ABSTRACT

Two main technologies are used in water desalination: thermal distillation (phase-change) processes and membrane processes. The thermal distillation processes include multistage flash distillation, multi-effect distillation, and vapor compression. The common membrane desalination processes are reverse osmosis and electrodialysis. In thermal distillation processes, two energy forms are required for operation. The first is heat, which represents the main portion of the energy input and is usually supplied to the system by a number of external sources. The second is electricity, which drives the system’s pumps and other electrical components. For membrane processes, only electricity is required as an energy input. This paper overviews the technical and economics of the main desalination processes. It also discusses renewable energy (thermal and electrical) as viable options for renewable energy-driven desalination installations. Power consumption and current projected cost of water produced from each process are discussed and compared.

1. INTRODUCTION

Desalination is a technology that removes salt and other minerals from feed water such as seawater, underground brackish water, or industrial waste water. Today, it is the most reliable source and cost-effective means of producing fresh water in most Arab Gulf countries and some other parts of the world. Its technology may be divided to three categories: phase-change processes, membrane processes, and chemical-bond processes. The phase-change processes involves either liquid-to-vapor phase change such in multi-stage flash (MSF), multi-effect (MED), and vapor-compression (VC) distillation processes, or liquid-to-solid phase change such as the freezing process. The membrane processes involve using the membrane either to allow fresh water to pass through and reject the salt as a concentrate such as in the reverse-osmosis (RO) process, or to allow certain ions to pass through as in the electrodialysis (ED) process. The chemical-bond process includes the ion-exchange process and some other processes that are not commercially available. The ion-exchange process is composed of organic or inorganic solids capable of exchanging one type of cation (or anion) immobilized on the solid for another type of cation (or anion) in solution, resulting in complete demineralization of NaCl in the water. This is a very expensive process, and in practice, it is used where high-purity water is required, such as water used in high-pressure boilers or in special industrial processes [1]. Phase-change distillation (MSF, MED) processes are only viable at high-salinity feed water and used at large plant capacities. It is mostly used in cogeneration plants, where waste water from a power plant can be used as a heat source to the distillation processes. Membrane processes can be used for both high-salinity water and brackish water and in both large- and small-capacity plants. The freezing process and other alternative processes such as humidification-dehumidification, membrane distillation, and renewable energy-powered processes are currently either at laboratory scale or used in remote areas where conventional energy is not available [2]. The choice of using a certain technology depends on several factors, such as plant capacity, quality of feed water, type of energy sources, and the conditions of brine disposal. The technical operation and the economics of the main desalination processes will be discussed in this paper.

2. TECHNICAL FEATURES OF THE CONVENTIONAL PROCESSES

2.1 Phase-Change Distillation

Saline water is composed of fresh water, salts, and other molecules. When heat is applied to saline water, the water molecules evaporate at a lower temperature than other constituents, and the water vapor is then condensed to fresh water. Three distillation technologies have emerged and are used commercially: MSF, MED, and VC. The performance of the distillation processes is measured by a dimensionless parameter called the gain output ratio (G.O.R.), which is defined as the mass of distilled water (in kg) per mass of
input steam (in kg). The produced fresh water salinity is around 10 ppm; therefore, it needs to be blended with a small amount of brine to buffer the salt to an acceptable level. Thermal distillation technologies are mostly used in regions where cheap energy is available, and it is often coupled with electricity production [1–3].

2.1.1 Multi-stage flash distillation
In the MSF process, the fresh water is produced in the evaporator of each stage by flashing some of the hot feed saline water due to low pressure. The produced water vapor passes through a demister to remove the entrainment of brine droplets, and condenses on the external surface of the heat exchanger. The heat released from condensation is transferred to the flowing feed seawater through successive stages resulting in increasing its temperature. After the feed seawater brine passes the first stage, its temperature is increased to the required temperature (90°C to 110°C) in a brine heater. The brine heater receives the low-grade steam discharged brine from the once-through system at some 10% water is high when free or cheap waste heat is not supplied to 15% higher than seawater TDS [1–6]. The vapor resulting from the last stage is condensed and the external surface of the heat exchanger. The heat released from condensation is transferred to the flowing feed seawater through successive stages resulting in increasing its temperature. After the feed seawater brine passes the first stage, its temperature is increased to the required temperature (90°C to 110°C) in a brine heater. The brine heater receives the low-grade steam discharged brine from the once-through system is some 10% to 15% higher than seawater TDS [1–6].

2.1.2 Multi-effect distillation
This method was widely used before the MSF method. In an MED system, the evaporation in the first stage occurs by heat supplied from an external source such as a fossil fuel boiler, waste heat from a power plant, industrial waste heat, or solar energy. The required top brine temperature (TBT) of this process ranges from 64°C to 70°C and the process continues in the subsequent stages until the vapor temperature drops to about 30°C–40°C [3]. This process also operates on the principle of reducing the ambient pressure at each successive stage, allowing the brine to undergo multiple boiling without the need of additional heat after the first stage. The vapor resulting from each stage is condensed in the following stage, where it can be used as a thermal source for evaporation. Thus, the process proceeds in a chain-reaction form, with each evaporator also serving as a condenser for the vapor resulting from the previous stage. The vapor resulting from the last stage is condensed and released into the cooling system. There are two types of MED systems: horizontal and vertical. In the first type, the seawater usually passes outside the horizontal evaporation tube where it is sprinkled. In some small units with small capacities, the water is evaporated inside vertical evaporation tubes [1–7]. The MED process consists of a series of stages, ranging from 2 to 16. The total number of stages is limited by the total temperature range available and the minimum allowable temperature difference between one stage and the next stage. Due to subsequent lower temperature operation and pressure reduction in the stages, MED energy consumption is lower than the MSF process. MED plants can consume energy at a rate in the range of 14.45–21.35 per m³ of distilled water [1–7].

2.1.3 Vapor-compression process
The VC distillation process is based on the principle of reducing the boiling-point temperature by reducing the pressure. Two methods are used to create the low pressure to evaporate incoming seawater: a mechanical compressor (MVC), which is electrically driven; and a steam jet (TVC), which is driven by low-temperature heat. In the MVC process, the compressor creates a vacuum in the evaporator, which results in partial water evaporation; then the vapor is compressed inside the tube of the heat exchanger (condenser) to exchange heat with the feed seawater sprayed on the surface of the heat exchanger. This will condense the vapor inside the heat exchanger and partially evaporates some of the sprayed feed seawater. In the TVC process, a thermo-compressor, a Venturi orifice at the steam jet, creates the same effect of the mechanical compressor and extracts water vapor from the evaporator. The extracted water vapor is compressed by the steam jet to the tube of the heat exchanger (condenser). This water vapor condenses inside the tube walls to provide the low-heat energy to evaporate the feed seawater sprayed on the other side of the tube walls in the evaporator. The VC process is usually used in small- and medium-sized plants. The MVC unit size ranges up to about 3000 m² per day, whereas the capacity of TVC units may range to about 30,000 m² per day [1–8]. In the MVC unit, the only energy requirement is mechanical power to drive the compressor and the pumps, whereas in the TVC unit, low-temperature steam is needed for the thermal compressor and electricity to drive the pumps. The operating temperature of both MVC and TVC is below 70°C, which reduces the potential for scale formation and corrosion. The MVC unit generally has a single stage because the unit has the same specific power consumption regardless of the number of stages; therefore, when a bigger system is needed, the compressor capacity could be increased. The TVC unit has several stages and the thermal efficiency of the system increased by adding more stages [1–9]. Minimal pre-treatment is required for the VC system and the energy requirement is lower than other distillation systems. The MVC power consumption ranges from 7–12
kWh per m$^3$ of product water and the TVC power consumption is about 16 kWh per m$^3$.

2.1.4 Distillation processes—pre-treatment
In distillation processes, corrosion depends on the amount of entering gases, operating temperature, pH, and concentration of chloride ions in the feed water. The feed water is typically deaerated and chemicals are usually added to lower the pH and to control the calcium carbonate (CaCO$_3$), calcium sulfate (CaSO$_4$), and magnesium hydroxide (Mg(OH)$_2$). Nanofiltration is sometimes used to reduce the potential of the calcium sulfate scaling [7].

2.1.5 Distillation processes—post-treatment
Disinfection of product water from desalinated plants is required before use as drinking water. Disinfection can be achieved by different ways, such as adding chlorine and ozone. Also the concentration of dissolved solids in the permeate is very low. However, if it is not stabilized, it will do so by dissolving materials it comes in contact with; therefore, it needs to be stabilized by mixing with seawater and using some chemicals such as sodium bicarbonate, caustic soda, and hydrate lime [8].

2.2 Membrane Processes
Membranes can selectively permit or prohibit the passage of certain solid ions, and they play an important role in separating salts in natural processes of dialysis and osmosis. The two main membrane processes currently in commercial use are reverse osmosis (RO) and electrodialysis (ED). Three other membrane processes that are not desalination processes, but are relevant and used in feed water pre-treatment are microfiltration (MF), ultrafiltration (UF), and nanofiltration (NF).

2.2.1 Reverse osmosis
RO is a pressure-driven process in which a pressure is applied to a membrane to separate salt and other minerals from water. The quantity of fresh water that penetrates the membrane depends on the difference between the applied pressure and the osmotic pressure of the feed salt water. The osmotic pressure is directly related to the salt concentration in the saline water. The discharge brine from an RO unit ranges from 20% to 70% of the flow feed water, depending on salinity of the feed water, applied pressure, and type of membrane. The usual quality of the fresh water produced from a single-stage seawater RO unit is less than 500 ppm [1–8]. An RO plant is cheap to build, needs less capital investment, is simple to operate, and can be built with a system capacity that ranges from a few liters to hundreds of thousands of m$^3$ per day. It also has a high production /space ratio, low energy consumption, and there is no need to shut down the whole plant when there is a problem or for routine maintenance due to the modular design of the plant. The main disadvantages of an RO system are the following: high maintenance cost resulting from replacing the membrane (usually every two years or more); bacterial growth on the membrane, which can bring odors and bad tests of the product water; and expectation of some mechanical failure in system equipment due to the system’s high pressure. A number of devices have been developed to recover the energy from the membrane reject stream and to return it to the feed of the RO process. Implementation of efficient energy-recovery devices (ERDs) into the RO desalination technologies boosted the growth of RO plants worldwide. The major types of ERDs are the turbocharger, pressure exchanger, Pelton wheel, and Francis turbine. Specific energy consumption is largely dominated by two factors—the amount of trans-membrane pressure difference required to achieve the necessary permeate flow rate at various mass-transfer conditions, as well as the design and efficiency of the feed water pump in combination with the respective energy-recovery system installed to recover the available hydraulic energy in the discharge brine. The energy consumption of a salt water RO (SWRO) unit ranges from 4–6 kWh per m$^3$ of desalinated water. For a brackish water RO (BWRO) unit, the consumption ranges from 1.5–2.5 kWh per m$^3$ of desalinated water [1–11]. An RO system performs similarly if it is used for brackish or sea water; however, there are some differences between the two cases. These include, for a BWRO system, a lower pressure needed on the membrane, lower energy requirement, and high recovery rate. In addition, there is a considerable difference in the pre-treatment of both types of water.

2.2.2 Electrodialysis system
An ED system produces fresh water by using a low-voltage direct current (DC) electric field to remove salt ions from the feed water. It consists of two outside electrodes and several hundreds of cell pairs forming chambers separated by membranes that are permeable to either positive (cation) or negative (anion) ions. Feed water moves in parallel paths through all of the cells. When DC is applied, the positive and negative salt ions migrate to the oppositely charged electrode through the appropriate membrane, thus forming compartments of fresh water and highly concentrated water. The electrodialysis reversal (EDR) process was developed to help eliminate membrane fouling. In this process, the membrane polarity is reversed several times in an hour. It also involves a reversal of water flow to clean the chambers from the depositing of scales, slimes, and other types of fouling. This reversal water flow allows the ED unit to use less pre-treatment chemicals, which results in cost minimization [11–14]. ED is only suitable for brackish water with TDS of less than 10,000 ppm. The primary energy requirement of the process is the DC used to separate the salt ions. Power consumption is required for the low-pressure pump used to circulate water through the narrow chambers. When high-TDS feed water is used, the DC
consumption will rapidly increase, which results in a high cost of desalinated water. ED can produce water with a high recovery ratio of about 90% for one stage, can be operated at low pressure, needs low chemical usage, and can be used to treat water with high levels of suspended solids. The major problem to be expected in ED systems is the possible occurrence of leaks in the membrane stacks. The total power consumption of ED units range from 0.7 to 2.5 kWh/m³ of desalinated water for feed water salinity of 2500 ppm and from 2.64–5.5 kWh/m³ of desalinated water for feed water salinity of 5000 ppm [3,11–14].

2.2.3 Membrane processes—pre-treatment
The main goal of the membrane pre-treatment is to control scaling such as calcium carbonate and calcium sulfate, metal oxide fouling such as oxides of iron and manganese, biological activity such as biofouling, and biofilm formation and colloidal and particulate fouling such as clays and colloidal color [8]. The conventional media filtration uses sand or cartridge filtration in addition to chemicals to remove turbidity, algae, organic, and other particulate matter for the feed water. Microfiltration, ultrafiltration, or nanofiltration are also used to remove suspended and dissolved solids. MF screens particles from 0.1–0.5 microns; UF screens particles from 0.005–0.05 microns; and NF screens particles from 0.0005–0.001 microns. Ineffective pre-treatment creates problems in membrane process systems that include higher operating pressure, which increases power consumption, lower permeate production rate, increased membrane fouling, reduced membrane life, and more frequent need of membrane cleaning. Precipitation of scale can be facilitated by the change of pH that occurs near the membrane due to the transport of H⁺ and OH⁻. Because nonionic solids (silica) are not concentrated by the process, these components are not of concern [1–8]. Chemicals may be added to the stream of water flowing through the chambers to reduce scaling.

2.2.4 Membrane processes—post-treatment
Disinfection to eliminate water-borne diseases is required before sending the produced water to the municipal water system. Chlorine may also be added to the feed water before it enters the desalination process to disinfect it. Permeate water from processes have low mineral content, low alkalinity, and high corrosion potential; therefore, stabilization is needed. The bacteria, nonionic substances, and residual turbidity are not affected by an ED system, and they can remain in the product water, which needs to be further treated [8].

3. RENEWABLE ENERGY APPLICATIONS IN WATER DESALINATION

Desalination processes require thermal and/or electrical energy, which can be supplied by renewable energy (RE) systems. The selection of the appropriate RE technology for water desalination depends on several factors: availability of RE resources, feed water salinity, permeate water-quality, economics, and plant capacity. If a renewable energy resource is available at a site, experience has shown no significant technical problems in combining RE systems and desalination units. The only current limitation is the economic factor. Solar and geothermal energies could produce low-temperature heat and electricity to drive MSF, MED and TVC and electricity to drive RO, ED, and MVC. Wind energy could provide electricity to drive RO, ED, and MVC. Examples of some RE desalination coupling will be discussed briefly, and Table 1 presents the cost of desalinated water produced from RE-coupled desalination systems.

3.1 Solar Thermal Desalination Coupling
Solar thermal energy can be converted to low-temperature heat or electricity to drive desalination units. For medium- and large-capacity desalination plants, concentrating solar power (CSP) technologies are the best candidate. CSP technologies could be used to provide energy in the form of low-temperature heat and electricity to desalination plants. The primary aim of CSP is to produce high-temperature heat to generate electricity, but it can also produce low-temperature heat either from the electricity generation turbine exhaust or directly from the CSP through heat exchangers. The parabolic trough CSP system is currently the best candidate for desalination coupling, and two types of desalination processes (MED and RO) are good candidates for this. In a CSP/MED plant, the needed temperature of the supplied heat should be around 70°C; therefore, there is sufficient energy in the turbine exhaust to provide this heat. In a CSP/RO plant, the CSP system could provide electricity to run the pumps of the RO unit and some low-temperature heat from the turbine exhaust to raise the temperature of the feed water to the unit to improve the performance of the membrane, which results in reducing the RO unit power consumption. Another alternative to operate this system is to use the CSP system to provide low-temperature heat to the MED unit for water evaporation and solar photovoltaic (PV) system to produce electricity for the pumps of the MED unit [17–20].

3.2 Solar PV Desalination Coupling
Solar PV is a mature technology with systems having a life expectancy of more than 25 years. It could provide both DC and AC electricity to a desalination unit. PV systems are currently used to drive RO and ED units. This type of system could be used without batteries to run only when the solar energy is available, or with batteries for 24-hour operation. PV/RO plants are the most promising system, and many projects of this type have been installed in different
parts of the world. Two types of PV/RO systems are currently available in the market. One is used to desalinate brackish water (PV/BWRO system) and the other is to desalinate seawater (PV/SWRO system). The PV/ED system is used to desalinate brackish water. The ED units need only DC electricity for the electrodes, and DC or AC electricity to drive the low-pressure pumps [21–27].

3.3 Wind Desalination Coupling

In areas with suitable wind speed, wind turbines can provide mechanical energy and electricity for RO, ED, and MVC desalination systems. The most commonly used systems are wind/RO and wind/MVC systems. Typical capacities of the implemented wind/RO systems range from 50–2000 m³ per day, whereas the typical capacities of wind/MVC systems range from 5–50 m³ per day [25–30].

3.4 Geothermal Desalination

Geothermal energy could be used to drive all desalination units. High-pressure geothermal sources could mechanically drive RO or MVC units or produce electricity to drive RO, ED, and MVC units. Low-temperature geothermal sources can drive MSF, MED, and MVC units. So far, several geothermal/MED plants have been constructed in the United States, Tunisia, Greece, and Kimolos Island [31–33].

4. TECHNICAL AND ECONOMIC COMPARISON OF DIFFERENT DESALINATION PROCESSES

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

Compared to distillation processes, membrane processes have lower capital cost, less energy consumption, higher recovery ratio, higher space-to-production ratio, and less corrosion and scaling due to ambient temperature operation. RO processes, which use a membrane, are more compact and modular than distillation processes and can be expanded to desalinate a large capacity of water. However, compared to thermal processes, the RO process needs more feed water pre-treatment because of the sensitivity of the membrane to scaling, fouling, and pH of the feed water.

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

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

The water production cost of RE-coupled desalination systems is highly related to the cost of energy produced from these systems, which reflect a high water cost. But with further improvement and more use of RE systems, their capital cost will be reduced and the water production cost of desalination system operated by RE power will also be reduced. Table 1 presents the energy consumption and water production cost of all processes.

5. CONCLUSIONS

For seawater desalination, three distillation processes (MSF, MED and VC) and one membrane process (RO) are currently used. For brackish water desalination, only RO and ED processes are currently used. The selection of any process depends on many factors, such as salinity and quality of the feed water, plant capacity, site conditions, energy cost, operation and maintenance cost, and the availability of qualified labor. The energy cost is the largest segment of the total water production cost—around 60% of the water cost produced from the distillation plants and about 45% of the water cost produced by the RO plants. The thermal distillation processes have several advantages over the membrane processes. These include better quality of the produced water, less impact with the change of feed water quality, and no membrane replacement. The membrane processes have lower capital cost, better space-to-production
### Table 1: Overview of Main Desalination and Renewable Energy-Coupled Processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Thermal consumption (MJ/m³)</th>
<th>Equivalent electrical of thermal consumption (kWh/m³)</th>
<th>Electrical consumption (kWh/m³)</th>
<th>Total consumption (kWh/m³)</th>
<th>Product water quality</th>
<th>Product water cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSF</td>
<td>190–282</td>
<td>15.83–23.5</td>
<td>2.5–5</td>
<td>19.58–27.25</td>
<td>~10</td>
<td>0.56–1.75</td>
</tr>
<tr>
<td>MED</td>
<td>145–230</td>
<td>12.2–19.1</td>
<td>2–2.5</td>
<td>14.45–21.35</td>
<td>~10</td>
<td>0.52–1.5</td>
</tr>
<tr>
<td>MVC</td>
<td>none</td>
<td>none</td>
<td>7–12</td>
<td>7–12</td>
<td>~10</td>
<td>2.0–2.6</td>
</tr>
<tr>
<td>TVC</td>
<td>227</td>
<td>14.5</td>
<td>1.6–1.8</td>
<td>16.26</td>
<td>~10</td>
<td>0.87–0.95</td>
</tr>
<tr>
<td>SWRO</td>
<td>none</td>
<td>none</td>
<td>4–6</td>
<td>4–6</td>
<td>400–500</td>
<td>0.45–1.72</td>
</tr>
<tr>
<td>BWRO</td>
<td>none</td>
<td>none</td>
<td>1.5–2.5</td>
<td>1.5–2.5</td>
<td>200–500</td>
<td>0.26–1.33</td>
</tr>
<tr>
<td>ED</td>
<td>none</td>
<td>none</td>
<td>1.5–4</td>
<td>1.5–4.0</td>
<td>150–500</td>
<td>0.6–1.05</td>
</tr>
<tr>
<td>Solar CSP/MED</td>
<td>145–230</td>
<td>12.2–19.1</td>
<td>2–2.5</td>
<td>14.45–21.35</td>
<td>~10</td>
<td>2.4–2.8</td>
</tr>
<tr>
<td>Solar PV/RO</td>
<td>none</td>
<td>none</td>
<td>4–6</td>
<td>4–6</td>
<td>400–500</td>
<td>11.7–15.6</td>
</tr>
<tr>
<td>Solar PV/ED</td>
<td>none</td>
<td>none</td>
<td>1.5–2.5</td>
<td>1.5–2.5</td>
<td>200–500</td>
<td>6.5–9.1</td>
</tr>
<tr>
<td>Wind/RO</td>
<td>none</td>
<td>none</td>
<td>4–6</td>
<td>4–6</td>
<td>400–500</td>
<td>1.9–9.0</td>
</tr>
<tr>
<td>Wind/MVC</td>
<td>none</td>
<td>none</td>
<td>1.5–2.5</td>
<td>1.5–2.5</td>
<td>200–500</td>
<td>5.2–7.8</td>
</tr>
<tr>
<td>Geo /MED</td>
<td>145–230</td>
<td>12.2–19.1</td>
<td>2–2.5</td>
<td>14.45–21.35</td>
<td>~10</td>
<td>2–2.8</td>
</tr>
</tbody>
</table>

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Ratio, higher recovery ratio, easy to enlarge the plant due to the process modularity, less affected by corrosion and scaling due to low-temperature operation. Normally, the water production cost from the RO process is lower than for any of the distillation processes. But this is not the case in cogeneration plants, where low-pressure steam is extracted from the power plant turbine exhaust. For brackish water of less than 5000 ppm, ED performs better than RO, whereas at TDS above 5000 ppm, RO is the best process. Renewable resources such as solar thermal, solar PV, wind, and geothermal can be used to power desalination processes. Matching any RE system with desalination processes requires a number of factors to be considered, and the water production cost from these systems is currently very high. Because of this high cost, desalination processes incorporating renewable energy resources are currently economic only in remote areas.

6. **ACKNOWLEDGMENTS**
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