Advances in Desalination Technologies: Solar Desalination

Magdy M. Abou Rayan and Berge Djebedjian

Abstract Availability of freshwater is the prime mover of the human life activities. The advances in desalination technologies clearly show that desalinated water can be used as a substitute for freshwater to be used as potable water. A breakthrough in reverse osmosis costs has been reached, particularly in decreasing energy consumption. The introduction of nanotechnology in the membrane manufacture has resulted in reducing the volume of rejected brine which in turn alleviates the brine disposal issue. Several recent studies show that desalinated water for development of isolated areas is economically competitive to transportation of freshwater by pipeline. The introduction of solar energy to power desalination process has given a new dimension to the expansion of desalination technology. Several studies show the importance of solar desalination in countries suffering from freshwater shortage, particularly in isolated areas. This chapter presents an overview of desalination technologies with emphasis on solar energy-driven units. Some case studies are highlighted. The chapter concludes with a discussion of future avenues in solar desalination.

Keywords Solar desalination • Potable water • Water supply for remote areas • Economics of desalination

Acronyms and Abbreviations

AD	Aggregate Demand
ADIRA	*A*utonomous *D*esalination System Concepts for Seawater and Brackish Water *i*n *R*ural *A*reas with Renewable Energies—Potentials, Technologies, Field Experience, Socio-Technical and Socio-Economic Impacts

M.M. Abou Rayan (✉) • B. Djebedjian
Water Research and Industrial Projects Center, Mansoura University, El-Mansoura, Egypt
e-mail: magdy.abourayan@gmail.com

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ADS	Autonomous Desalination Systems
ANOVA	Analysis of Variance
BWRO	Brackish Water Reverse Osmosis
CCGT	Combined Cycle Gas Turbine
CHF	Swiss Franc
CLP	Chilean Peso
ED	Electrodialysis
EDR	Electrodialysis Reversal
FAO	Food and Agriculture Organization
FIC	Innovation Fund for Competitiveness
GWI	Global Water Intelligence
HCPVT	High Concentration Photovoltaic Thermal System
HDH	Humidification Dehumidification
IDA	International Desalination Association
ITC	Instituto Tecnológico de Canarias
KACST	King Abdul Aziz City for Science and Technology
KSA	Kingdom of Saudi Arabia
kW/h	kilowatt per hour
kWp	kilowatt peak
LCZ	Lower Convective Zone
m^3	Cubic meter
MD	Membrane Distillation
ME	Multiple-Effect Distillation
MEB	Multiple-Effect Boiling
MED	Multiple-Effect Distillation
MEH	Multiple-Effect Humidification
MENA	Middle East and North Africa
mg/l	Milligrams per liter
MGZ	Main Gradient Zone
MIT	Massachusetts Institute of Technology
MNT	Institute for Micro- and Nanotechnology
MSF	Multi-Stage Flash Distillation
MVC	Mechanical Vapor Compression
NA	Nanofiltration
NCZ	Nonconvective Zone
PTSS	Portable Thermoelectric Solar Still
PV	Photovoltaic
R&D	Research and Development
RO	Reverse Osmosis
RSM	Response Surface Methodology
SGSP	Salinity-Gradient Solar Pond
SMC	Southern Mediterranean Countries

SWCC	Saudi Arabia's Saline Water Conversion Corporation
SWRO	Seawater Reverse Osmosis
TDS	Total Dissolved Solids
UAE	United Arab of Emirates
UCZ	Upper Convective Zone
UHCPV	Ultrahigh Concentrator Photovoltaic
UNEP	United Nations Environment Program
UPC	Unit Product Cost
VC	Vapor Compression
WDS	Water Distribution System
WHO	World Health Organization

1 Introduction

In several regions around the world, the water shortage problems, together with the tremendous urban growth, and population reallocation plans have increased the demand for freshwater. A review of advances in seawater desalination technologies shows the steady and increasing usage of seawater desalination around the world [1, 2].

Desalination is a treatment process that removes salts from water. Saline solutions other than seawater with a salt concentration from 1,000 mg/l to 11,000 mg/l total dissolved solids (TDS) are typically described as brackish water. The TDS concentration of normal seawater is 35,000 mg/l–40,000 mg/l or higher, mostly sodium chloride.

Historically, seawater desalination has been considered as the most expensive way to produce drinking water at the commercial scale because of the high capital and energy costs [3–5]. However, desalination is increasingly recognized as a needed and viable option in order to respond to the freshwater shortage worldwide. The rapid increase of the world population [6] and also reduction in desalination installation cost have resulted in the increased implementation of desalination. It is projected that close to 70 % of the world population will face water shortage issues by 2025 [7–9] and approximately 50 % of the world's population lives within 200 km from seashore.

A typical desalination plant consists of a water pretreatment system, the desalination unit, and a posttreatment system. A desalination plant, as depicted in Fig. 1, may be considered as a "black box" through which streams of water and energy flow.

Table 1 shows the largest ten seawater reverse osmosis (SWRO) plants in the world. Mega plants over 100,000 m^3/day capacity are becoming common around the world.

The cost and availability of energy required to drive desalination process present a challenge for the expansion of desalination technologies. Solar energy is a viable tool to power desalination process and an emerging and promising renewable

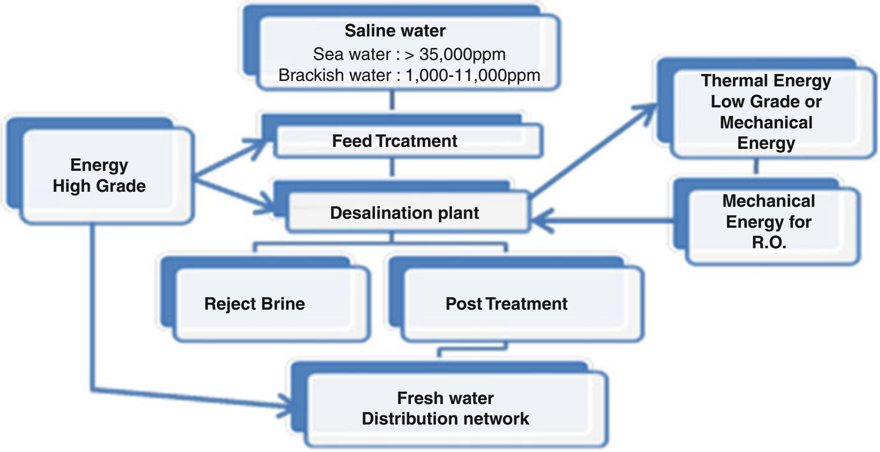

Fig. 1 Water and energy flow diagram of a desalination unit (*Source*: Authors)

Table 1 Largest 10 SWRO desalination plants in the world by capacity

Plant	Country	Capacity (m^3/d)	Contractor	Status
Soreq	Israel	510,000	IDE	Planned
Mactaa	Algeria	500,000	Hyflux	Planned
Hadera	Israel	456,000	IDE	Online
Wonthaggi	Australia	444,000	Degrémont	Online
Ashdod	Israel	380,000	Valoriza	Planned
Ashkelon	Israel	326,144	IDE	Online
Tuaspring	Singapore	318,500	Hyflux	Planned
Ras Al-Khair	Saudi Arabia	309,128	Doosan	Planned
Adelaide	Australia	300,000	Acciona	Online
SSDP Perth	Australia	280,000	Valoriza/Técnicas Reunidas	Online

Source: Global Water Intelligence, [10]

energy technology for producing freshwater [6, 11–17]. Particularly, solar desalination is considered an ideal solution for providing cost-effective water supplies to rural and isolated areas. Furthermore, solar desalination would permit providing potable water by means of an environmentally friendly process.

The objective of this chapter is to present an overview of desalination technologies with focus on solar desalination technologies.

2 Desalination Technologies: Overview

Desalination technologies can be classified into major and minor desalination processes. The major desalination processes are split into two main categories: thermal (or distillation) and membrane processes (Fig. 2). The major processes

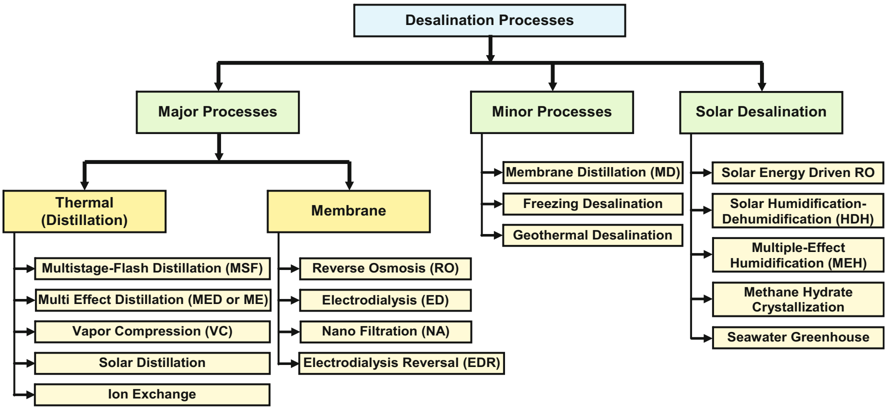

Fig. 2 Classification of the desalination processes (*Source*: Authors)

have the largest capacities. The minor processes including direct solar desalination are suitable for remote and isolated areas with expected low freshwater demand.

2.1 Thermal Processes

Thermal or distillation processes use heat energy. In this process, the seawater is heated to the boiling point to produce water vapor which is then condensed to form freshwater. Major thermal processes for desalination are described below.

2.1.1 Multiple-Stage Flash Distillation

Multiple-Stage Flash (MSF) distillation is the most widely used thermal desalination process. There are two configurations concerning MSF process: The "Once-Through" configuration and "Brine Recirculation." "The Once-Through" configuration consists of two sections: (1) heat rejection section and (2) brine heater. The "Brine Recirculation" consists of three sections: (1) heat rejection section, (2) heat recovery section, and (3) brine heater (Fig. 3).

An MSF desalination plant can contain from 4 up to 40 stages. Increasing the number of stages reduces the required heat transfer surface, thus reducing the capital cost. To offset the cost of providing extra stages, complicated optimization calculations have to be undertaken where the main decision parameters are capital cost versus operating cost.

MSF distillation is being developed and adapted to large-scale applications, usually with capacities greater than 5,000 m^3/day. At present, the largest MSF plant (Eljubil, Saudi Arabia) has a water production capacity of 60,000 m^3/day [17]. The MSF process is also widely used in the Gulf countries with 75 % of the

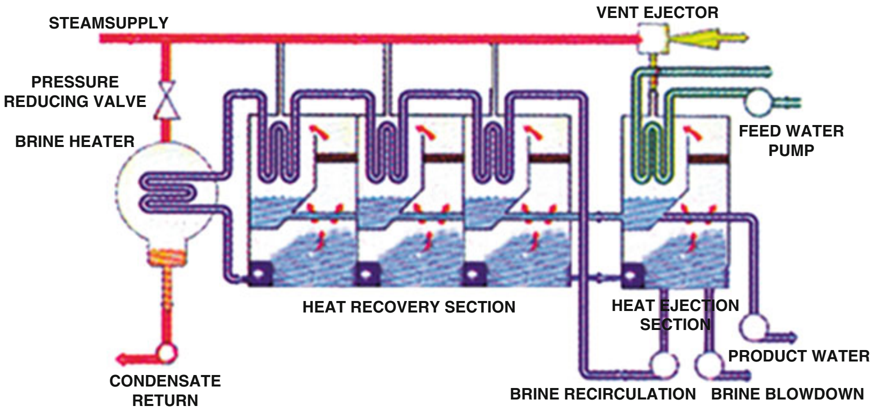

Fig. 3 Typical flow diagram of Multi-Stage Flash distillation plant [17]

global total installed capacity. In Europe, the MSF process is mainly used in Italy and in Spain.

2.1.2 Multiple-Effect Distillation

Multiple-Effect Distillation (MED or ME) was the first thermal process used for seawater desalination. It is widely used in the chemical industry where the process was originally developed. The MED process is similar to the MSF process. MED, like MSF, takes place in a series of vessels (called effect) and uses the principle of reducing the ambient pressure with various effects. This permits the feed water to undergo multiple boiling without supplying additional heat after the first effect. The principle of MED operation is shown in Fig. 4. MED plants tend to have a smaller number of effects than MSF stages. Usually 8–16 effects are used in typical large plants, due to the relation of the number of effects with the performance ratio (which cannot exceed the number of effects of the plant). As in an MSF plant, special attention is required concerning the operating temperature in order to avoid scaling and corrosion of materials. Also, extra care is required concerning the control of the brine level in each effect.

2.1.3 Vapor Compression

At present, two Vapor Compressor (VC) processes are widely in use: Mechanical Vapor Compression (MVC), in which a mechanical compressor is used; and Thermal Vapor Compression (TVC), in which a thermo compressor or ejector is used to increase the vapor pressure.

The fundamental concept of VC process is inherently simple, in that after vapor has been produced it is then compressed to increase its pressure and consequently

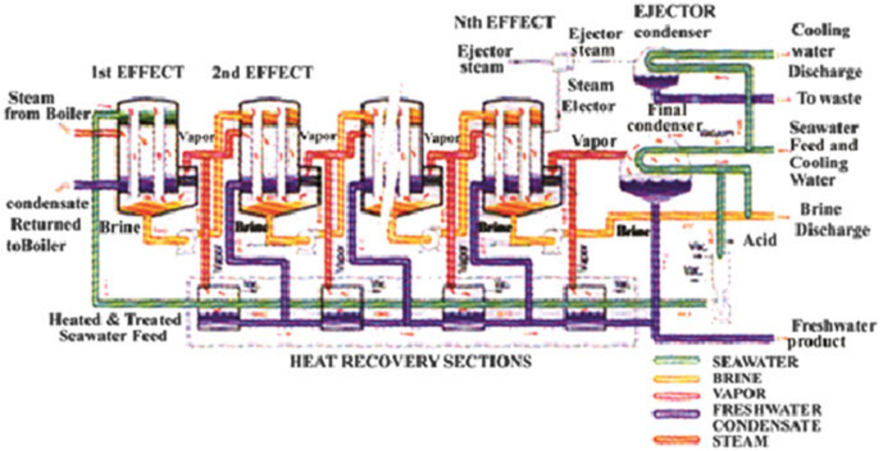

Fig. 4 Typical flow diagram of Multi-Effect distillation plant—Horizontal falling film plant [18]

its saturation temperature before it is returned to the evaporator as the heating vapor for the evaporation of more liquid. The main equipment used in the VC compression process includes the evaporator, the compressor, pumps, and the heat exchanger. In this process, the feed water is preheated using a heat exchanger or a series of heat exchangers by the hot discharge of the brine (Fig. 5).

The power consumption of the compressor, and therefore the efficiency of the process, depends on pressure difference. Thus, the compressor represents the main energy consumer in the system. Extra care is required with the control of the brine level in the evaporator and the proper maintenance of the compressor. Some manufacturers use compressors that rotate at very high speeds. Operation at low temperatures minimizes the formation of scaling and corrosion of materials.

2.2 Membrane Technologies

Membrane technologies, particularly reverse osmosis, are the most common desalination technologies used around the world. These technologies are described below.

2.2.1 Reverse Osmosis

Reverse Osmosis (RO) involves the forced passage of water through a membrane against the natural osmotic pressure to accomplish the separation of water and ions. Figure 6 shows the principle of RO process. A typical RO system consists of four

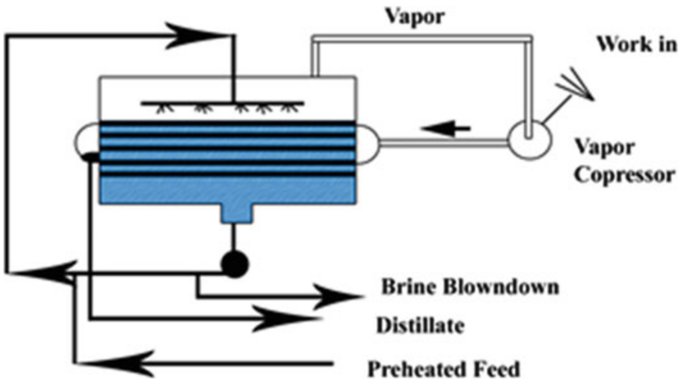

Fig. 5 Typical flow diagram of Vapor Compression plant (*Source*: Authors)

major subsystems (Fig. 7): (1) pretreatment system, (2) high-pressure pump, (3) membrane modules, and (4) posttreatment system.

Due to the RO unit operation at ambient temperature, corrosion and scaling problems are diminished in comparison with distillation processes. However, effective pretreatment of the feed water is required to minimize fouling, scaling, and membrane degradation. In general, the selection of the proper pretreatment, as well as the proper membrane maintenance, is critical to the efficiency and life of the RO system.

As a general rule, a seawater RO unit has a low capital cost but a significant maintenance cost due to the high cost of the membrane replacement. The cost of the energy use to drive the RO plant is also significant. The major energy requirement for RO desalination is for pressurizing the feed water. In recent years, energy requirements for seawater desalination (SWRO) have been reduced to 4.0 kWh/m^3 by using energy recovery systems. For brackish water desalination, the energy requirement for RO is between 1 and 3 kWh/m^3.

2.2.2 Electrodialysis Process

Electrodialysis (ED) is an electrochemical process and a low-cost method for the desalination of brackish water. In ED process, ions are transported through a membrane by an electrical field applied across the membrane. An ED unit (Fig. 8) consists of the following five basic components: pretreatment system, membrane stacks, low-pressure circulation pump, power supply for direct current (rectifier), and posttreatment.

The ED process is not economically attractive for the desalination of seawater due to the dependency of the energy consumption on salt concentration in feed water.

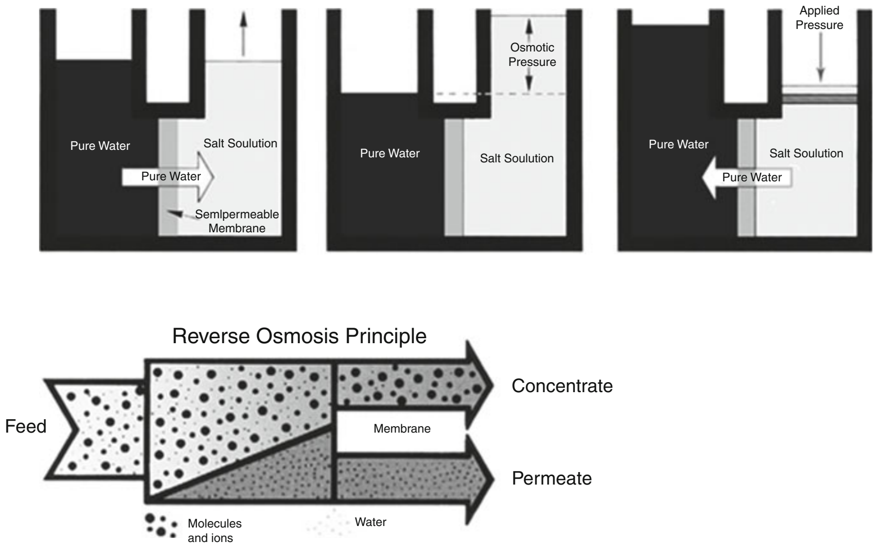

Fig. 6 Principles of RO process [18]

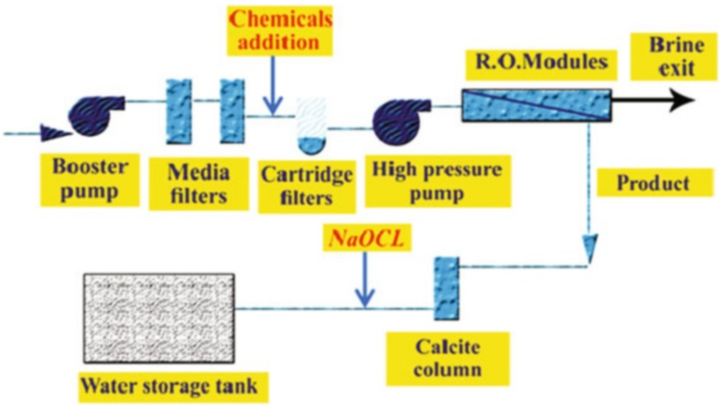

Fig. 7 Basic components of RO plant (*Source*: Authors)

2.3 Technology Selection

The choice of desalination technology is site specific and depends on the conditions of the feed water, energy availability and source, location, and cost. The cost of desalination is sensitive to plant capacity. Low capacity units have a higher installation cost per m^3 than the large units.

Table 2 shows a few selected desalination plants installed around the world. At present RO is the dominant desalination technology used worldwide.

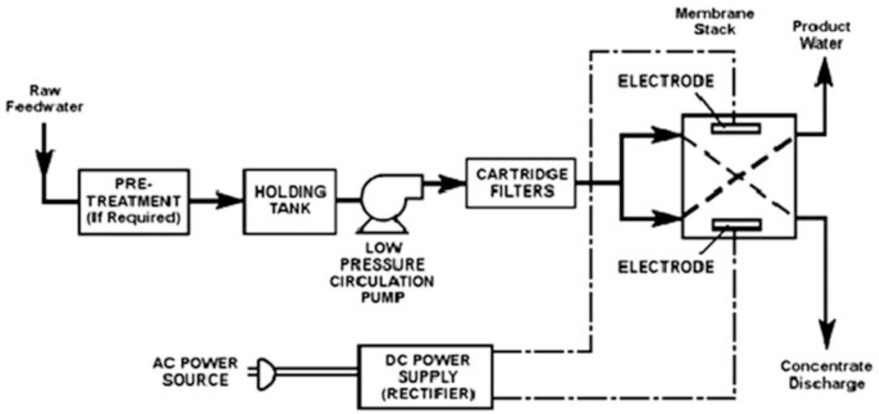

Fig. 8 Basic components of an ED plant (*Source*: Authors)

Table 2 Types of the major desalination technologies

Process	Feed water	Year of operation	Capacity (m^3/day)	Location
MSF	Seawater	2013	91,000	Ras al-Zour, KSA
MED	Seawater	2008	160,000	Jamnagar, India
	Seawater	2015	178,000	Sadara, KSA
MVC	Seawater	1999	172,000	Sardinia, Italy
SWRO	Seawater	2011	460,000	Hedra, Israel
EDR	Brackish water	2009	220,000	Lioberg Rivez, Spain
MED + TVC	Seawater	2009	800,000	Jubail, KSA

The research directives now are aiming at increasing RO efficiency through improvement of membranes. The target is to reduce the rejected brine to go below 50 %. The energy recovery in RO system has achieved great progress. The classical thermal process is still more expensive. At present, the thermal process is based mainly on fossil energy use and waste heat. The development in nanotechnology research will have an impact on both thermal and membrane processes. But the research results are not yet available for commercial applications [19].

3 Using Renewable Energy for Desalination

Renewable energy sources include solar, wind, geothermal, waves, and biomass (Fig. 9). The trend of increasing use of renewable energy for desalination is encouraged by environmental protection agencies around the world [20]. Solar distillation is an ancient technology employed by humans for thousands of years. Early Greek mariners and Persian alchemists used this basic technology to produce

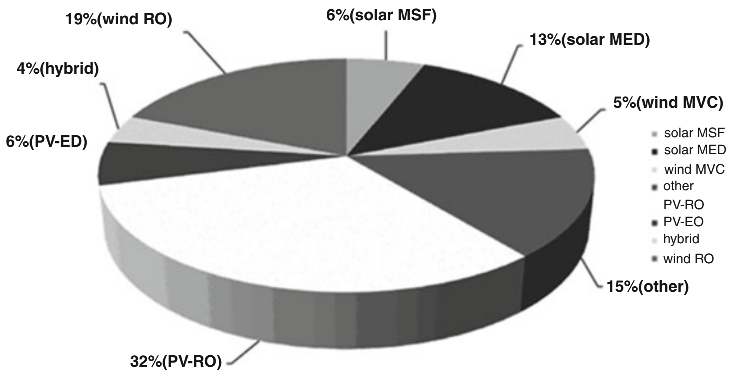

Fig. 9 Renewable energy use according to desalination technology (*Source*: Global Water Intelligence, Publisher GWI [10])

both freshwater and medicinal distillates. Solar stills were in fact the first treatment method used on a large scale to convert contaminated water to a potable form [21].

Table 3 shows some common combinations of renewable energy that can be used for desalination. Some of these combinations are mature enough and commercially available.

4 Solar Desalination

At present, of the estimated 22 million m^3 of freshwater produced a day using desalination processes worldwide, less than 1 % is using solar energy [21]. Though solar desalination processes have not been fully commercialized at a large scale yet, the ongoing research shows that solar desalination is a valid option for future desalination plants [22]. At present, the energy storage system remains the real challenge for the use of solar energy.

There are two primary approaches for desalination using solar energy; through a phase change by thermal input or in a single phase through mechanical separation of salt and water [23]. Phase change (or multiphase) or thermal input can be accomplished by either direct or indirect distillation. Single phase or mechanical separation is predominantly accomplished by using photovoltaic cells to produce electricity that drive pumps, although there are experimental methods being researched using solar thermal collection to provide this mechanical energy [24]. An overview of solar desalination technologies is provided below.

Table 3 Renewable energy and desalination technology combinations

Energy sources	Method	Desalination process	Energy storage	Backup
Solar	Thermal System	MSF	Hot fluid insulated tanks	Oil or gas
	Parabolic collectors	MEB		
	Flat plates	MEB-TC		
	Evacuated tubes			
	Deep ponds			
	Electrical system			
	Solar thermal electric	EDR	Batteries and insulated	Grid or diesel
	Power generation	RO	Tanks	
	Photovoltaic	RO	Batteries	Grid or diesel
		EDR		
Wind	Wind turbine	RO	Batteries	Grid or diesel
		EDR	Fly wheel	
		MVC	Pumped storage	
Wave	Wells turbine	RO	Batteries	Grid or diesel
		EDR	Fly wheel	
		MVC	Pumped storage	
Waste heat and biomass thermal		MSF		Oil or gas
		MEB		
		MEB-TC		
Thermal electric power generation		RO		Oil or gas
		MVC		
		EDR		

4.1 Direct Solar Desalination

Direct solar energy use includes solar stills, solar ponds, and other technologies. Sampathkumar et al. [25] provide a detailed review of direct solar distillation systems. The direct solar desalination is by definition the use of direct solar energy without conversion. In the direct method, a solar collector is coupled with a distilling mechanism and the process is carried out in one simple cycle [26].

A schematic view of a solar still is provided in Fig. 10. The original solar still can be described as a basin with a transparent cover (e.g., glass). The interior of the still contains seawater and air. When the seawater is heated by solar radiation, it starts to evaporate. The formed vapor is mixed with the air above the water surface and then condensate on the surface. The formed condensation drops will start running down the cover by gravitational forces and may then be collected at the side of the still.

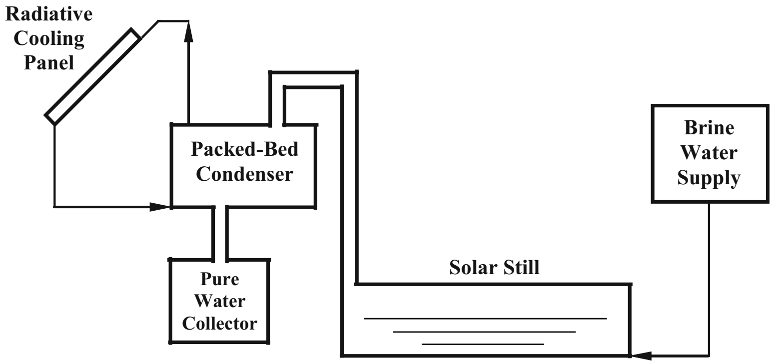

Fig. 10 Schematics of the solar still and condenser [27]

Direct solar distillation potential is proportional to the area of the solar surface and the incidence angle and has an average estimated value of 3–4 L/m^2/day [21]. Because of this proportionality and the relatively high cost of land and material for construction, direct solar distillation tends to favor plants with production capacities less than 200 m^3/day [21]. There are some small commercial solar still units in existence in areas where freshwater demand is less than 200 m^3/day [28].

Solar ponds (Fig. 11) are another direct method for desalination. Solar ponds are simple in design and low in cost. Such ponds may be a reliable source of heat for a wide range of industrial and agricultural applications such as process heating, space heating, desalination, and electricity generation [29]. The principal mechanism of solar pond is as follows. As the sun shines over a lake or a pond, the water absorbs irradiation and is warmed. However, surface water quickly loses this added heat due to heat and mass convection with the ambient air. Since the underlying water in the pond is now warmer and thereby lighter than the surface, it causes convective circulation, where warm water from the bottom rises and the colder water from the surface layer sinks [30]. Solar ponds require plenty of land area. Thus, it is reasonable to locate them in wastelands or in deserts, close to saltwater. Countries, such as Libya, which greatly depend on seawater desalination, are appropriate locations for solar ponds. Using solar ponds instead of fossil fuel for heating the desalination plants results in significantly lower water production costs [30].

Salinity-gradient solar ponds (SGSPs) combine solar energy collection with long-term storage potential [29]. A typical salinity-gradient solar pond (SGSP), Fig. 11, has three regions. The top region is called the surface zone, or upper convective zone (UCZ); the middle region is called the main gradient zone (MGZ), or nonconvective zone (NCZ); and the lower region is called the storage zone, or lower convective zone (LCZ) [29].

Figure 12 shows a more sophisticated direct use of solar energy. The process is using Membrane Distillation (MD), a process that can be adapted effectively for water desalination. This process requires moderate temperatures to produce the

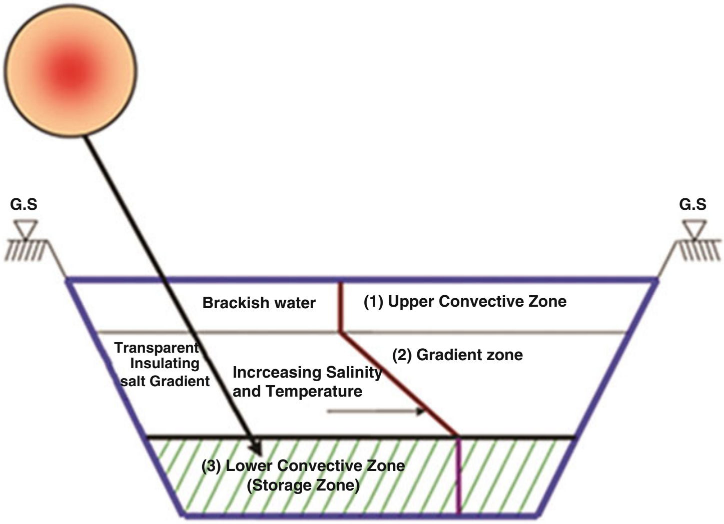

Fig. 11 Solar pond—typical salinity gradient [30]

driving force across the membrane—the difference between the partial vapor pressures at both sides of the membrane (Fig. 12).

4.2 Indirect Solar Desalination

Indirect solar desalination employs two separate systems: a solar collection array, consisting of either photovoltaic or fluid-based collectors, and a conventional desalination plant [26]. Production by indirect method is dependent on the thermal efficiency of the plant and the cost per unit produced is generally reduced by an increase in scale. Many different plant arrangements have been theoretically analyzed, experimentally tested, and in some cases installed. They include, but are not limited to Multiple-Effect Humidification (MEH), Multiple-Stage Flash Distillation (MSF), Multiple-Effect Distillation (MED), Multiple-Effect Boiling (MEB), Humidification Dehumidification (HDH), Reverse Osmosis (RO), and Freeze effect distillation [32].

5 Comparison of Water Supply Systems

The economics and environmental impacts of a water supply system are important criteria. The economic evaluation of a municipal water supply project is subject to two important aspects: (1) the availability and quality of water source and (2) the

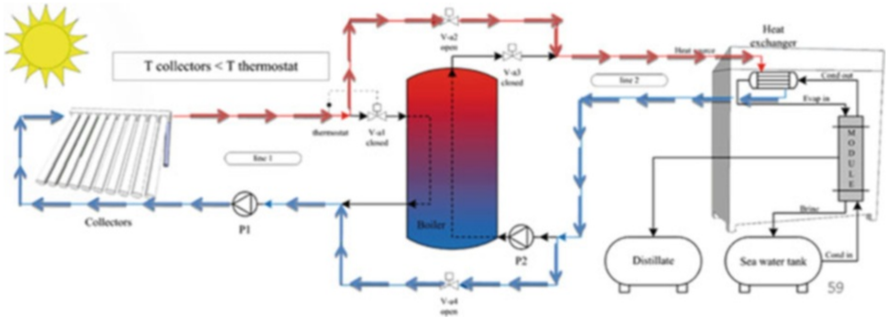

Fig. 12 Schematic representation of the operating configuration 1 (cold hours of a sunny day): Solar energy is directly used to power the MD plant [31]

plant location, i.e., the plant distance from the water source and the existing water distribution network.

Whereas in most urban regions a secure, continuous energy supply is guaranteed, in many rural and coastal regions the lack of potable water is connected to unavailability of energy source. This often provokes a situation like "without energy there is no water." Due to the fact that almost 60 % of the investment costs for energy supply systems are needed for the installation of the distribution system in rural regions, decentralized and renewable energy supply systems become increasingly important. By the utilization of renewable energy systems the water producer becomes independent from any supply of fossil fuel resources such as gas or diesel, but has to take into account the intermittent energy supplied by the sun or wind. However, the combination of renewable energies and water production by reverse osmosis has become the key technology for decentralized water supply plants.

In calculating the cost of supplying water through centralized and decentralized water systems, socioeconomic as well as environmental considerations should be taken into account (Table 4). These costs vary from one country to the other depending on labor cost, availability of local skills and expertise, and the extent of environmental damage. However, in all cases the benefit of developing isolated and remote areas is considered as an aggregate demand (AD) to the economy of many countries.

5.1 Cost of Conventional Water Supply Systems

The future capital expenditures up to the year 2018 show the increments of approximately 50 % cost increase for water supply infrastructure in the span of 7 years (Fig. 13).

Table 5 presents the marginal cost of a new conventional water supply system including water treatment and water transportation costs.

Table 4 Characteristics of centralized and decentralized water supply systems [33, 34]

	Freshwater	Alternative sources of water
Centralized infrastructure	*Pros* – Scale effects – Provides consistent services – Financial solidarity at municipal level *Cons* – A number of negative externalities (environmental, financial) – Capital intensive and fails to attract private capital	*Pros* – Positive environmental externalities (resources, wastewater discharge) – Financial solidarity at municipal level *Cons* – Costly (several networks) – Energy intensive
Decentralized infrastructure	*Pros* – Less water leakage in mains and less energy used to transport water – Reduced energy use – Flexible and resilient – Deferred and reduced investment costs *Cons* – Additional connections are needed for reliable sourcing – Unequal service provision in the municipality – Inadequate monitoring systems	*Pros* – Positive environmental externalities (resource, wastewater discharge) – Reduced energy use – Flexible and resilient – Deferred and reduced investment costs – May harness new sources of finance *Cons* – Health issues related to potable reuse – Questions about relevance when central infrastructure is in place – Scale effect – Unequal service provision in the municipality – Inadequate monitoring and regulatory systems

The transport of water over long distances will increase the use of energy and the associated costs. Research shows that transporting water over long distances becomes more expensive than desalinated water produced locally [36]. The average cost of long-distance transporting potable water can be increased by 300 % over desalinated water which is produced and supplied to consumers locally.

5.2 Cost of Desalinated Water Systems

The cost of supplying desalinated water has gradually decreased with advances in desalination technologies. Table 6 shows the marginal cost of desalinated water.

The scale effect is an important deciding factor for desalination cost. Table 7 shows the capital cost and Unit Product Cost (UPC) for four desalination technologies and four different capacities. These costs were calculated using the correlations and cost breakdown for each plant [33].

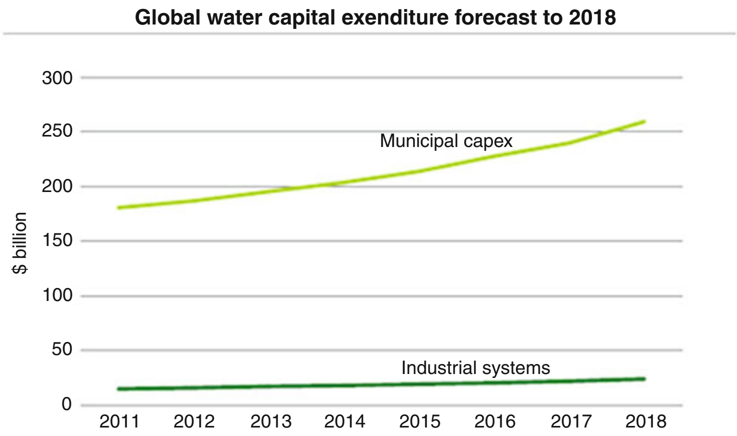

Fig. 13 Global water capital expenditure forecast to 2018 (*Source*: Global Water Market Report 2014, Publisher GWI [35])

Table 5 The marginal cost of new water resources

Water source	Capital cost (per ^{3}/d)	O&M cost per m^3	Notes
Shallow freshwater aquifer	$3	<$0.01	10,000 m^3/d at 10 m depth
Deep freshwater aquifer	$7	$0.07	10,000 m^3/d at 200 m depth
Long-distance transfer	$3,000	$0.15	500 km long; 100 m elevation; two million m^3/d capacity
New reservoir and conveyance	$1,700	<$0.01	250,000 m^3/d output with 20 km conveyance
Indirect potable reuse	$800	$0.45	50,000 m^3/d facility with UF, RO, and UV—water returned to aquifer
Shipping water by bladder	$60	$1.50	10,000 m^3 bladder to port unloading facility 50 km away
Shipping water by tanker	$120	$1	100,000 m^3 tanker traveling 50 km with loading and unloading facilities

Source: Global Water Market Report 2014, Publisher GWI [35]

Table 8 shows the total costs for different energy sources in a desalination plant with a capacity of 20,000 m^3. The indirect cost includes the environmental damage cost, CO_2 emission, pollution of water ways, etc. Cost calculations are subject to the prevailing prices in each country. Table 8 cost estimates are based on average US costs.

The actual and increased trend to supply desalinated water is based on availability of renewable energy. A good example is Saudi Arabia's Saline Water Conversion Corporation (SWCC) which is looking into a string of new membrane desalination plants, including a 600,000 m^3/day plant in Rabigh that would be the largest of its type in the world [10]. The move by SWCC, the world's largest

Table 6 The marginal cost of desalinated water

Water source	Capital cost (per m^3/d)	O&M cost (per m^3)	Notes
Brackish water desalination	$480	$0.29	10,000 m^3/d facility
Indirect potable reuse	$800	$0.45	50,000 m^3/d facility with UF, RO, and UV—water returned to aquifer
Membrane seawater desalination	$1,200	$0.47	100,000 m^3/d capacity
Thermal seawater desalination	$1,500	$0.57	300,000 m^3/d capacity

Source: Global Water Market Report 2014, Publisher GWI [35]

Table 7 Cost for four desalination technologies of different capacities [33]

Desalination technology	Capacity (m^3/d)	Capital cost (US$ × 10^6)	UPC (US$)
SWRO	10,000	20.1	0.95
	50,000	74.0	0.70
	275,000	293.0	0.50
	500,000	476.7	0.45
BWRO	10,000	8.1	0.38
Source (Wittholz et al. [37])	50,000	26.5	0.25
	275,000	93.5	0.16
	500,000	145.4	0.14
MSF	10,000	48.0	1.97
	50,000	149.5	1.23
	275,000	498.1	0.74
	500,000	759.6	0.62
MED	10,000	28.5	1.17
	50,000	108.4	0.89
	275,000	446.7	0.67
	500,000	734.0	0.60

Table 8 Cost of desalination plants by source of energy including environmental costs (US dollars) [33]

	Coal	Oil	Natural gas	Nuclear	Solar	Wind
Operating cost of a desalination plant	5,110,000	5,110,000	5,110,000	5,110,000	7,950,000	6,570,000
Energy cost	1,422,624	9,584,929	2,005,011	973,608	6,668,550	3,867,750
Environmental cost	775,325	534,000	318,702	2,546	0	0
Total	5,885,325	5,644,000	5,428,000	5,112,546	7,950,000	6,570,000

desalination procurement body, ties in with a broader plan to shift the Kingdom's power generation system away from its reliance on fossil fuels by investing in nuclear, wind, and solar energy. This shift is likely to mean a change in the country's long-running ties with thermal desalination, which has remained a favored option in the Gulf even as it has been overtaken by membrane desalination elsewhere. This was due to the artificially low operating costs that came with a ready supply of subsidized fuel and steam from collocated oil- or gas-fired power plants. Saudi Arabia's ambitious plans for renewable energy will mean changes for the country's pipeline of desalination projects—including what could be the world's largest membrane desalination plant.

5.3 *Cost of Solar Desalination Systems*

The produced water from solar desalination has the advantage of being a decentralized system due to the local availability of solar energy and saltwater. At present, the maximum capacity of commercial solar-powered desalination units is 170,000 m^3/day. These small solar-powered desalination units are ideal for remote areas and it most often forces governments to subsidize its operations.

The approximate cost of solar-driven desalination units was presented in Fig. 9. Even if at the present time the capital cost of solar desalination is higher than the traditional energy-driven desalination process, solar desalination realizes two important objectives: reducing CO_2 emissions and reducing the reliance on fossil energy.

From information related to general desalination cost discussed earlier, it is evident that, in general, energy presents about half of the projected desalination cost. This cost will increase if environmental cost is added. Generally, the environmental cost evaluation of solar desalination depends on several factors that include CO_2 emission, environmental damage, and the development of isolated areas. The economic benefits that can be attributed to the development of isolated areas must be incorporated in cost evaluation. Therefore, the traditional cost–benefit analysis cannot be applied to solar desalination. Costs and benefits for solar desalination must be analyzed in the context of the macroeconomy. Even with the aforementioned facts, sometimes the absolute value of solar desalination becomes competitive with the increased cost of fossil energy.

5.4 *Water Quality Concerns*

The rising proportion of desalinated seawater consumed by both the domestic and agricultural sectors constitutes a public health risk. Seawater desalination provides freshwater that typically lacks minerals essential to human health. While heavy minerals such as mercury are harmful to human health, some other minerals such as magnesium and fluoride are indispensable for human health. The World Health Organization (WHO) reported on a relationship between sudden cardiac death rates and magnesium intake deficits [38]. A recent study undertaken to provide recommendations for water distribution system (WDS) quality control in terms of meeting optimal water quality requirements shows the importance of remineralization

Table 9 WHO standards for potable water [39]

Constitutes	Concentration (mg/l) (Limited values)	TDS (mg/l) (Max. allowed values)
Total dissolved salts	500	1,500
Cl	200	600
SO_4^{2+}	200	400
Ca^{2+}	75	100
Mg^{2+}	30	150
F	0.7	1.7
NO^{3-}	<50	100
Cu^{2+}	0.05	1.5
Fe^{3+}	0.10	1.0
pH	7–8	6.5–9

through blending desalinated water with natural water to achieve the desired quality [38].

The posttreatment of desalinated water is a must in order to meet the WHO standards for potable water (Table 9). Also, as shown in Table 10, the potable water quality will be considered excellent if the total dissolved solids (TDS) concentration is less than 300 mg/l.

6 Solar Desalination Case Studies and Projects

Several desalination studies are carried out in the southern Mediterranean countries within the ADIRA Project [13]. The ADIRA project addresses autonomous desalination system concepts for seawater and brackish water in rural areas using renewable energy sources. Below are descriptions of some unique solar desalination case studies and projects implemented or planned in various countries.

6.1 DESSOL Project, Canary Islands

Scientists at the Technological Institute of The Canary Islands (ITC) and the Aachen University of Applied Sciences are investigating seawater desalination by reverse osmosis supplied by renewable energy [11]. The ITC installed a pilot plant called DESSOL (Desalination with Solar energy) in Pozo lzquierdo to demonstrate the technical feasibility of the technology. The reverse osmosis plant with a nominal production capacity of 10 m^3/day (specific energy consumption of 5.5 kWh/m^3) is supplied by a 4.8 kWp photovoltaic (PV) generator and a 19 kWh battery backup system. The energy system was optimized to supply energy for the reverse osmosis plant. The principle construction details of the PV supplied reverse osmosis plant, the description of the automatic control unit which adjusts the plant operation to the changing and discontinuous PV energy supply generator, the plant

Table 10 The water quality according to its TDS concentration

Quality	Total dissolved solids (mg/l)
Excellent	<300
Good	300–600
Fair	600–900
Poor	900–1,200
Unacceptable	>1,200

Source: WHO, 1984 [40]

operation performance, and the option of preheating the feed water are presented and discussed in the ITC report [11].

The DESSOL pilot operation has yielded important results related to the optimization of the plant operation and the coordination and timing of using solar energy in conjunction with RO system. For example, a solar thermal system was integrated into the energy supply system to increase the daily water production. As a result, the RO plant is now supplied with preheated seawater. This pilot plant experience has served for the manifestation of the technical concept of this technology and could be transformed into much larger drinking water production systems.

6.2 Agricultural University, Greece

The design of a stand-alone hybrid wind-PV system to power seawater RO desalination unit, with energy recovery using a simplified spreadsheet model, was tested at the Agricultural University of Athens, Greece [12]. A daily and monthly production simulation and economic analysis were also performed. The calculated freshwater production cost was 5.2 Euro/m^3, and the realized energy saving was up to 48 % when a pressure-exchanger-type energy recovery unit is considered.

6.3 Madrid University, Spain

A solar thermal and photovoltaic-powered RO desalination plant has been constructed and optimized for desalination of brackish water at Madrid University [41]. The central composite experimental design of orthogonal type and response surface methodology (RSM) was used to develop predictive models for simulation and optimization of different responses such as the salt rejection coefficient, the specific permeate flux, and the RO-specific performance index that takes into consideration the salt rejection coefficient, the permeate flux, the energy consumption, and the conversion factor. The considered input variables were the feed water temperature, feed water flow rate, and the feed pressure. Analysis of variance (ANOVA) has been employed to test the significance of the RSM polynomial models. The optimum operating conditions have been determined using the step adjusting gradient method. An optimum RO-specific performance index has been achieved experimentally under the obtained optimal conditions. The RO-optimized plant guarantees a potable water production of 0.2 m^3/day, with energy consumption lower than 1.3 kWh/m^3 [41].

6.4 Portable Thermoelectric Solar Still, Iran

A new type of Portable Thermoelectric Solar Still (PTSS) was designed in Semnan, Iran [42]. A thermoelectric module is used to improve the temperature difference between evaporating and condensing zones. Also, a heat-pipe cooling device is used to cool down the hot side of the thermoelectric cooler. To evaluate the performance of the PTSS, the equipment was tested under the climatic condition of Semnan (35° 33′ N, 53° 23′ E). The measurement of solar intensity, wind velocity, ambient temperature, water production, and temperature of model components, for example, thermoelectric module, water, walls, and heat pipe, was conducted in the same manner each day. The results show that ambient temperature and solar radiation have a direct effect on still performance, but there is a reduction in water productivity when wind speed was increased.

6.5 Dubai Project

The UAE would establish the world's largest solar-powered desalination plant that will process more than 80,000 m^3/day of potable water [43]. The new plant at Ras Al Khaimah emirate would also generate 20 MW of electricity. The project will implement the most advanced RO and filtration technologies, and when operational, it's expected to drastically push down the unit potable water production cost.

The Dubai project would set a new benchmark for the desalination business model and will be the world's greenest desalination plant with the least CO_2 emissions. The new solar-powered desalination plant will complement the clean coal power plant project announced in 2012. The two plants together will generate power and water while reducing CO_2 emissions by more than one million tonnes of CO_2 per year. Masdar city initiative aims to install up to five pilot solar-powered desalination plants in the Emirates of Abu Dhabi [44].

6.6 Saudi Arabia Project

Recently, an MED plant driven by an enhanced solar pond has been commissioned in Fujairah. Saudi Arabia. The project is expected to eclipse Kingdom's Al Khafji plant by generating twice as much power with output capacity of 10 MW and 40 m^3/day of water when completed [44]. Saudi Arabia's Saline Water Conversion Corporation (SWCC) is looking into a string of new membrane desalination plants, including a 600,000 m^3/day plant in Rabigh that would be the largest of its type in the world.

6.7 High Concentration Photovoltaic Thermal Project

In recent years, indirect solar desalination using modern solar photovoltaic technology alongside desalination methods such as coupling RO with Multiple-Effect Distillation (MED) and membrane distillation (MD), with potential to operate at a much larger scale, have been investigated [44]. The IBM in cooperation with the King Abdulaziz Research Center has developed the new system High Concentration Photovoltaic Thermal (HCPVT) based on research conducted at MIT [45] (Figs. 14, 15, and 16). The HCPVT approach can both eliminate the overheating of solar chips while also using the energy for thermal water desalination and cooling.

The prototype HCPVT system (Figs. 14, 15) uses a large parabolic dish, made from a multitude of mirror facets, which are attached to a sun tracking system. The tracking system positions the dish at the best angle to capture the sun's rays, which then reflect off the mirrors onto several microchannel-liquid cooled receivers with triple junction photovoltaic chips—each 1×1 cm chip can convert 25–50 W, on average, over a typical 8 h day in a sunny region.

The entire receiver of more than 500 chips can provide 25 kW of electricity. The coolant maintains the chips approximately at the same temperature for a solar concentration of 2,000 times and can keep chips at safe temperatures up to a solar concentration of 5,000 times. An initial demonstration of the multi-chip receiver was developed in a previous collaboration between IBM and the Egypt Nanotechnology Research Center [44].

In the HCPVT system shown in Fig. 16, instead of heating a building, the 90 ^{o}C water is used to heat salty water which then passes through a porous membrane distillation system (MD) where it is vaporized and desalinated. This system can provide 30–40 l of drinking water per square meter of receiver area per day and generate 2 kW hours per day of electricity.

An application of large-scale HCPVT technology is planned in KSA. A desalination plant with an expected production capacity of 30,000 cubic meters per day will be built in the city of Al Khafji to serve 100,000 people. King Abdul Aziz City for Science and Technology (KACST) plans to power the desalination plant with the ultrahigh concentrator photovoltaic (UHCPV) technology that is being jointly developed by IBM and KACST.

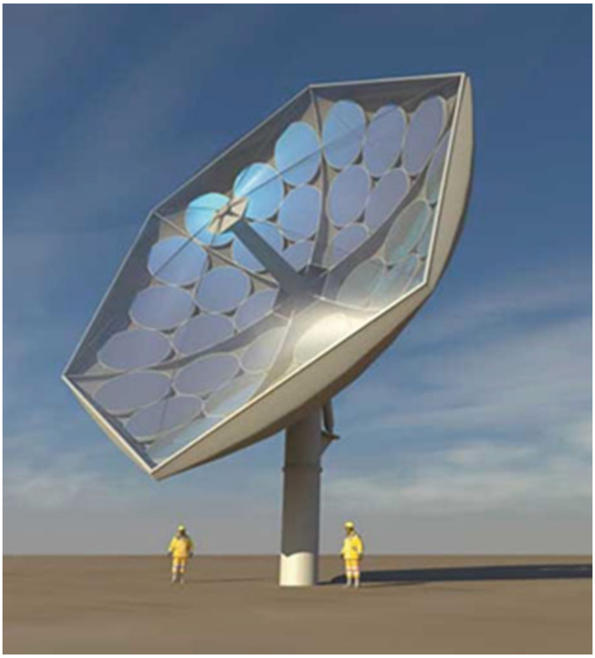

Fig. 14 The IBM's prototype HCPVT system uses a large parabolic dish constructed from a large array of mirror facets and connected to a sun tracking system (Courtesy of International Business Machines Corporation, ©International Business Machines Corporation [44])

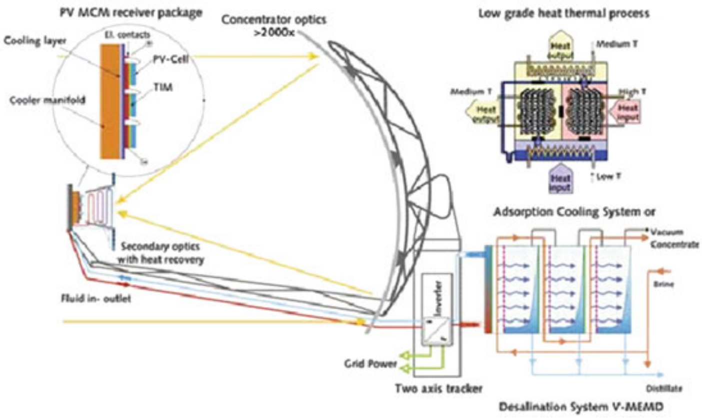

Fig. 15 The prototype HCPVT system under development (Courtesy of International Business Machines Corporation, ©International Business Machines Corporation [44])

Fig. 16 The IBM HCPVT system's heated waste water is diverted to a desalination system, where it vaporizes and purifies saltwater (Courtesy of International Business Machines (IBM) Corporation, ©International Business Machines Corporation [44])

6.8 Chile Project

Membrane-based technologies of the type described by Sommariva [44] using solar energy have recently been employed in Chile. The demonstration facility, established at the Padre Francisco Napolitano Agricultural School in the Lluta Valley, is powered by an array of solar photovoltaic panels. The plant is "simple in its construction and operation" and costs only US$ 210,000 (CLP 100 million). In the near future, the plant's operations will be closely monitored. In addition, a market study and business model will be created—with the ultimate aim to commercialize the technology for use at other locations across northern Chile. The project is established by the Chilean government supported Fundación Chile, via its Climate Change Fund, and is supported by Chile's national Innovation Fund for Competitiveness (FIC).

6.9 Australia Project

A Victorian company recently announced plans for the staged development of Australia's first solar-powered desalination plant near Port Augusta in South Australia [46]. The plan combines solar energy-based power generation, seawater desalination, and commercial salt production, all integrated into a single $370 million industrial complex.

The solar field will be laid out over a two-square-kilometer area with each solar mirror standing three meters tall. The captured heat will be used to create steam for electricity and desalination, with any excess heat going into thermal storage.

When the first stage is complete, the Point Paterson facility will produce 200 megawatts (MW) of electricity—50 MW solar thermal and 150 MW combined cycle gas turbine (CCGT). It will also produce 5.5 gigaliters of water per year—enough for 34,000 people. The plant will be configured to enable its expansion to produce more than 45 gigaliters of water—enough for more than 250,000 people per year.

Point Paterson will be a world-first plant that will combine large solar power station technologies and water desalination in a stand-alone, near-zero greenhouse gas emission facility. Unlike conventional desalination processes, Point Paterson will reduce or eliminate the need to dispose of by-product waste brine back into the sea. The technology is off-the-shelf, but the combination of the technologies in a high demand commercial environment for power, water, and salt is very unique.

7 Future Research Directives

The directives of future research needs are based on the mechanism of renewable energy use and innovations in membrane technologies. A few recent investigations are described below.

7.1 Thermal Processes

There are two inherent design problems facing solar thermal desalination projects. First, the system's efficiency is governed by preferably high heat and mass transfer during evaporation and condensation. The surfaces have to be properly designed within the contradictory objectives of heat transfer efficiency, economy, and reliability.

Second, the heat of condensation is valuable because it takes large amounts of solar energy to evaporate water and generate saturated, vapor-laden hot air. This energy is transferred to the condenser's surface during condensation. With most forms of solar stills, this heat of condensation is ejected from the system as waste heat. The challenge is to achieve the optimum temperature difference between the solar-generated vapor and the seawater-cooled condenser, maximal reuse of the energy of condensation, and minimizing the asset investment.

The directive in these trends is to reduce the temperature of phase change desalination process [14]. One possible solution is to create vacuum pressure within the feed saline water reservoir. In this process, saltwater is evaporated at near-ambient temperatures under near-vacuum pressures created by the barometric head without any mechanical energy input. This can be accomplished using a vacuum pump which significantly decreases the amount of energy required for desalination. For example, water at a pressure of 0.1 atm boils at 50 °C rather than 100 °C [47].

The prospect of developing a cost-effective solar desalination system is based on the following: (1) distillation processes driven by solar collectors and solar PV–RO systems have similar high costs, above $2/m^3 for large-capacity systems and even higher than $4/m^3 [42, 48] for smaller production; (2) capital costs of conventional distillation units with capacities suitable for rural areas are much higher than those of large capacities; (3) although unlike RO, MD is not yet a mature technology, similar costs are predicted in the literature by conventional energy-powered MD and RO systems; (4) the MD process is more suitable for stand-alone operation and for rural areas than RO because of its simpler operation and maintenance requirements, and it withstands changes in operational parameters and operation failures for human error with no damage [49].

7.2 Efficiency of Photovoltaic Cells

An important factor in solar desalination is the efficiency of photovoltaic panels. At present, the photovoltaic conversion efficiency in the laboratory is over 45 %, while the efficiency of commercial panels remains below 20 %.

The ongoing research at MIT aims to improve both photovoltaic and RO efficiencies at the same time [45]. In general, a solar panel produces more power at lower PV cell temperatures and an RO unit produces more freshwater with increasing water temperature. These complementary behaviors are exploited by cooling the solar panel using the RO feed water. Cooling the solar panel also permits the use of concentrating mirrors, which further increases system production. The control unit must prevent overheating of the panel and RO unit and balance the pressure within the system. The laboratory results show an improvement in overall efficiency of 49 % [45].

7.3 Nano-Composite RO Membranes

It has been demonstrated that desalinated water production of RO system cost can be reduced if high permeability membranes are used. The high permeability can be achieved through the proper incorporation of nanoparticles within thin film Nano-composite membranes (NanoH_2O) [50].

In the laboratory, Nano-composite membranes have shown performance exceeding that of existing commercial RO membranes. Nano-composite membrane technology is now in the process of being commercialized with trials and a specially designed full-scale manufacturing line is under way [51]. Moreover, other recent advances in membrane technology will provide further improvements in energy efficiency and cost savings [52–55].

7.4 *Large Diameter Spiral-Wound Membranes*

The 8-in. membrane elements have been the industrial standard size membranes used for RO in both seawater desalination and water reclamation processes (note: 1 in. = 2.540 cm) [48].

However, within large-scale RO plants, there is poor economy of scale for the 8-in. diameter membranes. Hallan et al. [56] reported that large diameter spiral-wound modules enable significant reductions in RO plant capital cost and lifecycle cost. The 16-in. diameter membrane was identified as the optimum diameter in view of the trade-off between cost savings and associated risks. The 16-in. diameter allows membrane active area and module productivity to increase 4.3 times more the standard SWRO module.

On the other hand, Koch Membranes recommends 18-in. as the optimum membrane diameter [57]. These different criteria over the standard format have resulted in the commercial development of elements and PVs of two dimensions. Dow Filmtec, Toray, and Hydranautics have developed 16-in. diameter × 40-in. length RO elements, and Koch Membranes has developed 18-in. diameter × 60-in. length RO elements. Today, large diameter RO membranes are commercially available and are being installed in demonstration SWRO plants [58].

8 Conclusions

The use of solar energy to drive desalination processes has become commercially feasible and in some cases an attractive option. The use of solar thermal energy in seawater desalination applications for capacities of up to 200 m^3 per day is a proven technology for providing potable water, but at present its implementation is mostly restricted to small-scale systems in rural and remote areas. The technical reasons are mainly the relatively low thermal efficiency and production rate of solar thermal energy compared to other systems.

However, the predicted shortages in fossil fuel supply and the growing need for freshwater demand for various uses have magnified the necessity for further development of desalination in conjunction with using renewable energies, particularly solar energy. At present, the most promising technologies are solar RO and the combination of different technologies such as MVC + RO. The conjunctive use of solar energy and large-scale desalination plants could also address some of the pressing environmental concerns such as CO_2 emission. The introduction of nano-technology to water treatment is expected to result in higher efficiencies in both mechanical and thermal desalination processes.

Disclaimer This chapter provides an overview of desalination technologies and available information on solar desalination. The authors make no representations or warranties of any kind and assume no liabilities of any kind with respect to the accuracy or completeness of the contents. References are provided for informational purposes only and do not constitute endorsement of any manufacturers, websites, or other sources cited in this chapter.

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