An energy-efficient submarine desalination plant. *Desalination* 1999;**122**:171–6.
[4] WHO/EU drinking water standards comparative table, Water treatment & Air purification and other supporting information. http://www.lenntech.com/WHO-EU-water-standards.html (26 October 2007).
[5] Tiwari GN, Singh HN, Tripathi R. Present status of solar distillation. *Solar Energy* 2003;**75**:367–73.
[6] Buros OK. *The ABCs of Desalting*, 2nd edn. ASIN: B0006S2DHY, International Desalination Association, 2000, 30.
[7] Buros OK. *The ABCs of Desalting*. International Desalination Association, 1999, 31.
[8] Gleick PH (ed.). *The World's Water: The Biennial Report of Fresh Water Resources 1998–1999*. Island Press, 1998.
[9] WDI. Water Desalination International: Introduction. Published by WDI. http://www.aterdesalination.com/introduction.htm (21 April 2008).
[10] Al-Kharabsheh S, Yogi Goswami D. Analysis of an innovative water desalination system using low-grade solar heat. *Desalination* 2003;**156**:323–32.
[11] Winter T, Pannell J, McCann Mc. *The Economics of Desalination and Its Potential Application in Australia*. University of Western Australia, 2005.
[12] Raluy RG, Serra L, Uche J, *et al*. Life-cycle assessment of desalination technologies integrated with energy production systems. *Desalination* 2004;**167**:445–58.
[13] Multi Stage Flash, Halcrow Water Services. http://www.hwsdesalination.com/multi%20stage%20flash%20desalination.html (2 October 2007).
[14] Hamed O, Mustafa GM, BaMardouf K, *et al*. Prospects of improving energy consumption of the multi-stage flash distillation process. In: *Proceedings of the Fourth Annual Workshop on Water Conservation in Dhahran the Kingdom of Saudi Arabia*, 2001.
[15] *Water Desalination Technologies in the ESCWA Member Countries*. UN-ESSWA, ASIN: E/ESCWA/TECH/2001/3. United Nations, 2001, 172.
[16] Introduction to desalination technologies. http://www.texaswater.tamu.edu/readings/desal/IntrotoDesal.pdf (2 October 2007).
[17] Khawaji AD, Wie J-M. Potabilization of desalinated water at Madinat Yanbu Al-Sinaiyah. *Desalination* 1994;**98**:135–46.
[18] Wangnick K. IDA worldwide desalting plants inventory: report No. 16. Produced by Wangnick Consulting for the International Desalination Association, 2000.
[19] Al-Shammiri M, Safar M. Multi-effect distillation plants: state of the art. *Desalination* 1999;**126**:45–59.
[20] Khawaji AD, Kutubkhanah IK, Wie J-M. Advances in seawater desalination technologies. *Desalination* 2008;**221**:47–69.
[21] Darwish MA, El-Dessouky H. The heat recovery thermal vapour-compression desalting system: a comparison with other thermal desalination processes. *Appl Thermal Eng* 1996;**16**:523–37.
[22] El-Nashar AM. Cogeneration for power and desalination—state of the art review. *Desalination* 2001;**134**:7–28.
[23] *The Desalting and Water Treatment Membrane Manual: A Guide to Membranes for Municipal Water Treatment, Water Treatment Technology Program*, Report No. 1, September 1993, published by the United States Department of the Interior, Bureau of Reclamation, Denver Office, Research and Laboratory Services Division, Applied Sciences Branch

(R-93-15). http://www.usbr.gov/pmts/water/publications/reportpdfs/report001.pdf (15 March 2008).

[24] Ayyash Y, Imai H, Yamada T, *et al*. Performance of reverse osmosis membrane in Jeddah Phase I plant. *Desalination* 1994;**96**:215–24.

[25] Khawaji AD, Kutubkhanah IK, Wie J-M. A 13.3 MGD seawater RO desalination plant for Yanbu Industrial City. *Desalination* 2007;**203**:176–88.

[26] AL Mobayed AA, Balaji S. Successful Operation of Pretreatment in Al-Jubail SWRO Plant. *Paper presented at IDA World Congress on Desalination & Water Reuse Conference*. 11–16 September 2005. , pp. 12.

[27] Al-Sheikh AHH. Seawater reverse osmosis pretreatment with an emphasis on the Jeddah Plant operation experience. *Desalination* 1997;**110**:183–92.

[28] Kayyal M. *Study on Wastewater Treatment and Water Desalination Technologies for ESCWA Countries*. United Nations, 2000.

[29] Bou-Hamad S, Abdel-Jawad M, Al-Tabtabaei M, *et al*. Comparative performance analysis of two seawater reverse osmosis plants: twin hollow fine fiber and spiral wound membranes. *Desalination* 1998;**120**:95–106.

[30] El-Dessouky H, Ettouny H. *Study on Water Desalination Technologies*. Prepared for ESCWA, United Nations, 2001.

[31] Strathmann H, Winston WS, Sirkar KK. *Membrane Handbook*, ISBN-0-442-23747-2. Van Nostrand Reinhold, 1992, 246–54.

[32] Kalogirou SA. Seawater desalination using renewable energy sources. *Prog Energy Combust Sci* 2005;**31**:242–81.

[33] Findley ME. Vaporization through porous membranes. *Ind Eng Chem Process Des Dev* 1967, **6**, 226.

[34] Mathioulakis E, Belessiotis V, Delyannis E. Desalination by using alternative energy: review and state-of-the-art. *Desalination* 2007;**203**:346–65.

[35] Tomaszewska M. Membrane distillation—examples of applications in technology and environmental protection. *Polish J Environ Stud* 2000;**9**:27–36.

[36] Rice W, Chau DSC. Freeze desalination using hydraulic refrigerant compressors. *Desalination* 1997;**109**:157–64.

[37] Xu T. Ion exchange membranes: State of their development and perspective. *J Membrane Sci* 2005;**263**:1–29.

[38] Miller J. *Review of Water Resources and Desalination Technologies*. Materials Chemistry Department, Sandia National Laboratories, 2003. http://www.prod.sandia.gov/cgi-bin/techlib/access-control.pl/2003/030800.pdf (3 March 2008).

[39] *Introduction to Desalination Technologies in Australia*, 2002. http://www.environment.gov.au/water/publications/urban/desalination-summary.html. (13 April 2008).

[40] Werner M, Schäfer AI. Social aspects of a solar-powered desalination unit for remote Australian communities. *Desalination* 2007;**203**:375–93.

[41] Renewable desalination market analysis in Oceania, South Africa, Middle East & North Africa, 2010. www.aquamarinepower.com (November 2011).

[42] Mahmoudi H, Abdellah O, Ghaffour N. Capacity building strategies and policy for desalination using renewable energies in Algeria. *Renew Sustain Energy Rev* 2008, in press.

[43] US Energy information administration International Energy Outlook 2010—highlights. http://www.eia.doe.gov (26 November 2011).

[44] Ali MT, Fath HES, Armstrong PR. A comprehensive techno-economical review of indirect solar desalination. *Renew Sustain Energy Rev* 2011;**15**:4187–99.

[45] Karagiannis IC, Soldatos PG. Water desalination cost literature: review and assessment. *Desalination* 2008;**223**:448–56.

[46] Tzen E. Renewable energy sources for desalination, *Paper presented at Workshop on Desalination Units Powered by RES*, Athens, 2006.

[47] Quteishat K, Abu Arabi M. Promotion of solar desalination in the MENA region report. Middle East Desalination Research Centre, 2004.

[48] Delyannis E. Historic background of desalination and renewable energies. *Sol Energy* 2003;**75**:357–66.

[49] Kreith F, Kreider JF. *Principles of Solar Engineering*. McGraw-Hill, 1978.

[50] Kalogirou SA. Solar thermal collectors and applications. *Prog Energy Combust Sci* 2004;**30**:231–95.

[51] Intermediate Technology Development Group. *Solar Distillation: Technical Brief*. The Schumacher Centre for Technology & Development. http://www.itdg.org/docs/technical_information_service (8 October 2007).

[52] Fath HES, Ghazy A. Solar desalination using humidification–dehumidification technology. *Desalination* 2002;**142**:119–33.

[53] Ali Samee M, Mirza UK, Majeed T, *et al*. Design and performance of a simple single basin solar still. *Renew Sustain Energy Rev* 2007;**11**:543–9.

[54] Abdel-Rehim ZS, Lasheen A. Improving the performance of solar desalination systems. *Renew Energy* 2005;**30**:1955–71.

[55] Kaushal A, Varun. Solar stills: a review. *Renew Sustain Energy Rev* 2010;**14**:446–53.

[56] Hamed OA, Eisa EI, Abdalla WE. Overview of solar desalination. *Desalination* 1993;**93**:563–79.

[57] *The Encyclopedia of Desalination and Water Resources (DESWARE)*. http://www.desware.net (8 October 2007).

[58] Parekh S, Farid MM, Selman J, *et al*. Solar desalination with a humidification–dehumidification technique—a comprehensive technical review. *Desalination* 2004;**160**:167–86.

[59] Orfi J, Galanis N, Laplante M. Air humidification–dehumidification for a water desalination system using solar energy. *Desalination* 2007;**203**:471–81.

[60] Müller-Holst H, Engelhardt M, Schölkopf W. Small-scale thermal seawater desalination simulation and optimization of system design. *Desalination* 1999;**122**:255–62.

[61] Renewable energy solutions. http://www.enviko.com/technology/solar-pv (29 November 2011).

[62] Solar energy markets and growth. http://www.solarbuzz.com/facts-and-Fig.s/retail-price-environment/module-prices (27 November 2011).

[63] Mahmoud MM, Ibrik IH. Techno-economic feasibility of energy supply of remote villages in Palestine by PV-systems, diesel generators and electric grid. *Renew Sustain Energy Rev* 2006;**10**:128–38.

[64] Voivontas D, Misirlis K, Manoli E, *et al*. A tool for the design of desalination plants powered by renewable energies. *Desalination* 2001;**133**:175–98.

[65] Zejli D, Benchrifa R, Bennouna A, *et al*. Economic analysis of wind-powered desalination in the south of Morocco. *Desalination* 2004;**165**:219–30.

[66] Fritzmann C, Löwenberg J, Wintgens T, *et al*. State-of-the-art of reverse osmosis desalination. *Desalination* 2007;**216**:1–76.

[67] Stover RL. Energy recovery devices for seawater reverse osmosis, 2006. Retrieved 4 May 2008 from the World Wide Web. http://www.energyrecovery.com/news/documents/ERDsforSWRO.pdf.

[68] Delyianni E, Belessiotis B. *Methods and Desalination Systems—Principles of the Desalination Process*, NCSR 'Demokritos', 1995.

[69] Liu C, Rainwater K, Song L. Energy analysis and efficiency assessment of reverse osmosis desalination process. *Desalination* 2011;**276**:352–8.

[70] Avlonitis SA. Operational water cost and productivity improvements for small-size RO desalination plants. *Desalination* 2002;**142**:295–304.

[71] Al-Wazzan Y, Safar M, Ebrahim S, *et al*. Desalting of subsurface water using spiral-wound reverse osmosis (RO) system: technical and economic assessment. *Desalination* 2002;**143**:21–8.

[72] Jaber IS, Ahmed MR. Technical and economic evaluation of brackish groundwater desalination by reverse osmosis (RO) process. *Desalination* 2004;**165**:209–13.

[73] Sambrailo D, Ivic J, Krstulovic A. Economic evaluation of the first desalination plant in Croatia. *Desalination* 2005;**179**:339–44.

[74] *IDA Desalination Yearbook 2006–2007*. Water Desalination Report, Global Water Intelligence and International Desalination Association.

[75] Ashkelon Desalination Plant, Seawater Reverse Osmosis (SWRO) Plant, Water technology net. http://www.water-technology.net/projects/Israel (21 November 2011).

[76] Wilf M, Bartels C. Optimization of seawater RO systems design. *Desalination* 2005;**173**:1–12.

[77] *Desalination for Safe Water Supply, Guidance for the Health and Environmental Aspects Applicable to Desalination*. 2007. http://www.who.int/water_sanitation_health/gdwqrevision/desalination/en (13 April 2008).

[78] Peters T, Pintó D. Seawater intake and pre-treatment/brine discharge—environmental issues. *Desalination* 2008;**221**:576–84.

[79] El-Nashar AM. The economic feasibility of small solar MED seawater desalination plants for remote arid areas. *Desalination* 2001;**134**:173–86.

[80] Shatat MIM, Mahkamov K. Determination of rational design parameters of a multi-stage solar water desalination still using transient mathematical modelling. *Renew Energy* 2010;**35**:52–61.

[81] Miller JE. *Review of Water Resources and Desalination Technologies*. Sandia National Laboratories, 2004, 49 pp. http://www.sandia.gov/water/docs/MillerSAND2003_0800.pdf.