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Renewable Energy Opportunities in Water Desalination

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1. Introduction

Desalination is a water-treatment process that separates salts from saline water to produce potable water or water that is low in total dissolved solids (TDS). Globally, the total installed capacity of desalination plants was 61 million m^3 per day in 2008 [1]. Seawater desalination accounts for 67% of production, followed by brackish water at 19%, river water at 8%, and wastewater at 6%. Figure 1 show the worldwide feed-water percentage used in desalination. The most prolific users of desalinated water are in the Arab region, namely, Saudi Arabia, Kuwait, United Arab Emirates, Qatar, Oman, and Bahrain [2].

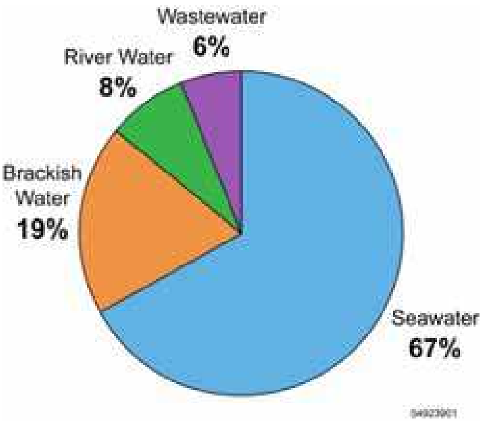


Fig. 1. Worldwide feed-water percentage used in desalination (http://desaldata.com/).

Desalination can be achieved by using a number of techniques. Industrial desalination technologies use either phase change or involve semi-permeable membranes to separate the solvent or some solutes. Thus, desalination techniques may be classified into two main categories [3]:

- Phase-change or thermal processes—where base water is heated to boiling. Salts, minerals, and pollutants are too heavy to be included in the steam produced from boiling and therefore remain in the base water. The steam is cooled and condensed. The main thermal desalination processes are multi-stage flash (MSF) distillation, multiple-effect distillation (MED), and vapor compression (VC), which can be thermal (TVC) or mechanical (MVC).

- Membrane or single-phase processes—where salt separation occurs without phase transition and involves lower energy consumption. The main membrane processes are reverse osmosis (RO) and electrodialysis (ED). RO requires electricity or shaft power to drive a pump that increases the pressure of the saline solution to the required level. ED also requires electricity to ionize water, which is desalinated by using suitable membranes located at two oppositely charged electrodes.

All processes require a chemical pre-treatment of raw seawater—to avoid scaling, foaming, corrosion, biological growth, and fouling—as well as a chemical post-treatment.

The two most commonly used desalination technologies are MSF and RO systems. As the more recent technology, RO has become dominant in the desalination industry. In 1999, about 78% of global production capacity comprised MSF plants and RO accounted for a modest 10%. But by 2008, RO accounted for 53% of worldwide capacity, whereas MSF consisted of about 25%. Although MED is less common than RO or MSF, it still accounts for a significant percentage of global desalination capacity (8%). ED is only used on a limited basis (3%) [4]. Figure 2 shows the global desalination plant capacity by technology in 2008.

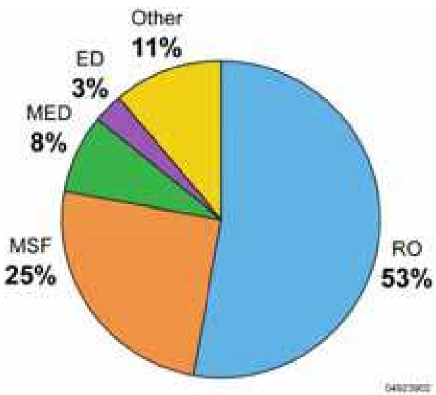


Fig. 2. Global desalination plant capacity by technology, 2008 (http://desaldata.com/).

The cost of water desalination varies depending on water source access, source water salinity and quality, specific desalination process, power costs, concentrate disposal method, project delivery method, and the distance to the point of use. Power costs in water desalination may account for 30% to 60% of the operational costs; thus, slight variations in power rates directly impact the cost of treated water.

Using renewable energy sources in water desalination has many advantages and benefits. The most common advantage is that they are renewable and cannot be depleted. They are a clean energy, not polluting the air, and they do not contribute to global warming or greenhouse gas emissions. Because their sources are natural, operational costs are reduced and they also require less maintenance on their plants. Using these resources in water desalination in remote areas also represents the best option due to the very high cost of providing energy from the grid. And implementing renewable energy in these areas will foster socioeconomic development. Renewable energy can be used for seawater desalination either by producing the thermal energy required to drive the phase-change processes or by producing electricity required to drive the membrane processes. The major sources of alternative energy discussed here are solar, wind, and geothermal.

This chapter provides insight into various aspects of desalination and how renewable energy resources can be coupled to desalination systems. A brief outline of the technical side of the main desalination processes is followed by an assessment of their respective advantages and disadvantages. The chapter then provides a general economic assessment of the conventional process versus desalination processes coupled with renewable energy. This analysis includes a range of cost estimates of competing processes as stated in the literature and how they compare to alternative sources of water supply.

2. Main desalination technologies

The two major types of desalination technologies used around the world can be broadly classified as either phase change (thermal) or membrane, and both technologies need energy to operate. Within these two types are sub-categories (processes) using different techniques, as shown below and in Figure 3:

- Phase-change processes, include:
  - Multi-stage flash distillation (MSF)
  - Multi-effect distillation (MED)
  - Vapor compression (VC)—thermal (TVC) and mechanical (MVC)
  - Other processes include solar still distillation, humidification-dehumidification , membrane distillation, and freezing.
- Membrane technology, include:
  - Reverse osmosis (RO)
  - Electrodialysis (ED and EDR).

Three other membrane processes that are not considered desalination processes, but that are relevant, are: microfiltration (MF), ultrafiltration (UF), and Nanofiltration (NF). The ion-exchange process is also not regarded as a desalination process, but is generally used to improve water quality for some specific purposes, e.g., boiler feed water [5].

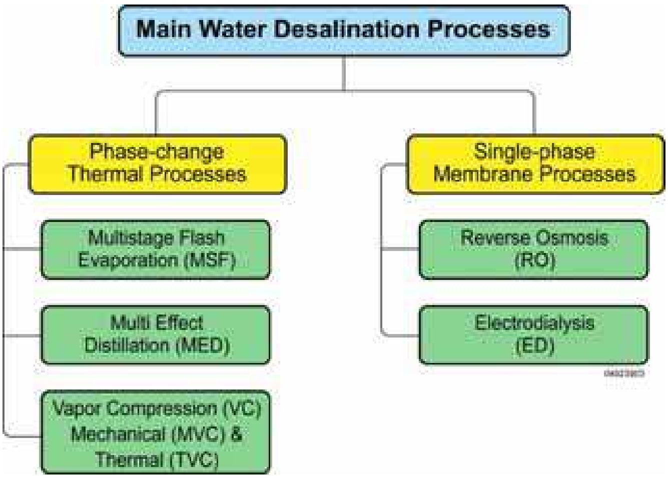


Fig. 3. Main desalination technologies.

2.1 Phase-change or distillation processes

Distillation processes mimic the natural water cycle as saline water is heated, producing water vapor, which, in turn, is condensed to form fresh water. The processes typically used include MSF, MED, and VC. Currently, about 25% of the world's desalination capacity is based on the MSF distillation principle. However, other distillation technologies, such as MED and VC distillation, are rapidly expanding and are anticipated to have a more important role in the future as they become better understood and more accepted. These processes require thermal or mechanical energy to cause water evaporation. As a result, they tend to have operating cost advantages when low-cost thermal energy is available [6].

2.1.1 Multi-stage flash distillation (MSF)

In MSF, seawater feed is pressurized and heated to the plant's maximum allowable temperature. When the heated liquid is discharged into a chamber maintained at slightly below the saturation vapor pressure of the water, a fraction of its water content flashes into steam. The flashed steam is stripped of suspended brine droplets as is passes through a mist eliminator and condenses on the exterior surface of the heat-transfer tubing [7]. The condensed liquid drips into trays as hot fresh-water product. Figure 4 is a diagram of a typical MSF unit.

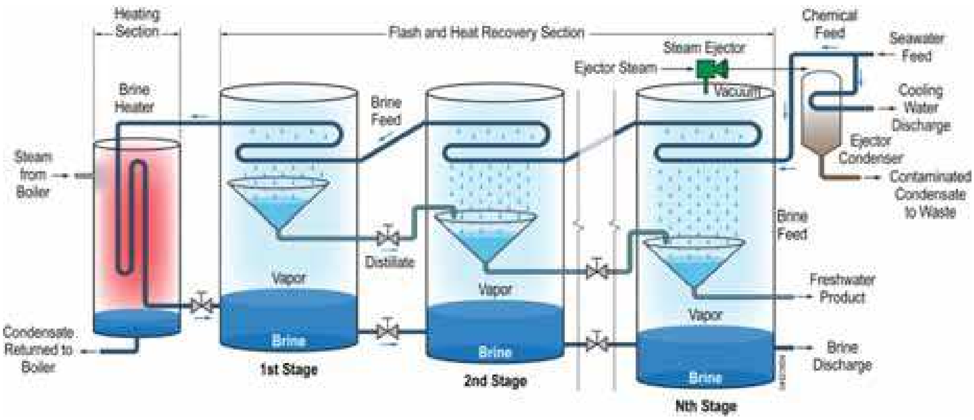


Fig. 4. Diagram of typical MSF unit (modified from [7])

2.1.2 Multi-effect distillation (MED)

MED units operate on the principle of reducing the ambient pressure at each successive stage, allowing the feed water to undergo multiple boiling without having to supply additional heat after the first stage. In this unit, steam and/or vapor from a boiler or some other available heat source (such as renewable sources or waste energy) is fed into a series of tubes, where it condenses and heats the surface of the tubes and acts as a heat-transfer surface to evaporate saline water on the other side. The energy used for evaporation of the saline water is the heat of condensation of the steam in the tube. The evaporated saline water—now free of a percentage of its salinity and slightly cooler—is fed into the next, lower-pressure stage where it condenses to fresh-water product, while giving up its heat to evaporate a portion of the remaining seawater feed [8]. Figure 5 is a diagram of an MED unit.

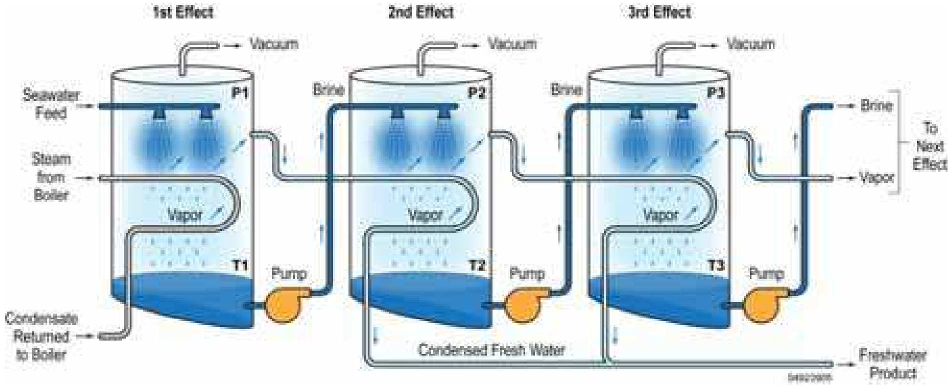


Fig. 5. Diagram of an MED unit (modified from [7])

2.1.3 Vapor-compression distillation

The VC distillation process is generally used for small- and medium-scale seawater desalting units. The heat for evaporating the water comes from the compression of vapor, rather than from the direct exchange of heat from steam produced in a boiler. Two primary methods are used to condense vapor so as to produce enough heat to evaporate incoming seawater: a mechanical compressor or a steam jet [9]. The mechanical compressor (MVC) is usually electrically driven, allowing the sole use of electrical power to produce water by distillation (Fig. 6a). With the steam jet-type of VC unit, also called a thermo compressor (TVC), a Venturi orifice at the steam jet creates and extracts water vapor from the main vessel by creating a lower ambient pressure in the main vessel. The extracted water vapor 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 vessel (Fig. 6b). MVC units typically range in size up to about 3,000m^3/day, whereas TVC units may range in size up to 20,000 m^3/day; they are often used for resort and industrial applications.

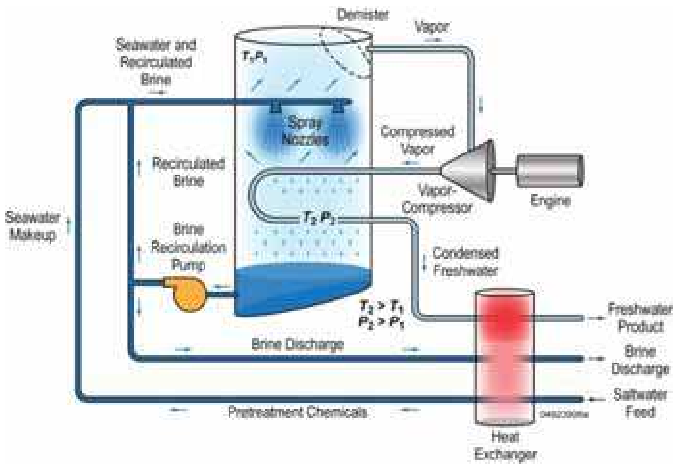


Fig. 6a. Diagram of a mechanical vapor-compression plant.

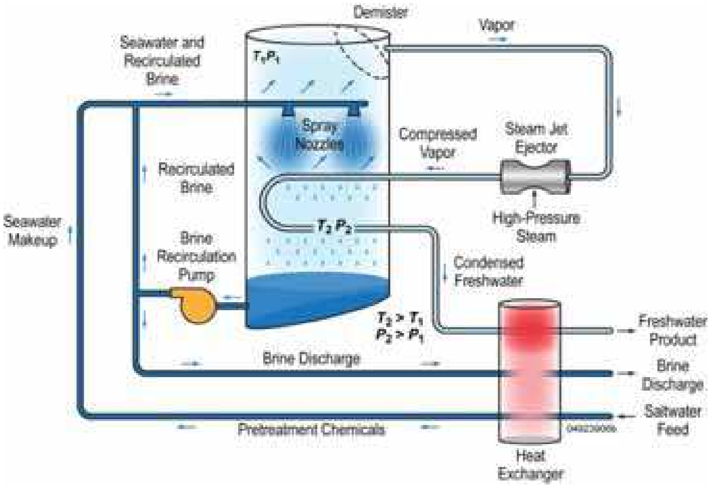


Fig. 6b. Diagram of a thermal vapor-compression plant (modified from [7])

2.2 Membrane processes

Membranes and filters can selectively permit or prohibit the passage of certain ions, and desalination technologies have been designed around these capabilities. Membranes play an important role in separating salts in the natural processes of dialysis and osmosis. These natural principles have been adapted in two commercially important desalting processes: electrodialysis (ED) and reverse osmosis (RO). Although they have typically been used to desalinate brackish water, versions are increasingly being applied to seawater, and these two approaches now account for more than half of all desalination capacity. A growing number of desalination systems are also adding filtration units prior to the membranes to remove contaminants that affect long-term filter operation. The filtration systems include microfiltration, nanofiltration, and ultrafiltration.

2.2.1 Reverse osmosis (RO)

RO technology description

Reverse osmosis is a form of pressurized filtration in which the filter is a semi-permeable membrane that allows water, but not salt, to pass through. A typical RO system consists of four major subsystems (see Fig. 7): pretreatment system, high-pressure pump, membrane module, and post-treatment system [10].

Feed-water pretreatment is a critical factor in operating an RO system because membranes are sensitive to fouling. Pretreatment commonly includes sterilizing feed water, filtering, and adding chemicals to prevent scaling and bio-fouling. Using a high-pressure pump, the pretreated feed water is forced to flow across the membrane surface. RO operating pressure ranges from 17 to 27 bars for brackish water and from 55 to 82 bars for seawater. Part of the feed water—the product or permeate water—passes through the membrane, which removes the majority of the dissolved solids [11]. The remainder, together with the rejected salts, emerges from the membrane modules at high pressure as a concentrated reject stream (brine). The energy efficiency of seawater RO depends heavily on recovering the energy

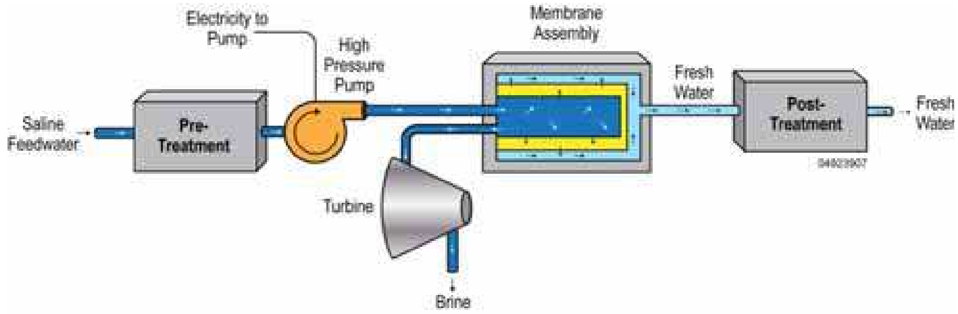


Fig. 7. Major subsystems in a reverse-osmosis system.

from the pressurized brine. In large plants, the reject brine pressure energy is recovered by a turbine—commonly a Peloton-wheel turbine—recovering 20% to 40% of the consumed energy.

The RO membrane is semi-permeable, possessing a high degree of water permeability, but presents an impenetrable barrier to salts. It has a large surface area for maximum flow and is extremely thin so that it offers minimal resistance to water flow; but it is also sturdy enough to withstand the pressure of the feed stream [12].

Polymers currently used for manufacturing RO membranes are based on either cellulose acetates (cellulose diacetate, cellulose triacetate, or combinations of the two) or polyamide polymers. Two types of RO membranes commonly used commercially are spiral-wound (SW) membranes and hollow-fiber (HF) membranes. Other configurations, including tubular and plate-frame designs, are sometimes used in the food and dairy industries. Seawater membrane elements are most commonly manufactured from a cellulose diacetate and triacetate blend or a thin-film composite usually made from polyamide, polysulphone, or polyurea polymers.

A typical industrial SW membrane is about 100–150 cm long and 20–30 cm in diameter. An HF membrane is made from both cellulose acetate blends and non-cellulose polymers such as polyamide. Millions of fibers are folded to produce bundles about 120 cm long and 10–20 cm in diameter. SW and HF membranes are used to desalt both seawater and brackish water. The decision of which to use is based on factors such as cost, feed-water quality, and product-water capacity. The main membrane manufacturers are in the United States and Japan [13].

The post-treatment system consists of sterilization, stabilization, and mineral enrichment of the product water. Because the RO unit operates at ambient temperature, corrosion and scaling problems are diminished compared to distillation processes. However, effective pretreatment of the feed water is required to minimize fouling, scaling, and membrane degradation. In general, the selection of proper pretreatment and proper membrane maintenance are critical for the efficiency and life of the system.

RO technology deployment

RO units are available in a wide range of capacities due to their modular design. Large plants are made of hundreds of units that are accommodated in racks. A typical maximum plant capacity is 128,000 m^3 /day, and very small units (down to 0.1 m^3/day) are also used for marine purposes, houses, or hotels. PV power is used for small-size RO units especially in remote places due to initial-cost benefits [14].

Numerous RO plants have been installed for both seawater and brackish-water applications. The process is also widely used in manufacturing, agriculture, food processing, and pharmaceutical industries. The worldwide total installed capacity of RO units in the United States is 32%, followed by 21% in Saudi Arabia, 8% in Japan, and 8.9% in Europe. Some 23% of RO units are manufactured in the United States, 18.3% in Japan, and 12.3% in Europe [14].

2.2.2 Electrodialysis

Electrodialysis (ED) is an electrochemical separation process that uses electrical currents to move salt ions selectively through a membrane, leaving fresh water behind. ED is a low-cost method for desalinating brackish water. Due to the dependence of energy consumption on the feed-water salt concentration, the ED process is not economically attractive for desalinating seawater. In the ED process, ions are transported through a membrane by an electrical field applied across the membrane. An ED unit consists of the following basic components: pretreatment system, membrane stack, low-pressure circulation pump, power supply for direct-current (rectifier or PV system), and post-treatment system.

The principle of ED operation is as follows: electrodes (generally constructed from niobium or titanium with a platinum coating) are connected to an outside source of direct current (such as a battery or PV source) in a container of salt water. The electrical current is carried through the solution, with the ions tending to migrate to the electrode with the opposite charge. Positively charged ions migrate to the cathode and negatively charged ions migrate to the anode. Salinity of the water is removed as water passes through ion-selective membranes positioned between the two electrodes (see Fig. 8). These membranes consist of flat-sheet polymers subjected to special treatment in which micro-sized cracks or crevices are produced in the plastic film surface. These devices permit the transport of ions, while ion-exchange sites incorporated into the membrane's polymer matrix promote membrane selectivity. Anion-permissible membranes allow anions to pass through to the positively charged electrode, but reject cations. Conversely, cation permissible membranes allow cations to pass through to the negatively charged electrode, but reject anions.

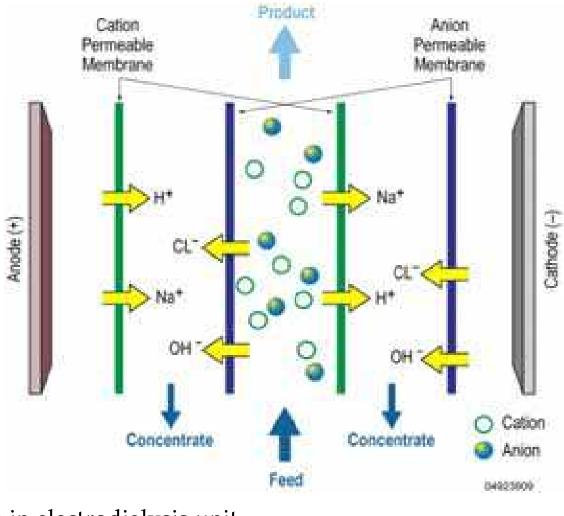


Fig. 8. Ion exchange in electrodialysis unit.

Between each pair of membranes, a spacer sheet is placed to permit water flow along the face of the membrane and to induce a degree of turbulence. One spacer provides a channel that carries feed water (and product water), whereas the next spacer carries brine. By this arrangement, concentrated and diluted solutions are created in the spaces between the alternating membranes. ED cells can be stacked either horizontally or vertically. In practice, several membrane pairs are used between a single pair of electrodes, forming an ED stack. Feed water passes simultaneously in parallel paths through all the cells, providing a continuous flow of product water and brine out of the stack (see Fig. 9). Stacks on commercial ED plants contain a large number of cell pairs, usually several hundred [15].

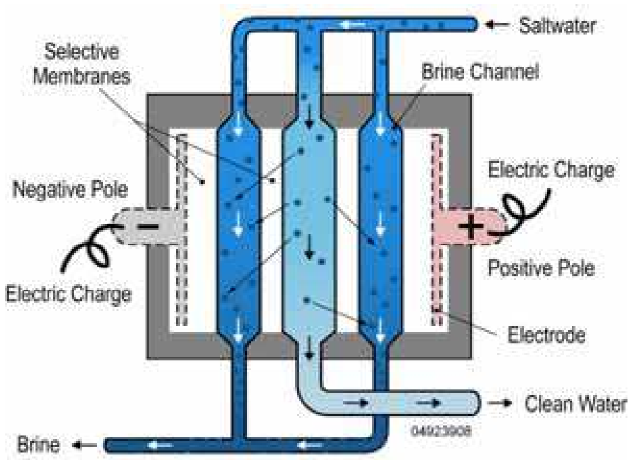


Fig. 9. Diagram of electrodialysis unit (modified from [7])

A modification to the basic ED process is electrodialysis reversal (EDR). An EDR unit operates on the same general principle as a standard ED plant, except that the product and brine channels are both identical in construction. In this process, the polarity of the electrodes changes periodically in time, reversing the flow through the membranes. This inhibits deposition of inorganic scales and colloidal substances on the membranes without the addition of chemicals to the feed water. This development considerably enhances the viability of this process because the process is now self-cleaning. In general, EDR requires minimum feed-water pretreatment and minimum use of chemicals for membrane cleaning [16].

ED and EDR technology deployment

The ED process is usually only suitable for brackish water with a salinity of up to 12,000 ppm TDS. With higher salinity, the process rapidly becomes more costly than other desalination processes because the power consumption is directly proportional to the salinity of the water to be desalinated. ED has been in commercial use since 1954, more than ten years before RO. Since then, this process has seen widespread applications, especially for the production of potable water. Due to its modular structure, ED is available in a wide range of sizes, from small capacities (down to 2 m^3/d) to large capacities (145,000 m^3/day). ED is widely used in the United States, which has 31% of the total installed capacity. In

Europe, the ED process accounts for 15% and the Middle East has 23% of the total installed capacity. The EDR process was developed in the early 1970s. Today, the process is used in about 1,100 installations worldwide. Typical industrial users of EDR include power plants, semiconductor manufacturers, the pharmaceutical industry, and food processors. The installed PV-ED units are only of small capacity and are used in remote areas.

3. Desalination with renewable energy systems

Using desalination technologies driven by renewable energy resources is a viable way to produce fresh water in many locations today. As the technologies continue to improve—and as fresh water and cheap conventional sources of energy become scarcer—using renewable energy technology in desalination will become even more attractive. The selection of the appropriate renewable energy desalination technology depends on a number of factors, including plant size, feed-water salinity, remoteness, availability of grid electricity, technical infrastructure, and the type and potential of the local renewable energy resources. Figure 10 shows the possible combination of renewable energy systems with desalination units.

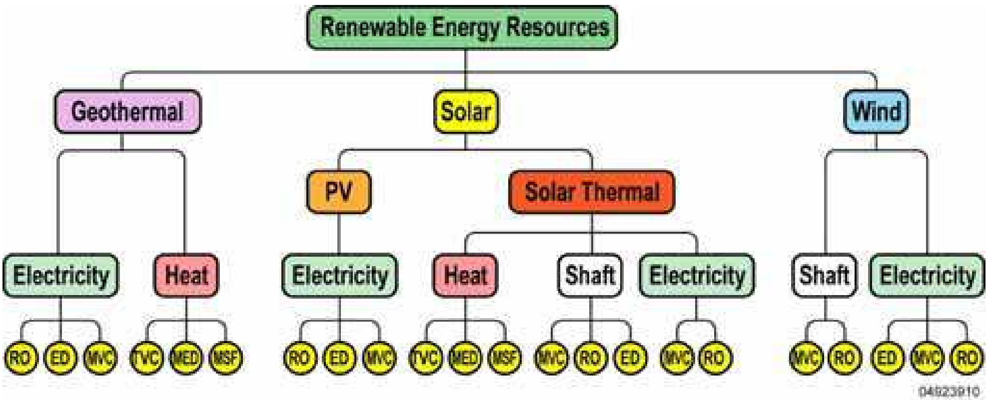


Fig. 10. Possible combinations of renewable energy systems with desalination units.

Proper matching of standalone power-supply desalination systems has been recognized as being crucial if the system is to provide a satisfactory supply of power and water at a reasonable cost. Standalone renewable energy systems for electricity supply are now a proven technology and economically promising for remote regions, where connection to the public electric grid is either not cost effective or feasible, and where water scarcity is severe. Solar thermal, solar PV, wind, and geothermal technologies could be used as energy suppliers for desalination systems.

Table 1 presents the most promising combinations of renewable energy resources with desalination technologies. According to this table, solar energy—both solar thermal and solar PV—can be used to drive MSF, MED, RO, and ED. Wind energy can drive VC, RO, and ED. Geothermal energy reservoirs with moderate temperature can drive MSF and MED units, while geothermal high pressure reservoirs can be utilized to drive mechanically driven desalination units by shaft power or by producing electricity to drive VC, RO, and ED units.

RE Resource	Desalination Process				
	MSF	MED	VC	RO	ED
Solar thermal	◙	◙			
Solar PV				◙	◙
Wind			◙	◙	◙
Geothermal	◙	◙	◙	◙	◙

Table 1. Possible combination of RE resources with desalination units

3.1 Solar-assisted desalination systems

Solar energy can drive the desalination units by either thermal energy and electricity generated from solar thermal systems or by PV systems. The cost distribution of solar distillation is dramatically different from that of RO and MSF. The main cost is in the initial investment. However, once the system is operational, it is extremely inexpensive to maintain and the energy has minimal or even no cost. Solar-assisted desalination systems are divided into two parts: solar thermal-assisted systems and solar photovoltaic-assisted systems.

3.1.1 Solar thermal-assisted systems

Solar thermal energy can be harnessed directly or indirectly for desalination. Collection systems that use solar energy to produce distillate directly in the solar collector are called direct-collection systems, whereas systems that combine solar energy collection devices with conventional desalination units are called indirect systems. In indirect systems, solar energy is used either to generate the heat required for desalination and/or to generate electricity used to provide the required electric power for conventional desalination plants such as MED and MSF plants. Direct solar desalination requires large land areas and has a relatively low productivity. However, it is competitive with indirect desalination plants in small-scale production due to its relatively low cost and simplicity.

3.1.1.1 Direct solar thermal desalination

Direct systems are those where the heat collection and distillation processes occur in the same equipment. Solar energy is used to produce the distillate directly in the solar still. The method of direct solar desalination is mainly suited for small production systems, such as solar stills, and it is used in regions where the freshwater demand is low. This device has low efficiency and low water productivity due to the ineffectiveness of solar collectors to convert most of the energy they capture, and to the intermittent availability of solar radiation. For this reason, direct solar thermal desalination has so far been limited to small-capacity units, which are appropriate in serving small communities in remote areas having scarce water. Solar-still design can generally be grouped into four categories: (1) basin still, (2) tilted-wick solar still, (3) multiple-tray tilted still, and (4) concentrating mirror still.

The basin still consists of a basin, support structure, transparent glazing, and distillate trough. Thermal insulation is usually provided underneath the basin to minimize heat loss. Other ancillary components include sealants, piping and valves, storage, external cover, and a reflector (mirror) to concentrate light. Single basin stills have low efficiency, generally below 45%, and low productivity (4–6 liter/m^2/day) due to high top losses. Double glazing can potentially reduce heat losses, but it also reduces the transmitted portion of the solar radiation [17]. On a much smaller scale, a solar micro-desalination unit [18] may be used in remote areas and is capable of producing about 1.5 liter/day.

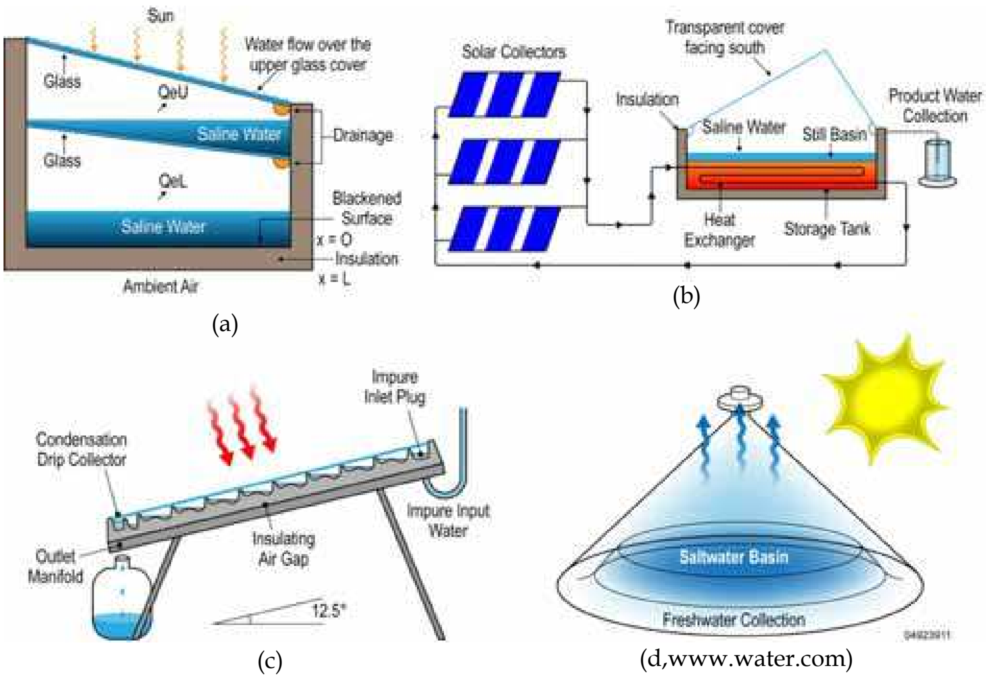


Fig. 11. Diagrams of various solar stills: (a) double-basin solar still, (b) single-basin solar still coupled with flat plate collector, (c) multi-steps tilted solar still, (d) micro-solar solar still.

A tilted-wick solar still uses the capillary action of fibers to distribute feed water over the entire surface of the wick in a thin layer. This allows a higher temperature to form on this thin layer. Insulation in the back of wick is essential. A cloth wick needs frequent cleaning to remove sediment built-up and regular replacement of wick material due to weathering and ultraviolet degradation. Uneven wetting of the wick can result in dry spots that reduce efficiency [19].

In a multiple-tray tilted still, a series of shallow horizontal black trays are enclosed in an insulated container with a transparent glazing on top. The feed-water supply tank is located above the still, and the vapor condenses and flows down to the collection channel and finally to the storage. The construction of this still is fairly complicated and involves many components that are more expensive than simple basin stills. Therefore, the slightly better efficiency it delivers may not justify its adoption [20].

The concentrating mirror solar still uses a parabolic mirror for focusing sunlight onto an evaporator vessel. The water is evaporated in this vessel exposed to extremely high temperature. This type of still entails high construction and maintenance costs [21].

Figure 11 shows four various types of solar stills.

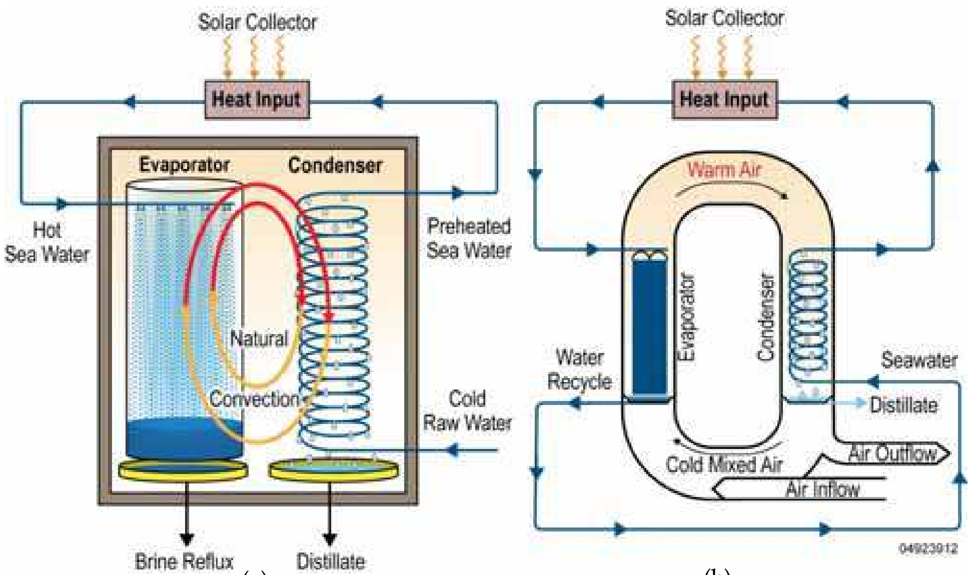
3.1.1.2 Indirect solar thermal desalination

Indirect solar thermal desalination methods involve two separate systems: the collection of solar energy by a solar collecting system, coupled to a conventional desalination unit.

Processes include humidification-dehumidification (HD), membrane distillation (MD), solar pond-assisted desalination, and solar thermal systems such as solar collectors, evacuated-tube collectors, and concentrating collectors (CSP) systems driving conventional desalination processes such as MSF and MED.

Humidification-dehumidification process

These units consist of a separate evaporator and condenser to eliminate the loss of latent heat of condensation. The basic idea in humidification–dehumidification (HD) process is to mix air with water vapor and then extract water from the humidified air by the condenser. The amount of vapor that air can hold depends on its temperature. Some advantages of HD units are the following: low-temperature operations, able to combine with renewable energy sources such as solar energy, modest level of technology, and high productivity rates. Two different cycles are available for HD units: HD units based on open-water closed-air cycle, and HD units based on open-air closed-water cycle. These two options are described below.
Figure12a shows an open-water closed-air cycle. In the process, seawater enters the system, is heated in the solar collector, and is then sprayed into the air in the evaporator. Humidified air is circulated in the system and when it reaches the condenser, a certain amount of water vapor starts to condense. Distilled water is collected in a container. Some of the brine can also be recycled in the system to improve the efficiency, and the rest is removed [22].
Figure12b shows an open-air closed-water cycle, which is used to emphasize recycling the brine through the system to ensure a high utilization of the salt water for freshwater production. As air passes through the evaporator, it is humidified. And by passing through condenser, water vapor is extracted [23].



(a) (b)

Fig. 12. Humidification-dehumidification systems: (a) open-water closed-air cycle, and (b) open-air closed-water cycle (modified from [64].

Membrane distillation

Membrane distillation (MD) is a separation/distillation technique, where water is transported between "hot" and a "cool" stream separated by a hydrophobic membrane, permeable only to water vapor, which excludes the transition of liquid phase and potential dissolved particles. The exchange of water vapor relies on a small temperature difference between the two streams, which results in a vapor pressure difference, leading to the transfer of the produced vapor through the membrane to the condensation surface. Figure 13 is a typical schematic diagram of the process. In the MD process, the seawater passes through the condenser usually at about 25°C and leaves at a higher temperature, and then it is heated to about 80°C by an external source such as solar, geothermal, or industrial waste [24]. The main advantages of membrane distillation lie in its simplicity and the need for only small differentials to operate. However, the temperature differential and the recovery rate determine the overall efficiency for the process. Thus, when it is run with a low temperature differential, large amounts of water must be used, which adversely affects its overall energy efficiency.

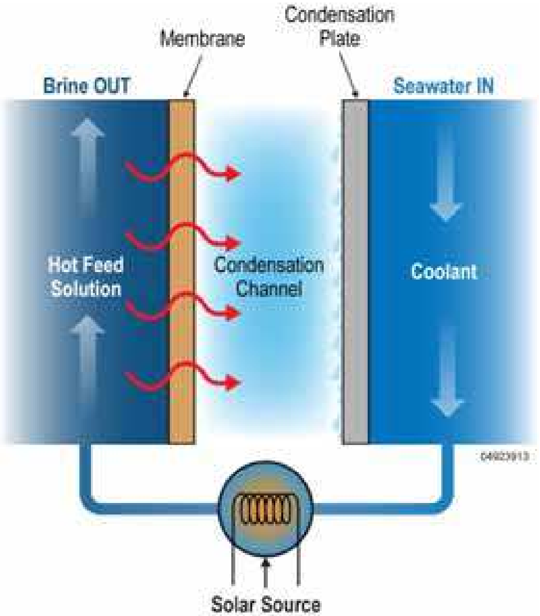


Fig. 13. Schematic of the membrane distillation process.

Membrane desalination is a promising process, especially for situations where low-temperature solar, geothermal, waste, or other heat is available. MD was introduced commercially on a small scale during the 1980s, but it has not demonstrated large-scale commercial success due to the high cost and problems associated with membranes. Therefore, more intensive research and development is needed, both in experimentation and modeling, focusing on key issues such as long-term liquid/vapor selectivity, membrane aging and fouling, feed-water contamination, and heat-recovery optimization. Scale-up studies and realistic assessment of the basic working parameters on real pilot plants, including cost and long-term stability, are also considered to be necessary [25].

Solar ponds-assisted desalination

Salinity-gradient solar ponds are a type of heat collector, as well as a mean of heat storage. Hot brine from a solar pond can be used as a heat source for MSF or MED desalination units. Solar ponds can store heat because of their unique chemically stratified nature. A solar pond has three layers: (1) upper or surface layer, called the upper convection zone, (2) middle layer, which is the non-convection zone or salinity-gradient zone, and (3) lower layer, called the storage zone or lower convection zone. Salinity increases with depth from near pure water at the surface to the bottom, where salts are at or near saturation. Salinity is relatively constant in the upper and lower convection zones, and increases with depth in the non-convection zone. Saline water is denser than fresh water; therefore, the water at the bottom of the pond is more dense (has a higher specific gravity) than water at the surface. The solar pond system is able to store heat because circulation is suppressed by the salinity-related density differences in the stratified water. Convection of hot water to the surface is repressed by the salinity (density) gradient of the non- convection zone. Thus, although solar energy can penetrate the entire depth of the pond, it cannot escape the storage zone [26]. Figure 14 show how a typical MSF unit operates using solar pond brine as a heat source.

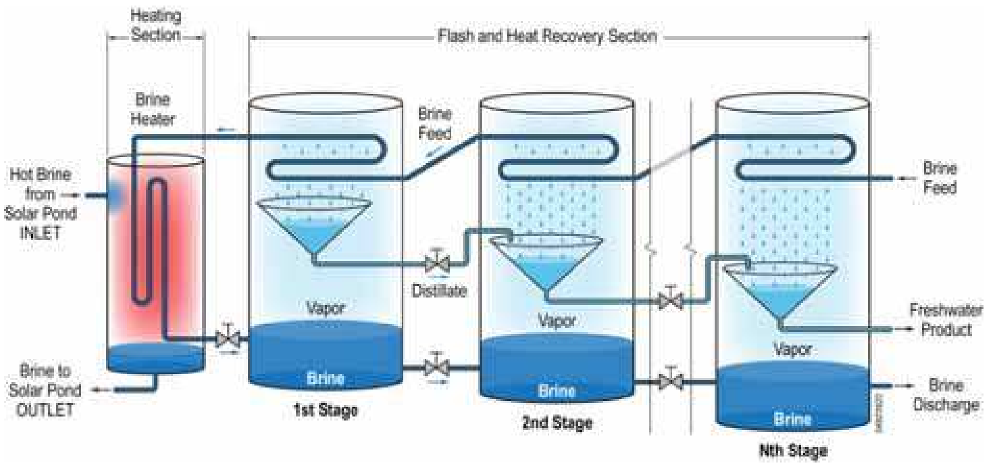
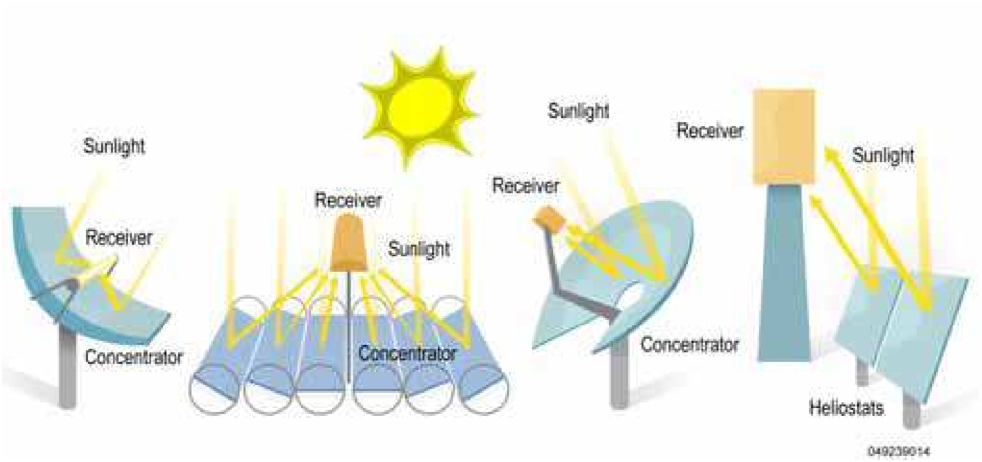


Fig. 14. MSF desalination unit operated by solar pond.

Concentration solar thermal desalination

Concentrating solar thermal power technologies are based on the concept of concentrating solar radiation to provide high-temperature heat for electricity generation within conventional power cycles using steam turbines, gas turbines, or Stirling and other types of engines. For concentration, most systems use glass mirrors that continuously track the position of the sun. The four major concentrating solar power (CSP) technologies are parabolic trough, Fresnel mirror reflector, power tower, and dish/engine systems. Debate continues as to which of these is the most effective technology [27]. Figure 15 shows diagrams of these systems.

Parabolic trough. Parabolic trough power plants consist of large parallel arrays of parabolic trough solar collectors that constitute the solar field. The parabolic collector is made of



(a) (b) (c) (d)

Fig. 15. Solar concentrating systems, (a) parabolic trough, (b) Fresnel lenses, (c) dish engine, and (d) power tower.

reflectors, each of which focuses the sun's radiation on a receiver tube that absorbs the reflected solar energy. The collectors track the sun so that the sun's radiation is continuously focused on the receiver. Parabolic troughs are recognized as the most proven CSP technology, and at present, experts indicate the cost to be 10 US cents/kWh or less.

Fresnel mirror reflector. This type of CSP is broadly similar to parabolic trough systems, but instead of using trough-shaped mirrors that track the sun, flat or slightly curved mirrors mounted on trackers on the ground are configured to reflect sunlight onto a receiver tube fixed in space above these mirrors. A small parabolic mirror is sometimes added atop the receiver to further focus the sunlight. As with parabolic trough systems, the mirrors change their orientation throughout the day so that sunlight is always concentrated on the heat-collecting tube.

Dish/Stirling engine systems and concentrating PV (CPV) systems. Solar dish systems consist of a dish-shaped concentrator (like a satellite dish) that reflects solar radiation onto a receiver mounted at the focal point. The receiver may be a Stirling or other type of engine and generator (dish/engine systems) or it may be a type of PV panel that has been designed to withstand high temperatures (CPV systems). The dish is mounted on a structure that tracks the sun continuously throughout the day to reflect the highest percentage of sunlight possible onto the thermal receiver. Dish systems can often achieve higher efficiencies than parabolic trough systems, partly because of the higher level of solar concentration at the focal point. Dish systems are sometimes said to be more suitable for stand-alone, small power systems due to their modularity. Compared with ordinary PV panels, CPV has the advantage that smaller areas of PV cells are needed; because PV is still relatively expensive, this can mean a significance cost savings.

Power tower. A power tower system consists of a tower surrounded by a large array of heliostats, which are mirrors that track the sun and reflect its rays onto the receiver at the top of the tower. A heat-transfer fluid heated in the receiver is used to generate steam, which, in turn, is used in a conventional turbine generator to produce electricity. Some power towers use water/steam as the heat-transfer fluid. Other advanced designs are experimenting with molten nitrate salt because of its superior heat-transfer and energy-storage capabilities. Power towers also reportedly have higher conversion efficiencies than parabolic trough systems. They are projected to be cheaper than trough and dish systems, but a lack of commercial experience means that there are significant technical and financial risks in deploying this technology now. As for cost, it is predicted that with higher efficiencies, 7–8 cents/kWh may be possible. But this technology is still in its early days of commercialization.

CSP systems coupled with desalination plant

The primary aim of CSP plants is to generate electricity, yet a number of configurations enable CSP to be combined with various desalination methods. When compared with photovoltaics or wind, CSP could provide a much more consistent power output when combined with either energy storage or fossil-fuel backup. There are different scenarios for using CSP technology in water desalination [28], and the most suitable options are described below.

Parabolic trough coupled with MED desalination unit. Figure 16 shows a typical parabolic trough configuration combined with a MED system, where steam generated by the trough (superheated to around 380^{o}C) is first expended in a non-condensing turbine and then used in a conventional manner for desalination. The steam temperature for the MED plant is around 135^{o}C; therefore, there is sufficient energy in the steam to produce electricity before it is used in the MED plant. It is important to emphasize that water production is the main purpose of the plant—electricity is a byproduct. Although conventional combined-cycle

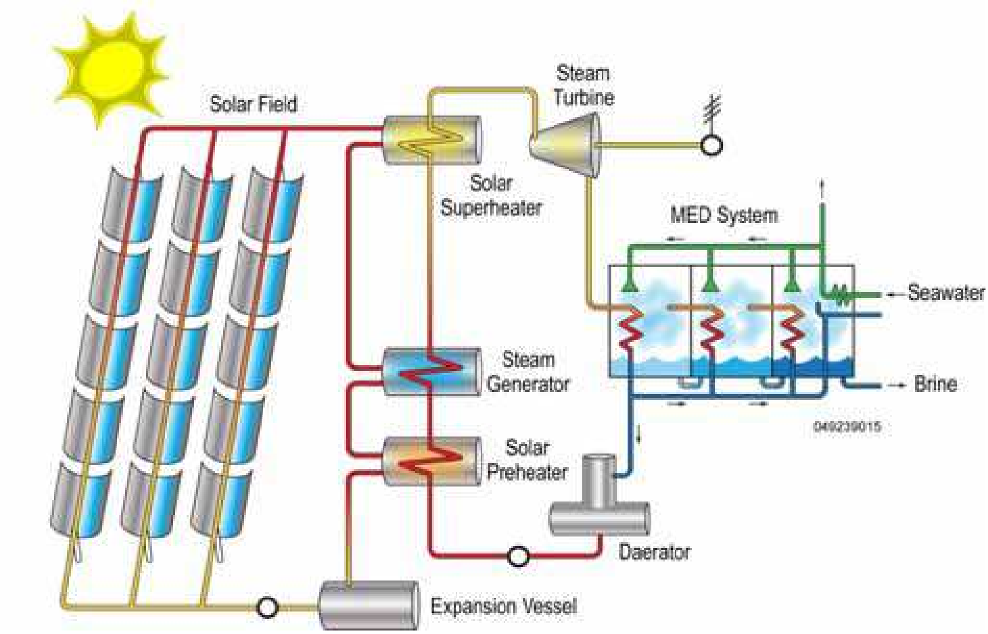


Fig. 16. Parabolic trough power plant with oil steam generator and MED desalination (Source: Bechtel Power)

(CC) power plants can be configured in a similar manner for desalination, a fundamental difference exists in the design approach for solar and for fossil-fuel-fired plants. The fuel for the solar plant is free; therefore, the design is not focused primarily on efficiency but on capital cost and capacity of the desalination process. In contrast, for the CC power plant, electricity production at the highest possible efficiency is the ultimate goal [29].

Parabolic trough coupled with RO desalination unit. In this case, as in MED, the steam generated by the solar plant can be used through a steam turbine to produce the electric power needed to drive the RO pumps. As an alternative for large, multi-unit RO systems, the high-pressure seawater can be provided by a single pump driven by a steam turbine. This arrangement is similar to the steam-turbine-driven boiler feed pumps in a fossil-fuel power plant. Often, MED and RO are compared in terms of overall performance, and specifically for energy consumption. Based on internal studies by Bechtel [30], one can conclude that in specific cases, the CSP/RO combination (see Fig. 17) requires less energy than a similar CSP/MED combination.

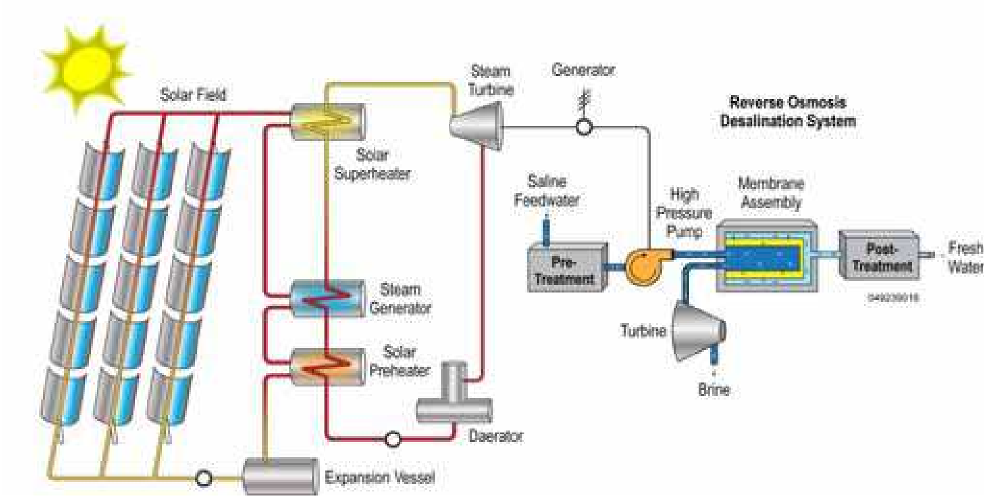


Fig. 17. Parabolic trough coupled with seawater RO desalination unit (modified from Bechtel Power)

However, an analysis presented in [31] suggests that, for several locations, CSP/MED requires 4% to 11% less input energy than CSP/RO. Therefore, before any decision can be made on the type of desalination technology to be used, we recommend that a detailed analysis be conducted for each specific location, evaluating the amount of water, salinity of the input seawater, and site conditions. It appears that CSP/MED provides slightly better performance at sites with high salinity such as in closed gulfs, whereas CSP/RO appears to be more suitable for low-salinity waters in the open ocean.

One additional advantage of the RO system is that the solar field might be located away from the shoreline. The only connection between the two is the production of electricity to drive the RO pumps and other necessary auxiliary loads.

3.1.1.3 Solar thermal applications

Although the strong potential of solar thermal energy to seawater desalination is well recognized, the process is not yet developed at the commercial level. The main reason is that the existing technology, although demonstrated as technically feasible, cannot presently compete, on the basis of produced water cost, with conventional distillation and RO technologies. However, it is also recognized that there is still potential to improve desalination systems based on solar thermal energy.

Among low-capacity production systems, solar stills and solar ponds represent the best alternative in low fresh water demands. For higher desalting capacities, one needs to choose conventional distillation plants coupled to a solar thermal system, which is known as indirect solar desalination [32]. Distillation methods used in indirect solar desalination plants are MSF and MED. MSF plants, due to factors such as cost and apparent high efficiency, displaced MED systems in the 1960s, and only small-size MED plants were built. However, in the last decade, interest in MED has been significantly renewed and the MED process is currently competing technically and economically with MSF [33]. Recent advances in research of low-temperature processes have resulted in an increase of the desalting capacity and a reduction in the energy consumption of MED plants providing long-term operation under remarkable steady conditions [34]. Scale formation and corrosion are minimal, leading to exceptionally high plant availabilities of 94% to 96%.

Many small systems of direct solar thermal desalination systems and pilot plants of indirect solar thermal desalination systems have been implemented in different places around the world [35]. Among them are the de Almería (PSA) project in 1993 and the AQUASOL project in 2002. Study of these systems and plants will improve our understanding of the reliability and technical feasibility of solar thermal technology application to seawater desalination. It will also help to develop an optimized solar desalination system that could be more competitive against conventional desalination systems. Table 2 presents several of the implemented indirect solar thermal pilot systems.

Plant Location	Year of Commission	Water Type	Capacity (L/hr)	RES Installed Power	Unit Water Cost (US$/m^3)
Almeria, Spain, CIEMAT	1993	SW	3000	2.672 m^2 solar collector area	3.6-4.35
Hazeg, Sfax, Tunisia	1988	BW	40-50	80 m^2 solar collector area	25.3
Pozo Izquierdo, Gran Canaria, SODESA Project	2000	SW	25	50 m^2 solar collector area	-
Sultanate of Oman, MEDRC Project	2002	SW	42	5.34 m^2 solar collector area	-
AQUASOL Project	2002	SW	3000	14 cells of parabolic concentrator	-

SW: seawater, BW: brackish water

Table 2. Solar thermal distillation plants

On a commercial basis, CSP technology will take many years until it becomes economic and sufficiently mature for use in power generation and desalination.

3.2 Solar PV desalination

General description of a PV system

A photovoltaic or solar cell converts solar radiation into direct-current (DC) electricity. It is the basic building block of a PV (or solar electric) system. An individual PV cell is usually quite small, typically producing about 1 or 2 watts of power. To boost the power output, the solar cells are connected in series and parallel to form larger units called modules. Modules, in turn, can be connected to form even larger units called arrays. Any PV system consists of a number of PV modules, or arrays. The other system equipment includes a charge controller, batteries, inverter, and other components needed to provide the output electric power suitable to operate the systems coupled with the PV system. PV systems can be classified into two general categories: flat-plate systems and concentrating systems. CPV system have several advantages compared to flat-plate systems: CPV systems increase the power output while reducing the size or number of cells needed; and a solar cell's efficiency increases under concentrated light.
Figure 18 is a schematic diagram of a PV solar system that has everything needed to meet a particular energy demand, such as powering desalination units.

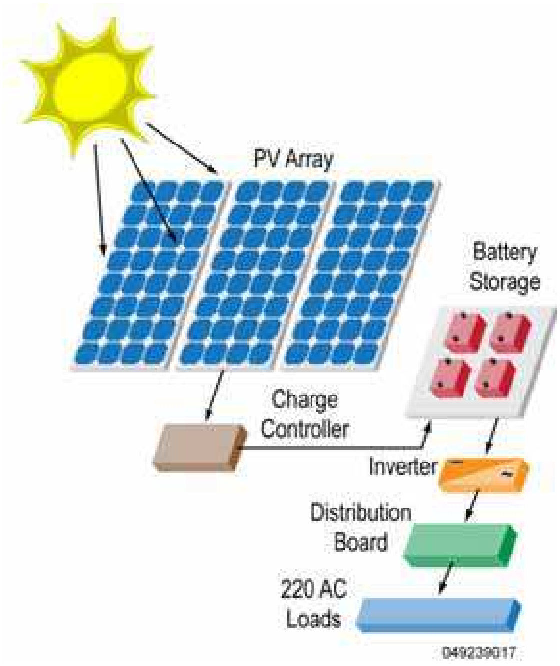


Fig. 18. Schematic of a typical photovoltaic system.

Typical PV system driving RO-ED units

PV is a rapidly developing technology, with costs falling dramatically with time, and this will lead to its broad application in all types of systems. Today, however, it is clear that PV/RO and PV/ED will initially be most cost competitive for small-scale systems installed in remote areas where other technologies are less competitive. RO usually uses alternating current (AC) for the pumps, which means that DC/AC inverters must be used. In contrast, ED uses direct current for the electrodes at the cell stack, and hence, it can use the energy supply from the PV panels without major modifications. Energy storage is again a concern, and batteries are used for PV output power to smooth or sustain system operation when solar radiation is insufficient.

PV/RO systems applications

PV-powered reverse osmosis is considered one of the most promising forms of renewable-energy-powered desalination, especially when it is used in remote areas. Therefore, small-scale PV/RO has received much attention in recent years and numerous demonstration systems have been built. Figure 19 is a schematic diagram of a PV/RO system. Two types of PV/RO systems are available in the market: brackish-water (BWRO) and seawater (SWRO) PV/RO systems. Different membranes are used for brackish water and much higher recovery ratios are possible, which makes energy recovery less critical [36].

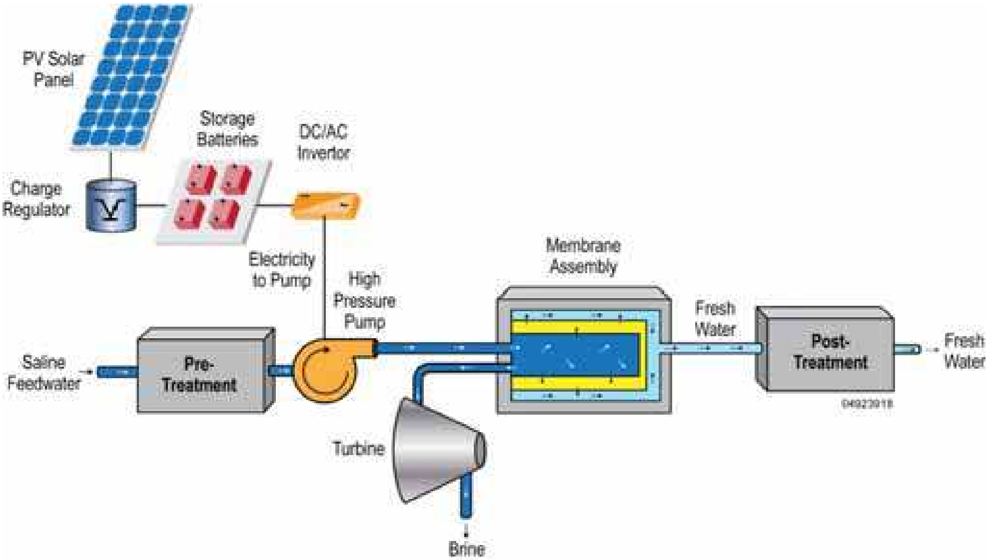


Fig. 19. Schematic of a PV/RO system.

Brackish water PV/RO systems

Brackish water has a much lower osmotic pressure than seawater; therefore, its desalination requires much less energy and a much smaller PV array in the case of PV/RO. Also, the lower pressures found in BWRO systems permit the use of low-cost plastic components. Thus, the total cost of water from brackish water PV/RO is considerably less than that from seawater, and systems are beginning to be offered commercially [37]. Table 3 presents information on installed brackish water PV/RO systems [38–42]. Many of the early PV/RO demonstration systems were essentially a standard RO system, which might have been designed for diesel or mains power, but powered from batteries charged by PV. This approach generally requires a rather large PV array for a given flow of product because of poor efficiencies in the standard RO systems and batteries. Large PV arrays and the regular replacement of batteries typically make the cost of water from such systems rather high.

Location	Feedwater (ppm)	Capacity (m^3/day)	PV (kWp)	Batteries (kWh)	Energy Consumption (kWh/m^3)	Water Cost (US$/$m^3$)	Year
Sadous, Riyadh, SA	5,800	15	10.08	264			1994
Magan, Isreal	4,000	3	3.5+0.6 wind	36		11.6	1997
Elhamarawien, Egypt	3,500	53	19.8+0.64 control	208	0.89		1986
Heelafar Rahab Oman	1,000	5	3.25	9.6		6.25	1995
White Cliffs, Australia	3,500	0.5	0.34	none	2-8		
Solar flow, Australia	5,000	0.4	0.12	none	1.86	10–12	
Hassi-Kheba, Algeria	3,200	0.95	2.59			10	
INETI, Lisbon, Portugal	5,000	0.1–0.5	0.05–0.15	none			2000
Conception del Oro, Mexico	3,000	0.71	2.5	none	6.9		1982
Thar desert, India	5,000	1	0.45		1 kWh/kg salt		1986
Perth, Australia	BW	0.4–0.7	1.2		4-5.8		1989
Gillen Bore, Australia	1,600	1.2	4.16	none			1996
Wano Road, Australia	BW		6				
Kasir Ghilen, Tunis	5,700	50				7.25	2006
Coite-Pedreias, Brazil	BW	0.25	1.1	9.6	3–4.7	14.9	
Mesquite, Nevada	3,500	1.5	0.4		1.38	3.6	2003
N. Jawa, Indonesia	BW	12	25.5				
Univ. of Almeria, Spain	BW	2.5	23.5				

Table 3. Brackish water RO plants driven by PV power

Seawater PV/RO application systems

The osmotic pressure of seawater is much higher than that of brackish water; therefore, its desalination requires much more energy, and, unavoidably, a somewhat larger PV array. Also, the higher pressures found in seawater RO systems require mechanically stronger components. Thus, the total cost of water from seawater PV/RO is likely to remain higher than that from brackish water, and systems have not yet passed the demonstration stage. Table 4 shows some of the installed seawater PV/RO plants [38–42].

Location	Feedwater (ppm)	Capacity (m^3/day)	PV (kWp)	Batteries (kWh)	Energy Consumption (kWh/m^3)	Water Cost (US$/$m^3$)	Year
Lampedusa, Italy	SW	40	100	880	5.5	9.5	1990
Jeddah, S. Arabia	42,800	3.2	8				1981
St. Luice, FL	32,000	0.64	2.7		13		1995
Doha, Qatar	35,000	5.7	11.2	none	10.6		
Cress, Laviro, Greece	36,000	< 1	4+ 0.9 wind	44		33	2001
ITC Canaries Island, Spain	SW	3	4.8	19	5.5	13	1998
Crest, UK	SW	0.5 L/h	1.54	none		4.2	2003
Vancouver, Canada	SW	0.5–1.0	0.48				
Ponta Libeco, Italy	SW		9.8				1993

Table 4. Seawater RO plants driven by PV power.

PV/ED applications

ED uses DC for the electrodes; therefore, the PV system does not include an inverter, which simplifies the system. Figure 20 shows a schematic diagram of a PV-powered ED system. Currently, there are several installations of PV/ED technology worldwide. All PV/RD applications are of a standalone type, and several interesting examples are discussed below.

In the city of Tanote, in Rajasthan, India, a small plant was commissioned in 1986 that features a PV system capable of providing 450 peak watts (W_p) in 42 cell pairs. The ED unit includes three stages, producing 1 m^3/d water from brackish water (5000 ppm TDS). The unit energy consumption is 1 kWh/kg of salt removed [43]. A second project is a small experimental unit in Spencer Valley, New Mexico (USA), where two separate PV arrays are used: two tracking flat-plate arrays (1000 W_p power, 120 V) with DC/AC inverters for pumps, plus three fixed arrays (2.3 kW_p, 50 V) for ED supply. The ED design calls for 2.8 m^3/d product water from a feed of about 1000 ppm TDS. This particular feed water contains uranium and radon, apart from alpha particles. Hence, an ion-exchange process is required prior to ED. Unit consumption is 0.82 kWh/m^3 and the reported cost is 16 US$/$m^3$ [44-45]. A third project is an unusual application in Japan, where PV technology is used to drive an ED plant fed with seawater, instead of the usual brackish water of an ED system [46]. The solar field consists of 390 PV panels with a peak power of 25 kW_p, which can drive a 10 m^3/d ED unit. The system, located on Oshima Island (Nagasaki), has been operating since 1986. Product-water quality is reported to be below 400 ppm TDS, and the ED stack is provided with 250 cell pairs.

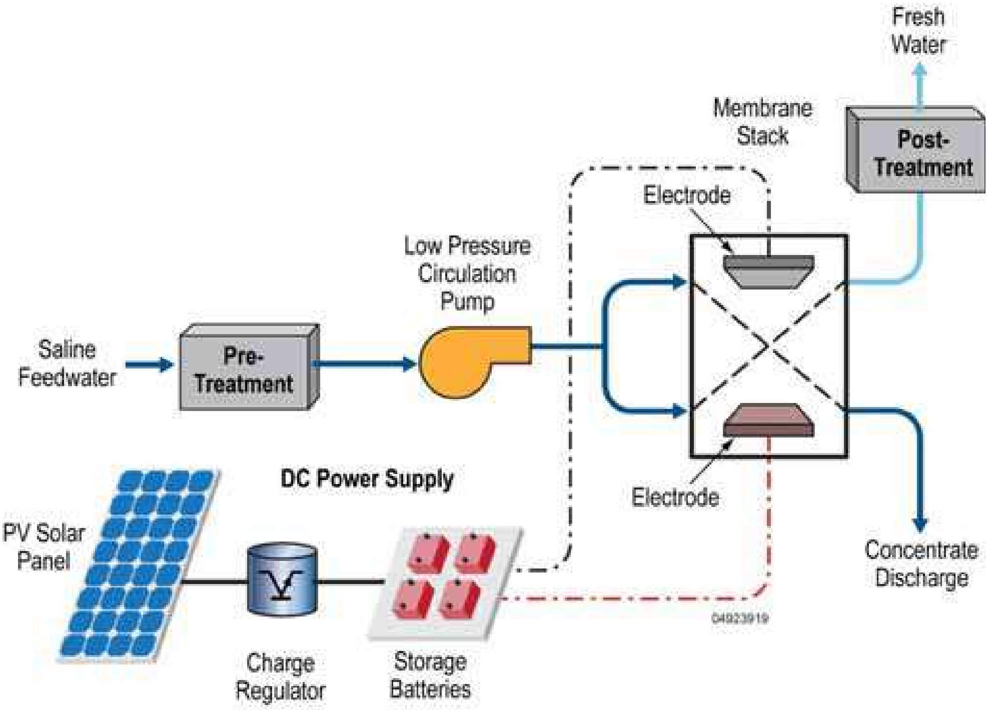


Fig. 20. Shows a schematic diagram of a PV-powered ED system.

3.3 Desalination systems driven by wind

Wind turbines can be used to supply electricity or mechanical power to desalination plants. Like PV, wind turbines represent a mature, commercially available technology for power production. Wind turbines are a good option for water desalination especially in coastal areas presenting a high availability of wind energy resources. Many different types of wind turbines have been developed. A distinction can be made between turbines driven mainly by drag forces versus those driven mainly by lift forces. As shown in Fig. 21, a distinction can also be made between turbines with axes of rotation parallel to the wind direction (horizontal) and with axes perpendicular to the wind direction (vertical). The efficiency of wind turbines driven primarily by drag forces is low compared with the lift-force-driven type. Therefore, all modern wind turbines are driven by lift forces. The most common types are the horizontal-axis wind turbine (HAWT) and the vertical-axis wind turbine (VAWT).

Wind-driven desalination has particular features due to the inherent discontinuous availability of wind power. For standalone systems, the desalination unit has to be able to adapt to the energy available; otherwise, energy storage or a backup system is required. Wind energy is used to drive RO, ED, and VC desalination units. A hybrid system of wind/PV is usually used in remote areas. Few applications have been implemented using wind energy to drive a mechanical vapor compression (MVC) unit. A pilot plant was installed in 1991 at Borkum, an island in Germany, where a wind turbine with a nominal power of 45 kW was coupled to a 48 m^3/day MVC evaporator. A 36-kW compressor was

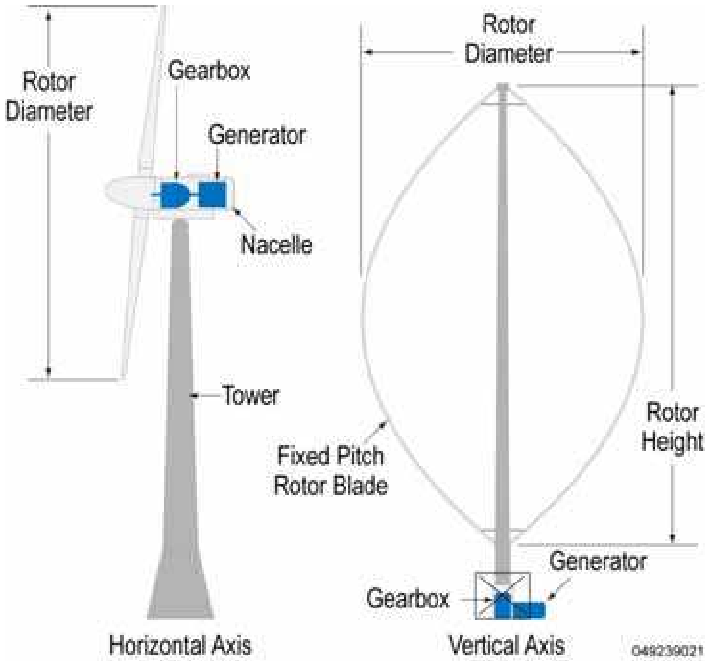


Fig. 21. Presents the horizontal and vertical wind turbine configurations.

required. The experience was followed in 1995 by another larger plant at the island of Ru¨ gen. Additionally, a 50 m^3/day wind MVC plant was installed in 1999 by the Instituto Tecnologico de Canarias (ITC) in Gran Canaria, Spain, within the Sea Desalination Autonomous Wind Energy System (SDAWES) project [47]. The wind farm is composed of two 230-kW wind turbines, a 1500-rpm flywheel coupled to a 100-kVA synchronous machine, an isolation transformer located in a specific building, and a 7.5- kW uninterruptible power supply located in the control dome. One of the innovations of the SDAWES project, which differentiates it from other projects, is that the wind generation system behaves like a mini power station capable of generating a grid similar to conventional ones without the need to use diesel sets or batteries to store the energy generated.

Regarding wind energy and RO combinations, a number of units have been designed and tested. As early as 1982, a small system was set at Ile du Planier, France [48], which as a 4-kW turbine coupled to a 0.5-m^3/h RO desalination unit. The system was designed to operate via either a direct coupling or batteries. Another case where wind energy and RO were combined is that of the Island of Drenec, France, in 1990 [48]. The wind turbine, rated at 10 kW, was used to drive a seawater RO unit. A very interesting experience was gained at a test facility in Lastours, France, where a 5-kW wind turbine provides energy to a number of batteries (1500 Ah, 24 V) and via an inverter to an RO unit with a nominal power of 1.8 kW. A 500 L/h seawater RO unit driven by a 2.5-kW wind generator (W/G) without batteries was developed and tested by the Centre for Renewable Energy Systems Technology (CREST) UK. The system operates at variable flow, enabling it to make efficient use of the naturally varying wind resource, without need of batteries [49].

Excellent work on wind/RO systems has been done by ITC within several projects such as AERODESA, SDAWES, and AEROGEDESA[50]. Additionally, a wind/RO system without energy storage was developed and tested within the JOULE Program (OPRODES-JORCT98-0274) in 2001 by the University of Las Palmas. The RO unit has a capacity of 43–113 m^3/h, and the W/G has a nominal power of 30 kW [51]. In addition, an excellent job on combining wind/RO was done by ENERCON, the German wind turbine manufacturer. ENERCON provides modular and energy-efficient RO desalination systems driven by wind turbines (grid-connected or standalone systems) for brackish and seawater desalination. Market-available desalination units from ENERCON range from 175 to 1400 m^3/day for seawater desalination and 350 to 2800 m^3/day for brackish water desalination. These units in combination with other system components, such as synchronous machines, flywheels, batteries, and diesel generators, supply and store energy and water precisely according to demand [52]. Table 5 shows several existing wind/RO installations.

Plant Location	Year of Commission	Water Type	Capacity (L/h)	W/T Nominal Power (kW)	Unit Water Cost ($/m³)
Ile de Planier, France	1983	SW/BW	500	4	-
Fuerteventura island, PUNTA JANDIA project	1995	SW	2,333	225	-
Therasia island, Greece	1997	SW	200	15	-
Pozo Izquierdo, Gran Canaria, AEROGEDESA project	2003	SW	800	15	4.4 -7.3
CREST, UK	2004	SW	500	2.5	2.6

Table 5. Installed wind/RO plants

3.4 Geothermal energy

The earth's temperature varies widely, and geothermal energy is usable for a wide range of temperatures from room temperature to well over 300°F. The main advantage of geothermal energy is that thermal storage is unnecessary in such systems. Geothermal reservoirs are generally classified as being either low temperature (<150°C) or high temperature (>150°C). Generally speaking, high-temperature reservoirs are suitable for, and sought out for, commercial production of electricity. Energy from the earth is usually extracted with ground heat exchangers, made of a material that is extraordinarily durable but allows heat to pass through efficiently. The direct use of moderate and high temperatures is for thermal desalination technologies. A high-pressure geothermal source allows the direct use of shaft power on mechanically driven desalination, whereas high-temperature geothermal fluids can be used to generate electricity to drive RO or ED plants.

The first geothermal energy-powered desalination plants were installed in the United States in the 1970s [53–57], testing various potential options for the desalination technology, including MSF and ED. An analysis [58] discussing a technical and economic analysis of an MED plant, with a capacity of 80 m^3/d, powered by a low-temperature geothermal source and installed in Kimolos, Greece showed that high temperature geothermal desalination could be a viable option. A study [59] presented results from an experimental investigation of two polypropylene-made HD plants powered by geothermal energy [60]. Recently, a study [61] discussed the performances of a hybrid system consisting of a solar still in which the feed water is brackish underground geothermal water. Finally, the availability and/or suitability of geothermal energy and other renewable energy resources for desalination is given by [62].

4. General economic assessment of desalination

The cost of desalinated water is usually expressed in US$ per cubic meter of product water. This figure is obtained by dividing the sum of all expenses (capital cost, plus operation and maintenance cost) related to the production of desalinated water by the total amount of desalted water produced. Capital cost includes both direct and indirect costs. Direct capital costs are the land cost, building cost, and all equipment costs. Indirect capital costs include freight, insurance, construction overhead, engineering and legal fees, and contingencies costs. Costs of energy, labor, chemicals, consumables, spare parts, and major replacements or refurbishment required over the lifetime of the plant are included in operational and maintenance costs.

The economies of desalination and the decision as to which approach to select depend on situation-specific parameters. Because energy is the main driver in the cost of operation, economic feasibility of either approach to desalination is highly correlated to the location-specific cost and availability of energy [63]. Table 6 presents a comparative illustration of cost distribution and energy share of total cost for the two widely used conventional systems (RO and MSF) installed in Libya with a capacity of 10 mgbd each.

Type of Plant	Capital Cost (%)	Energy Cost (%)	Maintenance and Repair Cost (%)	Membrane Replacement (%)	Labor (%)	Chemicals (%)
RO	31	26	14	13	9	7
MSF	42	41	8	0	7	2

Table 6. Percentage of cost for conventional systems

In the representative example above, the capital cost is considerably higher for the thermal process than for the membrane process. This reflects the prevailing situation in the desalination industry, in which the construction cost of thermal desalination plants exceeds that of membrane plants. All other main costs related to operating a desalination plant are usually higher for a membrane processes due to the greater complexity of maintenance tasks and operation. Accordingly, cost of chemicals is 7% vs. 2%, maintenance and parts are 14% vs. 7%, and labor cost is 9% vs. 7% of total operating cost for the representative RO and MSF plants, respectively. Membrane replacement, which is listed separately, adds further to the maintenance cost for RO, whereas this cost is obviously absent for thermal processes.

Strong inter-firm competition and advances in technology have resulted in average annual unit cost reductions of close to 6% for MSF processes since 1970. In addition, many MSF desalination plants, which are mostly located in the Middle East, have increasingly taken advantage of economies of scale. RO, which has been used commercially only since 1982, has seen even steeper cost declines since inception. Membrane costs have fallen by 86% between 1990 and 2002 [64]. Steeply declining maintenance cost, in combination with relatively low capital cost, has contributed greatly to the rapidly growing success of membrane technology.

The unit product cost of fresh water differs when it is produced from different plant capacities. Table 7 shows the unit product cost of water produced from plants of different type and capacity. Product unit prices generally take into account all relevant costs originating from direct capital, indirect capital, and annual operating costs.

Type of system and capacity (mgbd)	Product Cost ($/gallon)
MVC (0.03)	1.894
MVC (0.13)	1.220
MVC (1.06)	0.939
MVC (1.20)	0.920
MVC (5.28)	0.174
MSF (7.13-Dual purpose)	0.292
MSF (7.13-Single purpose)	0.621
MSF (Gas turbine, Waste heat boiler)	0.545
MSF (9.99)	0.473
MED (6-Dual purpose)	0.330
MED (6-Single purpose)	0.739
MED (9.99)	0.409
MED (Gas turbine, Waste boiler)	0.496
RO (5.28, Single stage)	0.242
RO (5.28, Two stage)	0.288
RO (0.03)	0.898
RO (1.06)	0.750
RO (1.20)	0.489
RO (9.99)	0.413
RO (30)	0.208
MED- TVC (Single purpose)	0.866
MED- TVC (Dual purpose)	0.496

Table 7. Fresh water cost for different types and capacities

Economic analysis for renewable energy desalination processes

The economics of operating solar desalting units tend to be related to the cost of producing energy with these alternative energy devices. Presently, most of the renewable energy systems have mature technology; but despite the free cost of renewable energy resources, their collecting systems tend to be expensive, although they may be expected to decline as further development of these devices reduces their capital cost. The economic aspects of each renewable energy desalination system will be discussed below.

We first look at the cost distribution of both conventional and renewable energy-operated desalination units. Table 8 shows the comparison of cost distribution for conventional systems (RO and MSF) and plants driven by a renewable energy system [65]. For the renewable systems, the investment costs are the highest and the energy costs are the lowest.

Type of Process	Capital Costs (%)	Operational Costs (%)	Energy Costs (%)
Conventional (RO)	22 – 27	14 – 15	59 – 63
Conventional (MSF)	25 – 30	38 – 40	33 – 35
Renewable	30 – 90	10 – 30	0 -10

Table 8. Distribution of costs for conventional (RO and MF) desalination systems and for systems driven by renewable energy technology

One study has considered the techno-economic viability of solar desalination using PV and low-grade thermal energy using solar ponds [66]. Table 9 presents a comparison of the cost of water produced by a conventional cogeneration system (producing electricity and water) and that of solar-powered MSF and RO systems. The figures in the table are based on a plant capacity of 1 m^3/d and an annual utilization factors of 90% for conventional systems and 75% for solar-based systems.

Parameter	MSF		
	Conventional System	Partial Solar-based System	Complete Solar-based System
Annual Water Production (m^3)	328	274	274
Cost of Water Production ($\$/m^3$)	1.75	1.79	2.84
	RO		
	Conventional System	Partial Solar-based System	Complete Solar-based System
Annual Water Production (m^3)	328	274	274
Cost of Water Production ($\$/m^3$)	1.30	5.70	12.05

Table 9. Cost of desalinated water using conventional and solar-powered MSF and RO systems

The results in Table 9 show that the cost of water produced by a conventional RO system is less than that by a conventional MSF system. However, for solar-based systems, the partial solar-based MSF system gives the lowest cost of water production.

Solar thermal desalination economics

Solar still economic

Because of limited capacity of solar units, the capital costs and operating costs are not as well established as for the other processes. For solar stills, the cost of water production is high due to the low productivity of these stills. However, this type of desalination is only used in remote areas where there is no access to conventional energy resources. Table 10 compares the water costs for simple and multi-effect solar stills [66]. As shown, the water costs for multi-effect solar stills are much lower than for simple stills.

Solar-assisted desalination systems

One study [67] showed that solar-pond desalting systems have considerable potential to be cost effective if favorable site conditions exist. Table 11 presents the cost comparison of solar-pond-powered desalination with conventional seawater RO (SWRO) for two production capacities (20,000 and 200,000 m^3/d). As seen from the table, the unit water-cost difference is relatively small. However, investment costs and specific investment cost for solar-powered systems are still higher compared with the SWRO systems, where the difference decreases as the capacity increases.

Type	Capacity / Productivity	Water Cost ($/m³)	Description	Reference
Solar Stills	4 L/m²d	23.80	20 yrs lifetime, collector cost: $315/m², 5% interest rate	66
Multi-effect Stills	12 L/m²d	9.95	Storage module, 20 year lifetime, 5% interest rate	66
Multi-effect Stills	20 L/m²d	< 9.0*	Non-corroding polymer absorbers, storage, 24-hour operation	66

*Predicted

Table 10. Water costs for simple and multi-effect solar stills

System Type	SWRO		SP-MED		SP-HYB	
	Capacity (m³/d)					
	20,000	200,000	20,000	200,000	20,000	200,000
Investment (mil/$)	20	160	48	380	32	250
Specific Investment ($/m³d)	1000	800	2400	1900	1600	1250
Unit Water Cost ($/m³)	0.77	0.66	0.89	0.71	0.79	0.65

Table 11. Cost comparison of solar pond-powered desalination with conventional SWRO

Using CSP systems with desalination is still in its experimental stage until now but from the several pilot plant projects results, it could be concluded that we need time for this technology to be economically competitive with other desalination technologies.

PV/RO system economics

Cost figures for desalination have always been difficult to obtain. The total cost of water produced includes the investment cost, as well as the operating and maintenance cost. In a comparison between seawater and brackish water desalination, the cost of the first is about 3–5 times the cost of the second for the same plant size. As a general rule, a seawater RO unit has low capital cost and significant maintenance cost due to the high cost of the membrane replacement. The cost of the energy used to drive the plant is also significant. The major energy requirement for RO desalination is for pressurizing the feed water. Energy requirements for SWRO have been reduced to about 5 kWh/m³ for large units with energy recovery systems, whereas for small units (without energy recovery system), this may exceed 15 kWh/m³. For brackish water desalination, the energy requirement is between 1 and 3 kWh/m³. The product water quality ranges between 350 and 500 ppm for both seawater and brackish water units. According to published reports [38–42], the water cost of a PV seawater RO unit ranges from 7.98 to 29 US$/m³ for product-water capacity of 120–12 m³/day, respectively. Also for a PV/RO brackish-water desalination unit, a water cost of about 7.25 US$/m³ for a product-water capacity of 250 m³/day has been reported in the literature [38–42].

PV/ED economics

In general, electrodialysis is an economically attractive process for low-salinity water. EDR has greater capital costs than ED because it requires extra equipment (e.g., timing controllers, automatic valves), but it reduces or almost eliminates the need for chemical pretreatment. In ED applications, the electricity from a PV system can power to electro-mechanical devices such as pumps or to DC devices such as electrodes. The total energy consumption of an ED system under ambient temperature conditions and assuming product water of 500 ppm TDS would be about 1.5 and 4 kWh/m^3 for a feed water of 1500–3500 ppm TDS, respectively. The water cost of a PV-operated ED unit ranges from 16 to 5.8 US$/m^3 [45–46]. The main advantage of PV desalination systems is the ability to develop small-scale desalination plants.

Wind-Renewable Energy economics

Wind energy could be used to drive RO, ED, and VC desalination units. A hybrid system of wind/PV was also used in remote areas. Few applications have been implemented using wind energy to drive a mechanical vapor compression unit, and a number of wind/RO combinations systems have been designed and tested. ENERCON provides modular and energy-efficient RO desalination systems driven by wind turbines for brackish and seawater desalination. The estimated water cost produced from the installed wind/RO unit ranges from 7.2 to 2.6 US$/m^3 of fresh water. According to a published report [68], the water cost of a wind brackish water RO unit (capacity of 250 m^3/day) is of the order of 2 Euro/m^3, whereas for the same feed-water salinity and size, the water cost of a wind/electrodialysis unit is around 1.5 Euro/m^3. For standalone wind-powered MVC units with a capacity range between 5 and12.5 m^3/h, the mean water cost varies between 3.07 and 3.73 Euro/m^3 [69].

5. Conclusion

Desalination technology has been in continuous development during the previous decades, making it possible to include salt water as part of the production of fresh water. However, the current cost of desalinated water is still high because of its extensive use of energy. The selection of a desalination process should be based on a careful study of the specific site conditions and applications. Local circumstances may play a significant role in determining the most appropriate process for an area. The use of renewable energy for desalination is a technically mature option toward emerging energy and water problems. And technological advances will continue to improve system efficiencies and reduce capital costs, making these systems competitive when used in desalination systems. Currently, the cost of fresh-water production from renewable-energy-powered desalinated systems is less than other alternatives in remote areas where access to electricity is not available. Numerous studies on a suitable technical match between renewable energy and desalination process have been reported in the literature. These studies conclude that renewable-energy-powered systems could compete with conventional systems under certain circumstances. Very few solar desalination plants have been reported in the literature. Several studies on a suitable technical match between renewable energy resources and desalination processes propose that solar thermal/MED, solar thermal/MSF, solar PV/RO, solar PV/ED, wind/RO, and geothermal/MED technologies are very promising options. The economic competitiveness of solar thermal/MED and solar thermal/MSF has been shown in a number of theoretical studies. However, this has not been verified experimentally, and therefore, cannot be used as a guide for decision-making regarding technology selection for a particular application. At present, small-scale PV and wind desalination systems appear to be especially suitable in remote regions without access to the electric grid and where water scarcity is a major problem. The large scale of these systems is hindered by non-technical barriers.

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The book comprises 14 chapters covering all the issues related to water desalination. These chapters emphasize the relationship between problems encountered with the use of feed water, the processes developed to address them, the operation of the required plants and solutions actually implemented. This compendium will assist designers, engineers and investigators to select the process and plant configuration that are most appropriate for the particular feed water to be used, for the geographic region considered, as well as for the characteristics required of the treated water produced. This survey offers a comprehensive, hierarchical and logical assessment of the entire desalination industry. It starts with the worldwide scarcity of water and energy, continues with the thermal - and membrane-based processes and, finally, presents the design and operation of large and small desalination plants. As such, it covers all the scientific, technological and economical aspects of this critical industry, not disregarding its environmental and social points of view. One of InTech's books has received widespread praise across a number of key publications. Desalination, Trends and Technologies (Ed. Schorr, M. 2011) has been reviewed in Corrosion Engineering, Science & Technology – the official magazine for the Institute of Materials, Minerals & Mining, and Taylor & Francis's Desalination Publications. Praised for its “multi-faceted content [which] contributes to enrich it,” and described as “an essential companion...[that] enables the reader to gain a deeper understanding of the desalination industry,” this book is testament to the quality improvements we have been striving towards over the last twelve months.

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