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Seawater desalination using renewable energy sources

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Abstract

The origin and continuation of mankind is based on water. Water is one of the most abundant resources on earth, covering three-fourths of the planet's surface. However, about 97% of the earth's water is salt water in the oceans, and a tiny 3% is fresh water. This small percentage of the earth's water—which supplies most of human and animal needs—exists in ground water, lakes and rivers. The only nearly inexhaustible sources of water are the oceans, which, however, are of high salinity. It would be feasible to address the water-shortage problem with seawater desalination; however, the separation of salts from seawater requires large amounts of energy which, when produced from fossil fuels, can cause harm to the environment. Therefore, there is a need to employ environmentally-friendly energy sources in order to desalinate seawater.

After a historical introduction into desalination, this paper covers a large variety of systems used to convert seawater into fresh water suitable for human use. It also covers a variety of systems, which can be used to harness renewable energy sources; these include solar collectors, photovoltaics, solar ponds and geothermal energy. Both direct and indirect collection systems are included. The representative example of direct collection systems is the solar still. Indirect collection systems employ two sub-systems; one for the collection of renewable energy and one for desalination. For this purpose, standard renewable energy and desalination systems are most often employed. Only industrially-tested desalination systems are included in this paper and they comprise the phase change processes, which include the multistage flash, multiple effect boiling and vapour compression and membrane processes, which include reverse osmosis and electrodialysis. The paper also includes a review of various systems that use renewable energy sources for desalination. Finally, some general guidelines are given for selection of desalination and renewable energy systems and the parameters that need to be considered.

Keywords: Desalination; Renewable energy; Solar collectors; Solar ponds; Photovoltaics; Wind energy; Geothermal energy; Solar stills; Phase change processes; Reverse osmosis

Contents

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1. Introduction

The provision of fresh water is becoming an increasingly important issue in many areas of the world. In arid areas potable water is very scarce and the establishment of a human habitat in these areas strongly depends on how such water can be made available.

Water is essential to life. The importance of supplying potable water can hardly be overstressed. Water is one of the most abundant resources on earth, covering three-fourths of the planet's surface. About 97% of the earth's water is salt water in the oceans and 3% (about 36 million km^3) is fresh water contained in the poles (in the form of ice), ground water, lakes and rivers, which supply most of human and animal needs. Nearly, 70% from this tiny 3% of the world's fresh water is frozen in glaciers, permanent snow cover, ice and permafrost. Thirty percent of all fresh water is underground, most of it in deep, hard-to-reach aquifers. Lakes and rivers together contain just a little more than 0.25% of all fresh water; lakes contain most of it.

1.1. Water and energy

Water and energy are two inseparable commodities that govern the lives of humanity and promote civilization. The history of mankind proves that water and civilization are two inseparable entities. This is proved by the fact that all great civilizations were developed and flourished near large sources of water. Rivers, seas, oases, and oceans have attracted mankind to their coasts because water is the source of life. History proves the importance of water in the sustainability of life and the development of civilization. Maybe the most significant example of this influence is the Nile River in Egypt. The river provided water for irrigation and mud full of nutrients. Ancient Egyptian engineers were able to master the river water and Egypt, as an agricultural nation, became the main wheat exporting country in the whole Mediterranean Basin [1]. Due to the richness of the river, various disciplines of science like astronomy, mathematics, law, justice, currency and police were created at a time when no other human society held this knowledge.

Nomenclature

c	mean specific heat under constant pressure for all liquid streams (kJ/kg K)
C	constant
d	average spacing between water and glass surface (m)
E	energy (kJ)
$E_{j,\mathrm{in}}$	input energy of stream j (kJ)
$E_{j,\mathrm{out}}$	output energy of stream j (kJ)
e_x	flow exergy (kJ/kg)
E_x	rate of exergy flow (kW)
F'	solar still efficiency factor (dimensionless)
f_n	mass rate of distillate obtained by flashing per stage (kg/h)
Gr	Grashof number (dimensionless)
G_t	solar radiation intensity (W/m^2)
h	specific enthalpy (kJ/kg)
H	total enthalpy (kJ)
h_cw	convective heat transfer coefficient from water surface to glass (W/m^2 K)
I_i	irreversibility rate of sub-system i (kJ/h)
I_T	rate of loss of exergy, or irreversibility rate, of process (kJ/h)
k	thermal conductivity (W/mK)
L	latent heat of vaporization on a mass or mole basis (kJ/kg); In Eqs. (3) and (5) units (J/kg)
L_m	average L (kJ/kg)
M	molar mass (kg/kmol)
m	mass (kg)
mf	mass fraction
M_d	mass rate of distillate (kg/h)
M_f	mass rate of feed (kg/h)
M_r	mass rate of recirculated brine (kg/h)
m_w	yield of still per unit area per hour (kg/m^2 h)
n	constant
N	total number of stages or effects, number of moles (kmol)
Nu	Nusselt number (dimensionless)
P	pressure (kPa)
P_g	partial vapour pressure at glass temperature (N/m^2)
Pr	Prandtl number (dimensionless)
P_w	partial vapour pressure at water temperature (N/m^2)
Q	rate of heating rate of heat transfer (kW)
q_cg	convective heat transfer rate from glass to ambient (W/m^2)
q_cw	convective heat transfer rate from water surface to glass cover (W/m^2)
q_ew	evaporative heat transfer rate from water surface to glass cover (W/m^2)
q_rg	radiative heat transfer rate from glass to ambient (W/m^2)
q_rw	radiative heat transfer rate from water surface to glass cover (W/m^2)
R	defined constant in Eq. (25), gas constant (kJ/kmol K)
R_g	reflectivity of glass (dimensionless)
R_w	reflectivity of water (dimensionless)
s	specific entropy (kJ/kg K)
S	total entropy (kJ/K)
T	temperature (K)
T_a	ambient air temperature (K)
T_b1	temperature of inlet brine (K)
T_bN	temperature of brine in the last effect (K)
T_g	average glass temperature (K)
T_h	top brine temperature (K)
T_o	environmental temperature (K)
T_v	vapour temperature (K)
T_w	average water temperature (K)
T_w0	temperature of basin water at $t=0$ (K)
U_L	overall heat transfer coefficient (W/m^2 K)
x	mole fraction
y_bN	mass fraction of salts in brine in the last effect (dimensionless)
y_o	mass fraction of salts at zero recovery (dimensionless)

Subscripts

br	brine
cond	condensate
m	mixture of salt and water
o	dead state
p	pressure
s	salt
w	water

Greek

α'_w	total absorptance at water mass
$(\alpha\tau)'_\mathrm{eff}$	effective absorptance-transmittance product
δ	exergy defect (Eq. (18))
ΔF	parameter equal to $T_\mathrm{h}-T_\mathrm{bN}=(T_\mathrm{b1}-T_\mathrm{bN})\times[N/(N-1)]$ (K).
ΔT_n	temperature drop between two stages or effects (K)
ε	boiling point rise augmented by vapour frictional losses (K)
η_i	instantaneous efficiency of solar still (dimensionless)
η_II	second law of efficiency
$\sum$	summation

Abbreviations

ED	electrodialysis
ER-RO	RO with energy recovery
LCZ	lower convecting zone

MEB	multiple effect boiling	PV	photovoltaics
MES	multiple effect stack	RES	renewable energy systems
MSF	multi-stage flash	RO	reverse osmosis
MVC	mechanical vapour compression	TDS	total dissolved solids
NCZ	non-convecting zone	TVC	thermal vapour compression
ppm	parts per million	UCZ	upper convecting zone
PR	performance ratio	VC	vapour compression

Energy is as important as water for the development of good standards of life because it is the force that puts in operation all human activities. Water is also itself a power generating force. The first confirmed attempts to harness waterpower occurred more than 2000 years ago in which time the energy gained was mainly used to grind grain [2].

The Greeks were the first to express philosophical ideas about the nature of water and energy. Thales of Militus (640–546 BC), one of the seven wise men of antiquity wrote about water [3,4] that it is fertile and moulded (can take the shape of its container). The same philosopher said that seawater is the immense sea that surrounds the earth, which is the primary mother of all life. Later on, Embedokles (495–435 BC) developed the theory of the elements [3] describing that the world consists of four primary elements: fire, air, water and earth. These with today's knowledge may be translated to: energy, atmosphere, water and soil, which are the four basic constituents that affect the quality of our lives [5].

Aristotle (384–322), who is one of the greatest philosophers and scientists of antiquity, described in a surprisingly correct way the origin and properties of natural, brackish and seawater. He wrote for the water cycle in nature [6]:

"Now the sun moving, as it does, sets up processes of change and becoming and decay, and by its agency the finest and sweetest water is every day carried out and is dissolved into vapor and rises to the upper regions, where it is condensed again by the cold and so returns to the earth. This, as we have said before, is the regular cycle of nature."

Even today no better explanation is given for the water cycle in nature. Really, the water cycle is a huge solar energy open distiller in a perpetual operational cycle. For the seawater Aristotle wrote [7]:

"Salt water when it turns into vapour becomes sweet, and the vapour does not form salt water when it condenses again. This is known by experiment."

1.2. Water demand and consumption

Man has been dependent on rivers, lakes and underground water reservoirs for fresh water requirements in domestic life, agriculture and industry. However, rapid industrial growth and the worldwide population explosion have resulted in a large escalation of demand for fresh water, both for the household needs and for crops to produce adequate quantities of food. Added to this is the problem of pollution of rivers and lakes by industrial wastes and the large amounts of sewage discharged. On a global scale, man-made pollution of natural sources of water is becoming one of the largest causes for fresh water shortage. Added to this is the problem of uneven distribution. For example, Canada has a tenth of the world's surface fresh water, but less than 1% of its population.

Of total water consumption, about 70% is used by agriculture, 20% is used by the industry and only 10% of the water consumed worldwide is used for household needs. It should be noted that before considering the application of any desalination method, water conservation measures should be considered first. For example drip irrigation, using perforated plastic pipes to deliver the water to crops, uses 30–70% less water than traditional methods and increases crop yield. This system was developed in the early 1960s but until today it is used in less than 1% of the irrigated land. In most places on the earth, governments heavily subsidise irrigation water and farmers have no incentive to invest in drip systems or any other water saving methods.

1.3. Desalination and energy

The only nearly inexhaustible sources of water are the oceans. Their main drawback, however, is their high salinity. Therefore, it would be attractive to tackle the water-shortage problem with desalination of this water. Desalinize in general means to remove salt from seawater or generally saline water.

According to World Health Organization (WHO), the permissible limit of salinity in water is 500 parts per million (ppm) and for special cases up to 1000 ppm, while most of the water available on earth has salinity up to 10,000 ppm, and seawater normally has salinity in the range of 35,000–45,000 ppm in the form of total dissolved salts [8]. Excess brackishness causes the problem of taste, stomach problems and laxative effects. The purpose of a desalination system is to clean or purify brackish water or seawater and supply water with total dissolved solids within the permissible limit of 500 ppm or less. This is accomplished by several desalination methods that will be analysed in this paper.

Desalination processes require significant quantities of energy to achieve separation of salts from seawater. This is highly significant as it is a recurrent cost, which few of the water-short areas of the world can afford. Many countries in the Middle East, because of oil income, have enough money to invest in and run desalination equipment. People in many other areas of the world have neither the cash nor the oil resources to allow them to develop in a similar manner. The installed capacity of desalinated water systems in year 2000 is about 22 million m^3/day, which is expected to increase drastically in the next decades. The dramatic increase of desalinated water supply will create a series of problems, the most significant of which are those related to energy consumption and environmental pollution caused by the use of fossil fuels. It has been estimated that the production of 22 million m^3/day requires about 203 million tons of oil per year (about 8.5 EJ/yr or 2.36×10^{12} kW h/yr of fuel). Given concern about the environmental problems related to the use of fossil fuels, if oil was much more widely available, it is questionable if we could afford to burn it on the scale needed to provide everyone with fresh water. Given current understanding of the greenhouse effect and the importance of CO_2 levels, this use of oil is debatable. Thus, apart from satisfying the additional energy demand, environmental pollution would be a major concern. If desalination is accomplished by conventional technology, then it will require burning of substantial quantities of fossil fuels. Given that conventional sources of energy are polluting, sources of energy that are not polluting will have to be developed. Fortunately, there are many parts of the world that are short of water but have exploitable renewable sources of energy that could be used to drive desalination processes.

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

Desalination of brackish water and seawater is one of the ways of meeting water demand. Renewable energy systems produce energy from sources that are freely available in nature. Their main characteristic is that they are friendly to the environment, i.e. they do not produce harmful effluents. Production of fresh water using desalination technologies driven by renewable energy systems is thought to be a viable solution to the water scarcity at remote areas characterized by lack of potable water and conventional energy sources like heat and electricity grid. Worldwide, several renewable energy desalination pilot plants have been installed and the majority have been successfully operated for a number of years. Virtually, all of them are custom designed for specific locations and utilize solar, wind or geothermal energy to produce fresh water. Operational data and experience from these plants can be utilized to achieve higher reliability and cost minimization. Although renewable energy powered desalination systems cannot compete with conventional systems in terms of the cost of water produced, they are applicable in certain areas and are likely to become more widely feasible solutions in the near future.

This paper presents a description of the various methods used for seawater desalination. Only methods, which are industrially matured, are reviewed. There are, however, other methods, like freezing and humidification/dehumidification methods, which are not included in this work as they are developed at a laboratory scale and have not been used on a large-scale for desalination. Special attention is given to the use of renewable energy systems in desalination. Among the various renewable energy systems, the ones that have been used, or can be used, for desalination are reviewed. These include solar thermal collectors, solar ponds, photovoltaics, wind turbines and geothermal energy.

2. History of desalination

As early as in the fourth century BC, Aristotle described a method to evaporate impure water and then condense it to obtain potable water. However, historically probably one of the first applications of seawater desalination by distillation is depicted at the drawing shown in Fig. 1. The need to produce fresh water onboard emerged by the time the long-distance trips were possible. The drawing illustrates an account by Alexander of Aphrodisias in AD 200, who said that sailors at sea boiled seawater and suspended large sponges from the mouth of a brass vessel to absorb what is evaporated. In drawing this off the sponges they found it was sweet water.

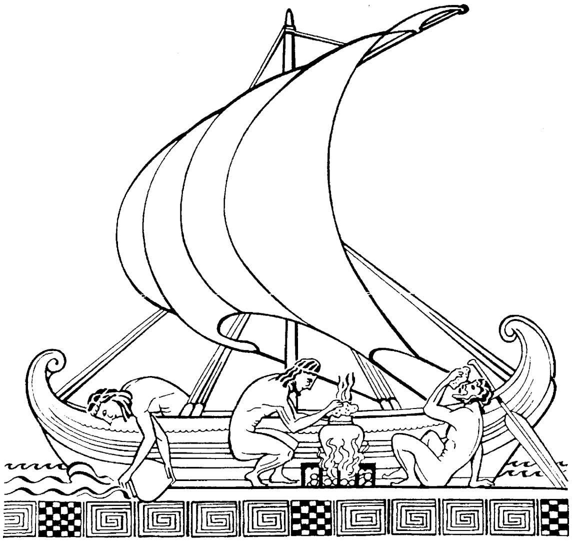


Fig. 1. Sailors producing fresh water with seawater distillation.

Solar distillation has been in practice for a long time. According to Malik et al. [9], the earliest documented work is that of an Arab alchemist in the 15th century reported by Mouchot in 1869. Mouchot reported that the Arab alchemist had used polished Damascus mirrors for solar distillation.

Until medieval times no important applications of desalination by solar energy existed. During this period, solar energy was used to fire alembics in order to concentrate dilute alcoholic solutions or herbal extracts for medical applications, to produce wine and various perfume oils. The stills or alembics were discovered in Alexandria, Egypt, during the Hellenistic period [10]. Cleopatra the Wise, a Greek alchemist, developed many distillers of this type [10]. One of them is shown in Fig. 2. The head of the pot was called the ambix, which in Greek means the 'head of the still', but this word was applied very often to the whole still. The Arabs who overtook science and especially alchemy about the seventh century, named the distillers Al-Ambiq, from which came the name alembic [1].

Mouchot [11] the well-known French scientist who experimented with solar energy, mentions in one of his numerous books that in the 15th century Arab alchemists used polished Damascus concave mirrors to focus solar radiation onto glass vessels containing salt water in order to produce fresh water. He also reports on his own solar energy experiments to distill alcohol and on an apparatus he developed with a metal mirror having a linear focus in which a boiler was located along its focal line [11].

Later on during the Renaissance, Giovani Batista Della Porta (1535–1615), one of the most important scientists of his time, wrote many books which were translated into French, Italian and German. In one of them, Magiae Naturalis, which appeared in 1558, he mentions three desalination systems [1]. In 1589 he issued the second edition, where in the volume on distillation he mentions seven methods of desalination. The most important of them is a solar distillation apparatus that converted brackish water into fresh water. In this, wide earthen pots were used, exposed to the intense heat of the solar rays to evaporate water and collect the condensate into vases placed underneath [12]. He also describes a method to obtain fresh water from the air (what is now known as the humidification/dehumidification method).

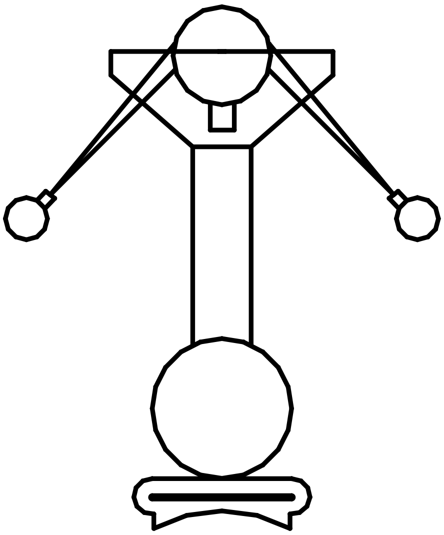


Fig. 2. The Cleopatra's alembic.

The great French chemist Lavoisier at about 1774 used large glass lenses, mounted on elaborate supporting structures, to concentrate solar energy on the contents of distillation flasks [1]. The use of silver or aluminium coated glass reflectors to concentrate solar energy for distillation has also been described by Mouchot.

In 1870 the first American patent on solar distillation was granted to the experimental work of Wheeler and Evans. Almost everything we know about the basic operation of the solar stills and the corresponding corrosion problems is described in that patent. The inventors described the greenhouse effect, analyzed in detail the cover condensation and re-evaporation, discussed the dark surface absorption and the possibility of corrosion problems. High operating temperatures were claimed as well as means of rotating the still in order to follow the solar incident radiation [13].

Two years later, in 1872, an engineer from Sweden, Carlos Wilson, designed and built the first large solar distillation plant, in Las Salinas, Chile [14], thus solar stills were the first to be used on large-scale distilled water production. The plant was constructed to provide fresh water to the workers and their families of a saltpeter mine and a nearby silver mine. They used the saltpeter mine effluents, of very high salinity (140,000 ppm), as feedwater to the stills. The plant was constructed of wood and timber framework covered with one sheet of glass. It consisted of 64 bays having a total surface area of 4450 m^2 and a total land surface area of 7896 m^2. It produced 22.70 m^3 of fresh water per day (about 4.9 l/m^2). The still was operated for 40 years and was abandoned only after a fresh-water pipe was installed supplying water to the area from the mountains.

In the First World Symposium on 'Applied Solar Energy', which took place in November 1955, Telkes described the Las Salinas solar distillation plant, and reported that it was in operation for about 36 continuous years [15].

The use of solar concentrators in solar distillation has been reported by Pasteur in 1928 [9] who used a concentrator to focus solar rays onto a copper boiler containing water. The steam generated from the boiler was piped to a conventional water cooled condenser in which distilled water was accumulated.

The renewal of interest on solar distillation occurred after the First World War at which time several new devices had been developed such as: roof type, tilted wick, inclined tray and inflated stills.

Until the Second World War only a few solar distillation systems existed. One of them designed by Abbot is a solar distillation device, similar to that of Mouchot [16,17].

At the same time some research on solar distillation was undertaken in the USSR [18,19]. During the years 1930–1940, the dryness in California initiated the interest in desalination of saline water. Some projects were started, but the depressed economy at that time did not permit any research or applications [1]. Interest grew stronger during World War II, when hundreds of Allied troops suffered from lack of drinking water while stationed in North Africa, the Pacific Ocean Islands and other isolated places. Then a team from MIT, led by Maria Telkes, began experiments with solar stills [20]. At the same time, the US National Research Defense Committee (NRDC) sponsored research to develop solar desalters for military use at sea. Many patents were granted [21–23] for individual small plastic solar distillation apparatuses that were developed to be used on lifeboats or rafts. These were designed to float on seawater when inflated and were used extensively by the US Navy during the War [24]. Telkes continued to investigate various configurations of solar stills including glass covered and multiple-effect solar stills [25–27].

The explosion of urban population and the tremendous expansion of industry after World War II, brought again the problem of good quality water into focus. In July 1952 the Office of Saline Water (OSW) was established in the United States, the main purpose of which was to finance basic research on desalination. OSW promoted desalination application through research. Five demonstration plants were built, and among them was a solar distillation in Daytona Beach, Florida, where many types and configurations of solar stills (American and foreign), were tested [28]. Loef, as a consultant to the OSW in the fifties, also experimented with stills, such as basin-type stills, solar evaporation with external condensers and multiple-effect stills, at the OSW experimental station in Daytona Beach.

In the following years many small capacity solar distillation plants were erected in some Caribbean Islands by McGill University of Canada. Howe from the Sea Water Conversion Laboratory of the University of California, Berkeley, was another pioneer in solar stills, who carried out many studies on solar distillation [29].

Experimental work on solar distillation was also performed at the National Physical Laboratory, New Delhi, India and in the Central Salt and Marine Chemical Research Institute, Bhavnagar, India [1]. In Australia, the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Melbourne, carried out a number of studies on solar distillation. In 1963, a prototype bay type still was developed, covered with glass and lined with black polyethylene sheet [30]. Using this prototype still, solar distillation plants were constructed in the Australian desert, providing fresh water from saline well water for people and livestock. At the same time, Baum in the USSR was experimenting with solar stills [31–33].

Between the years 1965 and 1970, solar distillation plants were constructed on four Greek Islands to provide small communities with fresh water [34–37]. The design of the stills was done at the Technical University of Athens and was of the asymmetric glass covered greenhouse-type with aluminum frames. The stills used seawater as feed and were covered with single glass. Their capacity ranged from 2044 to 8640 m^3/day. In fact the installation in the island of Patmos is the largest solar distillation plant ever built. In three more Greek Islands another three solar distillation plants were erected. These were plastic covered stills (tedlar) with capacities of 2886, 388 and 377 m^3/day that met the summer fresh water needs of the Young Men's Christian Association (YMCA) campus.

Solar distillation plants were also constructed on the Islands of Porto Santo, Madeira, Portugal and in India for which no detailed information exists. Today, most of these plants are not in operation. Although a lot of research is being carried out on solar stills no large capacity solar distillation plants have been constructed in recent years.

A survey of these simple methods of distilled water production, together with some other more complicated ones is presented in Sections 4 and 5.

3. Desalination processes

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 the following categories:

(i) phase-change or thermal processes; and
(ii) membrane or single-phase processes.

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

In Table 1, the most important technologies in use are listed. In the phase-change or thermal processes, the distillation of

Table 1
Desalination processes

Phase-change processes	Membrane processes
1. Multi-stage flash (MSF)	1. Reverse osmosis (RO)
2. Multiple effect boiling (MEB)	–RO without energy recovery
3. Vapour compression (VC)	–RO with energy recovery (ER-RO)
4. Freezing	2. Electrodialysis (ED)
5. Humidification/ dehumidification	
6. Solar stills –Conventional stills –Special stills –Cascaded type solar stills –Wick-type stills –Multiple-wick-type stills	

seawater is achieved by utilising a thermal energy source. The thermal energy may be obtained from a conventional fossil-fuel source, nuclear energy or from a non-conventional solar energy source or geothermal energy. In the membrane processes, electricity is used either for driving high-pressure pumps or for ionisation of salts contained in the seawater.

Commercial desalination processes based on thermal energy are multi-stage flash (MSF) distillation, multiple effect boiling (MEB) and vapour compression (VC), which could be thermal (TVC) or mechanical (MVC). MSF and MEB processes consist of a set of stages at successively decreasing temperature and pressure. MSF process is based on the generation of vapour from seawater or brine due to a sudden pressure reduction when seawater enters an evacuated chamber. The process is repeated stage by stage at successively decreasing pressure. This process requires an external steam supply, normally at a temperature around 100 °C. The maximum temperature is limited by the salt concentration to avoid scaling and this maximum limits the performance of the process. On MEB, vapours are generated due to the absorption of thermal energy by the seawater. The steam generated in one stage or effect is able to heat the salt solution in the next stage because the next stage is at a lower temperature and pressure. The performance of the MEB and MSF processes is proportional to the number of stages or effects. MEB plants normally use an external steam supply at a temperature of about 70 °C. On TVC and MVC, after initial vapour is generated from the saline solution, this vapour is thermally or mechanically compressed to generate additional production.

Not only distillation processes involve phase change, but also freezing and humidification/dehumidification processes. The conversion of saline water to fresh water by freezing has always existed in nature and has been known to man for thousands of years. In desalination of water by freezing fresh water is removed and leave behind concentrated brine. It is a separation process related to the solid–liquid phase change phenomenon. When the temperature of saline water is reduced to its freezing point, which is a function of salinity, ice crystals of pure water are formed within the salt solution. These ice crystals can be mechanically separated from the concentrated solution, washed and re-melted to obtain pure water. Therefore, the basic energy input for this method is for the refrigeration system [38]. Humidification/dehumidification method also uses a refrigeration system but the principle of operation is different. The humidification/dehumidification process is based on the fact that air can be mixed with large quantities of water vapour. Additionally, the vapour carrying capability of air increases with temperature [39]. In this process, seawater is added into an air stream to increase its humidity. Then this humid air is directed to a cool coil on the surface of which water vapour contained in the air is condensed and collected as fresh water. These processes, however, exhibit some technical problems which limit their industrial development. As these technologies have not yet industrially matured, they are not included in this paper.

The other category of industrial desalination processes does not involve phase change but membranes. These are the reverse osmosis (RO) and electrodialysis (ED). The first one requires electricity or shaft power to drive the pump that increases the pressure of the saline solution to that required. The required pressure depends on the salt concentration of the resource of saline solution and it is normally around 70 bar for seawater desalination.

ED also requires electricity for the ionisation of water which is cleaned by using suitable membranes located at the two appositively charged electrodes. Both of them, RO and ED, are used for brackish water desalination, but only RO competes with distillation processes in seawater desalination. The dominant processes are MSF and RO, which account for 44 and 42% of worldwide capacity, respectively [40]. The MSF process represents more than 93% of the thermal process production, while RO process represents more than 88% of membrane processes production [41]. All the above processes are described in more detail in Section 5.

Solar 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. Solar desalination systems are thus classified into two categories, i.e. direct and indirect collection systems. As their name implies, direct collection systems use solar energy to produce distillate directly in the solar collector, whereas in indirect collection systems, two sub-systems are employed (one for solar energy collection and one for desalination). Conventional desalination systems are similar to solar systems since the same type of equipment is applied. The prime difference is that in the former, either a conventional boiler is used to provide the required heat or mains electricity is used to provide the required electric power, whereas in the latter, solar energy is applied. The most promising and applicable renewable energy systems (RES) desalination combinations are shown in Table 2.

Over the last two decades, numerous desalination systems utilizing renewable energy have been constructed. Almost all of these systems have been built as research or demonstration projects and were consequently of a small capacity. It is not known how many of these plants still exist but it is likely that only some remain in operation. The lessons learnt have hopefully been passed on and are reflected in the plants currently being built and tested. A list of installed desalination plants operated with renewable energy sources is given by Tzen and Morris [43].

3.1. Desalination systems exergy analysis

Although the first law is an important tool in evaluating the overall performance of a desalination plant, such analysis does not take into account the quality of energy

Table 2
RES desalination combinations [42]

RES technology	Feed water salinity	Desalination technology
Solar thermal	Seawater	Multiple effect boiling (MEB)
	Seawater	Multi-stage flash (MSF)
Photovoltaics	Seawater	Reverse osmosis (RO)
	Brackish water	Reverse osmosis (RO)
	Brackish water	Electrodialysis (ED)
Wind energy	Seawater	Reverse osmosis (RO)
	Brackish water	Reverse osmosis (RO)
	Seawater	Mechanical vapor compression (MVC)
Geothermal	Seawater	Multiple effect boiling (MEB)

transferred. This is an issue of particular importance when both thermal and mechanical energy are employed, as they are in thermal desalination plants. First-law analysis cannot show, where the maximum loss of available energy takes place and would lead to the conclusion that the energy loss to the surroundings and the blowdown are the only significant losses. Second-law (exergy) analysis is needed to place all energy interactions on the same basis and to give relevant guidance for process improvement.

The use of exergy analysis in actual desalination processes from a thermodynamic point of view is of growing importance to identify the sites of greatest losses and to improve the performance of the processes. In many engineering decisions, other facts such as the impact on the environment and society must be considered when analyzing the processes. In connection with the increased use of exergy analysis, second law analysis has come into more common usage in recent years. This involves a comparison of exergy input and exergy destruction along various desalination processes. In this section initially the thermodynamics of saline water, mixtures and of separation processes is presented followed by the analysis of multi-stage thermal processes. The former also applies to the analysis of reverse osmosis which is a non-thermal separation process.

Saline water is a mixture of pure water and salt. A desalination plant performs a separation process in which the incoming saline water is separated into two outgoing streams of brine and product water. The product water contains a low concentration of dissolved salts, whereas the brine contains the remaining high concentration of dissolved salts. Therefore, when analyzing desalination processes, the properties of salt and pure water must be taken into account. One of the most important properties in such analysis is salinity. Salinity is usually expressed in parts per million (ppm), which is defined as $\text{ppm}=mf_s\times10^6$. Therefore, a salinity of 1000 ppm corresponds to a salinity of 0.1%, or a salt mass fraction of $mf_s=0.001$. Then the mole fraction of salt x_s becomes [44]

$$mf_s=\frac{m_s}{m_{sw}}=\frac{N_sM_s}{N_{sw}M_{sw}}=x_s\frac{M_s}{M_{sw}} \quad \text{and} \quad mf_w=x_w \tag{1}$$

where m is mass, M is the molar mass, N is the number of moles, and x is the mole fraction. The subscripts s, w, and sw stand for salt, water, and saline water, respectively. The apparent molar mass of the saline water is [45]:

$$M_{sw}=\frac{m_{sw}}{N_{sw}}=\frac{N_sM_s+N_wM_w}{N_{sw}}=x_sM_s+x_wM_w \tag{2}$$

The molar masses of NaCl and water are 58.5 and 18.0 kg/kmol, respectively. Salinity is usually given in terms of mass fractions, but the minimum work calculations require mole fractions. Combining Eqs. (1) and (2) and considering that $x_s+x_w=1$ gives the following relations for converting mass fractions to mole fractions:

$$x_s=\frac{M_w}{M_w(1/mf_s-1)+M_w} \quad \text{and} \quad x_w=\frac{M_s}{M_w(1/mf_w-1)+M_s} \tag{3}$$

Solutions that have a concentration less than 5% are considered to be dilute solutions. Dilute solutions closely approximate the behavior of an ideal solution, and thus the effect of dissimilar molecules on each other is negligible. Brackish underground water and even seawater are all ideal solutions since they have about a 4% salinity at most [45].

Extensive properties of a mixture are the sum of the extensive properties of its individual components. Thus, the enthalpy and entropy of a mixture are determined from:

$$\begin{aligned} H&=\sum m_ih_i=m_sh_s+m_wh_w \quad \text{and}\\ S&=\sum m_is_i=m_ss_s+m_ws_w \end{aligned} \tag{4}$$

Dividing by the total mass of the mixture gives the quantities per unit mass of mixture:

$$\begin{aligned} h&=\sum mf_ih_i=mf_sh_s+mf_wh_w \quad \text{and}\\ s&=\sum mf_is_i=mf_ss_s+mf_ws_w \end{aligned} \tag{5}$$

The enthalpy of mixing of an ideal gas mixture is zero (no heat is released or absorbed during mixing), and thus the enthalpy of the mixture (and the enthalpies of its individual components) do not change during mixing. Therefore, the enthalpy of an ideal mixture at a specified temperature and pressure is the sum of the enthalpies of its individual components at the same temperature and pressure [46]. This also applies for the saline solution.

The brackish or seawater used for desalination is at a temperature of about 15 °C (288.15 K), pressure of 1 atm, and a salinity of 1500–35,000 ppm. These conditions can be taken to be the conditions of the environment.

Properties of pure water are readily available in tabulated or computerized forms. Those of salt are calculated by using the thermodynamic relations for solids. These relations, however, require that the reference state of salt be chosen to determine the values of properties at specified states. The state of salt at 0 °C can be taken as the reference state, and the values of enthalpy and entropy of salt are assigned a value of zero at that state. Then the enthalpy and entropy of salt at temperature T can be determined from:

$$h_s = h_{so} + c_{ps}(T - T_o) \quad \text{and} \quad s_s = s_{so} + c_{ps}\ln(T/T_o) \tag{6}$$

The specific heat of salt can be taken to be c_{ps} = 0.8368 kJ/kg K. The enthalpy and entropy of salt at T_o = 288.15 K can be determined to be h_{so} = 12.552 kJ/kg and s_{so} = 0.04473 kJ/kg K, respectively. It should be noted that for incompressible substances and enthalpy and entropy are independent of pressure [45].

Mixing is an irreversible process, and thus the entropy of a mixture at a specified temperature and pressure must be greater than the sum of the entropies of the individual components (prior to mixing) at the same temperature and pressure. Then it follows that the entropies of the components of a mixture are greater than the entropies of their pure counterparts at the same temperature and pressure since the entropy of a mixture is the sum of the entropies of its components. The entropy of a component per unit mole in an ideal solution at a specified temperature T and pressure P is [47]:

$$s_i = s_{i,\text{pure}}(T, P) - R\ln(x_i) \tag{7}$$

Note that $\ln(x_i)$ is a negative quantity since $x_i < 1$, and thus $-R\ln(x_i)$ is always a positive quantity. Therefore, the entropy of component in a mixture is always greater than the entropy of that component when it exists alone at the mixture temperature and pressure. Then the entropy of a saline solution is the sum of the entropies of salt and water in the saline solutions [45]:

$$\begin{aligned} s = x_s s_s + x_w s_w &= x_s[s_{s,\text{pure}}(T,P) - R\ln(x_s)] \\ &+ x_w[s_{w,\text{pure}}(T,P) - R\ln(x_w)] = x_x s_{s,\text{pure}}(T,P) \\ &- R[x_s\ln(x_s) + x_w\ln(x_w)] \end{aligned} \tag{8}$$

The entropy of saline water per unit mass is determined by dividing the quantity above (which is per unit mole) by the molar mass of saline water. Thus:

$$\begin{aligned} s = mf_s s_{s,\text{pure}}(T,P) + mf_w s_{w,\text{pure}}(T,P) - R[x_s\ln(x_s) \\ + x_w\ln(x_w)]\ (\text{kJ/kg K}) \end{aligned} \tag{9}$$

The exergy of a flow stream is given as [47]:

$$e_x = h - h_o - T_o(s - s_o) \tag{10}$$

Then the rate of exergy flow associated with a fluid stream becomes:

$$E_x = me_x = m[h - h_o - T_o(s - s_o] \tag{11}$$

Using the relations above, the specific exergy and exergy flow rates at various points of a reverse osmosis system can be evaluated. Once exergy flow rates are available, exergy destroyed within any component can be determined from exergy balance. Note that the exergy of raw brackish or seawater is zero since its state is taken to be the dead state. Also, exergies of brine streams are negative due to salinities above the dead state level.

3.1.1. Exergy analysis of thermal desalination systems

From the first law of thermodynamics, the energy balance equation can be obtained as:

$$\sum_{\text{in}} E_j + Q = \sum_{\text{out}} E_j + W \tag{12}$$

The mass, species, and energy balance equations for all the plant sub-systems, and a few associated state and effect related functions yield a set of n independent equations. This set of simultaneous equations is solved by matrix algebra assuming equal temperature intervals for all effects, and assuming that all effects have adiabatic walls [48].

The boundary conditions are the specified sea water feed conditions (flow rate, salinity, temperature), the desired distillate production rate, and the specified maximum brine salinity and temperature. The matrix solutions obtained determine the distillation rates in the individual effects, the steam requirements, and hence the performance ratio.

The steady-state exergy balance equation may be written as:

Total exergy transported into system = Total exergy transported out of system + Energy destroyed within system (or total irreversibility).

Thus

$$\sum E_{x,\text{in}} = \sum E_{x,\text{out}} + I_T \tag{13}$$

where

$$\sum E_{x,\text{in}} = \sum E_{x,\text{sw,in}} + \sum E_{x,\text{steam}} + \sum E_{x,\text{pumps}} \tag{14}$$

and

$$\sum E_{x,\text{out}} = \sum E_{x,\text{cond}} + \sum E_{x,\text{br}} \tag{15}$$

The system overall irreversibility rate can be expressed as the summation of the sub-system irreversibility rate

$$I_T = \sum_J I_i \tag{16}$$

where J is the number of sub-systems in the analysis and I_i is the irreversibility rate of sub-system i. The exergy (or second law) efficiency η_{II}, given by

$$\eta_{II} = \frac{\sum E_{x,\text{out}}}{\sum E_{x,\text{in}}} \tag{17}$$

is used as a criterion of performance, with $E_{x,\text{in}}$ and $E_{x,\text{out}}$ defined by Eqs. (14) and (15), respectively. The total loss of exergy is made up of the individual exergy losses of the plant sub-systems. The exergy efficiency defect δ_i of each

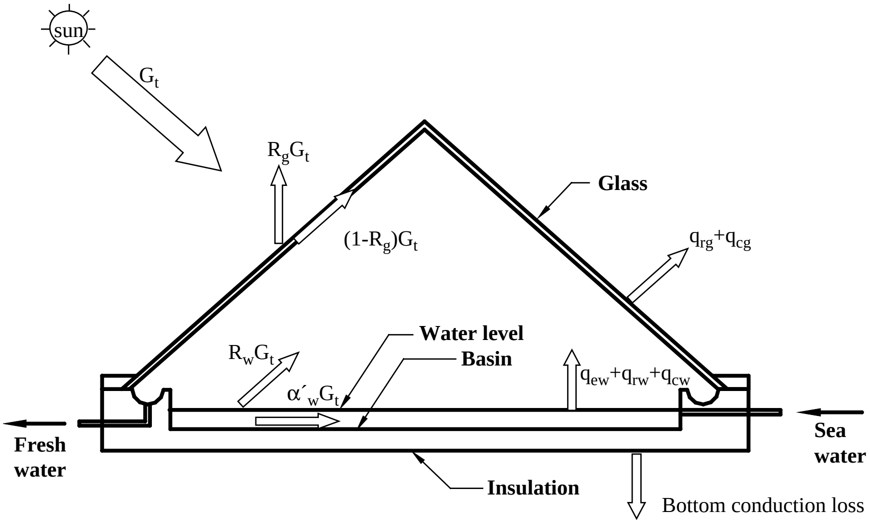


Fig. 3. Schematic of a solar still.

sub-system is defined by:

$$\delta_i = \frac{I_i}{\sum E_{\mathrm{x,in}}} \tag{18}$$

Combining Eqs. (17) and (18) gives:

$$I = \eta_{\mathrm{II}} + \delta_1 + \delta_2 + \cdots + \delta_j \tag{19}$$

The exergy of the working fluid at each point, calculated from its properties, is

$$E_{\mathrm{x}} = M[(h - h_{\mathrm{o}}) - T_{\mathrm{o}}(s - s_{\mathrm{o}})] \tag{20}$$

where the subscript 'o' indicates the 'dead state' or environment defined in the previous section.

A review of the energetics of desalination processes is given by Spiegler and El-Sayed [49].

4. Direct collection systems

Among the non-conventional methods to desalinate brackish water or seawater, is solar distillation. Comparatively, this requires a simple technology which can be operated by non-skilled workers. Also due to the low maintenance requirement, it can be used anywhere with lesser number of problems.

A representative example of direct collection systems is the conventional solar still, which uses the greenhouse effect to evaporate salty water. It consists of a basin, in which a constant amount of seawater is enclosed in a 'V'-shaped glass envelope (see Fig. 3). The sun's rays pass though the glass roof and are absorbed by the blackened bottom of the basin. As the water is heated, its vapour pressure is increased. The resultant water vapour is condensed on the underside of the roof and runs down into the troughs, which conduct the distilled water to the reservoir. The still acts as a heat trap because the roof is transparent to the incoming sunlight, but it is opaque to the infrared radiation emitted by the hot water (greenhouse effect). The roof encloses all of the vapour, prevents losses, and keeps the wind from reaching and cooling the salty water.

Fig. 3 shows the various components of energy balance and thermal energy loss in a conventional double slope symmetrical solar distillation unit (also known as roof type or greenhouse type solar still). The still consists of an air tight basin, usually constructed out of concrete/cement, galvanized iron sheet (GI) or fibre reinforced plastic (FRP) with a top cover of transparent material like glass or plastic. The inner surface of the base known as the basin liner is blackened to absorb efficiently the solar radiation incident on it. There is a provision to collect distillate output at the lower ends of top cover. The brackish or saline water is fed inside the basin for purification using solar energy.

The stills require frequent flushing, which is usually done during the night. Flushing is performed to prevent salt precipitation [50]. Design problems encountered with solar stills are brine depth, vapour tightness of the enclosure, distillate leakage, methods of thermal insulation, and cover slope, shape and material [50,51]. A typical still efficiency, defined as the ratio of the energy utilised in vaporising the water in the still to the solar energy incident on the glass cover, is 35% (maximum) and daily still production is about 3–4 l/m^2 [52].

Talbert et al. [28] gave an excellent historical review of solar distillation. Delyannis and Delyannis [53] reviewed the major solar distillation plants around the world. This review also included the work of Delyannis [54], Delyannis and Piperoglou [55], and Delyannis and Delyannis [56]. Malik et al. [57] reviewed the work on passive solar distillation system till 1982 and this was updated up to 1992 by Tiwari [58], which also included active solar distillation.

Kalogirou [59] also reviewed various types of solar stills. Gomkale [60] studied in detail the solar distillation systems as per the Indian scenario. Fath [61] reviewed the various designs of solar stills and studied the suitability of solar stills for providing potable water.

Several attempts have been made to use cheaper materials such as plastics. These are less breakable, lighter in weight for transportation, and easier to set up and mount. Their main disadvantage is their shorter life [52]. Many variations of the basic shape shown in Fig. 3 have been developed to increase the production rates of solar stills [51, 62,63]. Some of the most popular are shown in Fig. 4.

4.1. Classification of solar distillation systems

On the basis of various modifications and mode of operations introduced in conventional solar stills, these are classified as passive and active. In the case of active solar stills, an extra-thermal energy by external equipment is fed into the basin of passive solar still for faster evaporation. The external equipment may be a collector/concentrator panel [64–68], waste thermal energy from any chemical/industrial plant [69] or conventional boiler. If no such external equipment is used then that type of solar still is known as passive solar still [70–75]. Different types of solar still available in the literature are conventional solar stills, single-slope solar still with passive condenser, double condensing chamber solar still [76], vertical solar still [77–79], conical solar still [80], inverted absorber solar still [81] and multiple effect solar still [82–87].

Other researchers have used different techniques to increase the production of stills. Rajvanshi [88] used various dyes to enhance performance. These dyes darken the water and increase its solar radiation absorptivity. With the use of black napthalamine at a concentration of 172.5 ppm, the still output could be increased by as much as 29%. The use of these dyes is safe because evaporation in the still occurs at 60 °C, whereas the boiling point of the dye is 180 °C.

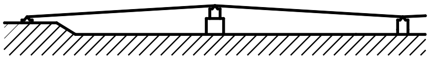
Akinsete and Duru [89] increased the production of a still by lining its bed with charcoal. The presence of charcoal leads to a marked reduction in start-up time. Capillary action by the charcoal partially immersed in a liquid and its reasonably black colour and surface roughness reduce the system thermal inertia.

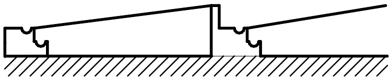
Lobo and Araujo [90] developed a two-basin type solar still. This still provides a 40–55% increase in fresh water produced as compared to a standard still, depending on the intensity of solar radiation. The idea is to use two stills, one on top of the other, the top one being made completely from glass or plastic and separated into small partitions. Similar results were obtained by Al-Karaghouli and Alnaser [91,92] who compared the performance of single and double-basin solar stills.

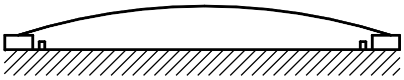
Frick and Sommerfeld [93], Sodha et al. [94] and Tiwari [95] developed a simple multiple-wick-type solar still in which blackened wet jute cloth forms the liquid surface. Jute-cloth pieces of increasing lengths were used, separated by thin black polyethylene sheets resting on foam insulation. Their upper edges are dipped in a saline water tank, where capillary suction provides a thin liquid sheet on the cloth, which is evaporated by solar energy. The results showed a 4% increase in still efficiency above conventional stills.

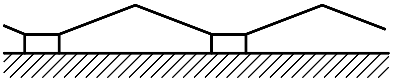
Evidently, the distance of the gap between the evaporator tray and the condensing surface (glass cover) has a considerable influence on the performance of a solar still which increases with decreasing gap distance. This led to the development of a different category of solar stills, namely, the cascaded type solar still [96]. This consists mainly of shallow pools of water arranged in cascade, as shown in Fig. 5, covered by a slopping transparent enclosure. The evaporator tray is usually made of a piece of corrugated aluminium sheet (similar to the one used for roofing) painted flat black.

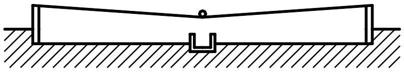
Thermodynamic and economic analysis of solar stills are given by Goosen et al. [97]. Boeher [98] reported a high-efficiency water distillation of humid air with heat recovery,


BASIN TYPE SOLAR STILL


SINGLE SLOPED COVER DESIGN


INFLATED PLASTIC COVER DESIGN


GREENHOUSE TYPE SOLAR STILL


V–SHAPE PLASTIC COVER DESIGN

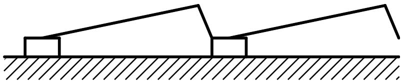

INCLINED GLASS COVER DESIGN

Fig. 4. Common designs of solar stills.

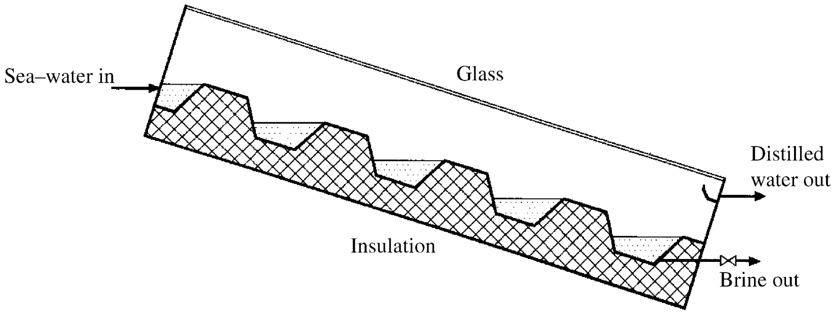


Fig. 5. Schematic of a cascaded solar still.

with a capacity range of 2–20 m^3/day. Solar still designs in which the evaporation and condensing zones are separated are described in Hussain and Rahim [99] and El-Bahi and Inan [100]. Besides that, a device that uses a ‘capillary film distiller’ was implemented by Bouchekima et al. [101] and a solar still integrated in a greenhouse roof is reported by Chaibi [102]. Active solar stills in which the distillation temperature is increased by flat plate collectors connected to the stills is given by Kumar and Tiwari [103], Sodha and Adhikari [104], Voropoulos et al. [105] and Yadav [106].

4.2. Performance of solar stills

The performance of a conventional solar distillation system can be predicted by various methods such as, computer simulation [107], thermic circuit and the sankey-diagrams [108], periodic and transient analysis [109–114], iteration methods [115] and numerical methods [116–118]. In most of the above-mentioned methods, the basic internal heat and mass transfer relations, given by Dunkle [119] has been used.

Following Dunkle [119], the hourly evaporation per square metre from solar still is given by

$$q_{\mathrm{ew}} = 0.0163 h_{\mathrm{cw}} (P_{\mathrm{w}} - P_{\mathrm{g}}) \tag{21}$$

where P_{w} and P_{g} are the partial vapour pressure at water and glass temperature, respectively, and h_{cw} is the convective heat transfer coefficient from water surface to glass given by:

$$Nu = \frac{h_{\mathrm{cw}} d}{k} = C (Gr\,\mathrm{Pr})^n \tag{22}$$

The hourly distillate output per square metre from a distiller unit (m_{w}) is given by

$$m_{\mathrm{w}} = 3600 \frac{q_{\mathrm{ew}}}{L} = 0.0163 (P_{\mathrm{w}} - P_{\mathrm{g}}) \left(\frac{k}{d}\right) \left(\frac{3600}{L}\right) C (Gr\,\mathrm{Pr})^n \tag{23}$$

or

$$\frac{m_{\mathrm{w}}}{R} = C (Gr\,\mathrm{Pr})^n \tag{24}$$

where

$$R = 0.0163 (P_{\mathrm{w}} - P_{\mathrm{g}}) \left(\frac{k}{d}\right) \left(\frac{3600}{L}\right) \tag{25}$$

where k is the thermal conductivity, d is the average spacing between water and glass and L is the latent heat of vaporisation.

The constants C and n are calculated by regression analysis for known hourly distillate output [119], water and condensing cover temperatures and design parameters for any shape and size of solar stills [120].

Following Tiwari [121], the instantaneous efficiency of a distiller unit is given as:

$$n_i = \frac{q_{\mathrm{ew}}}{G_{\mathrm{t}}} = \frac{h_{\mathrm{ew}} (T_{\mathrm{w}} - T_{\mathrm{g}})}{G_{\mathrm{t}}} \tag{26}$$

Simplifying the above equation we can write:

$$n_i = F' \left[(\alpha\tau)_{\mathrm{eff}} + U_{\mathrm{L}} \left(\frac{T_{\mathrm{w0}} - T_{\mathrm{a}}}{G_{\mathrm{t}}} \right) \right] \tag{27}$$

The above equation describes the characteristic curve of a solar still in terms of solar still efficiency factor (F'), effective transmittance-absorptance product, $(\alpha\tau)'_{\mathrm{eff}}$ and overall heat loss coefficient (U_{L}) [122].

A detailed analysis of the equations of n_i justifies that the overall heat loss coefficient (U_{L}) should be maximum for faster evaporation that will result in higher distillate output.

The meteorological parameters, namely wind velocity [123,124], solar radiation, sky temperature, ambient temperature, salt concentration, algae formation on water and mineral layers on basin liner affect significantly the performance of solar stills [125]. For better performance of a conventional solar still, the following modifications were suggested by various researchers:

- reducing bottom loss coefficient [114,126],
- reducing water depth in basin/multi-wick solar still [114, 127,128],
- using reflector [129,130],
- using internal [131] and external condensers [132],
- using back wall with cotton cloth [129],
- use of dye [88,111,133,134],

- use of charcoal [89,135,136],
- use of energy storage element [135,136],
- use of sponge cubes [137],
- multi-wick solar still [94],
- condensing cover cooling [138–140],
- inclined solar still [57], and
- increasing evaporative area [141].

It is observed that there is about a 10–15% change in overall daily yield of solar stills due to variations in climatic and operational parameters within the expected range.

4.3. General comments

Generally, the cost of water produced in solar distillation systems depends on the total capital investment to build the plant, the maintenance requirements, and the amount of water produced. No energy is required to operate the solar stills unless pumps are used to transfer the water from the sea. Thus, the major share of the water cost in solar distillation is that of amortization of the capital cost. The production rate is proportional to the area of the solar still, which means the cost per unit of water produced is nearly the same regardless of the size of the installation. This is in contrast with conditions for fresh water supplies as well as for most other desalination methods, where the capital cost of equipment per unit of capacity decreases as the capacity increases. This means that solar distillation may be more attractive than other methods for small sizes. Howe and Tleimat [142] reported that the solar distillation plants having capacity less than 200 m^3/day are more economical than other plants.

Kudish and Gale [143] have presented the economic analysis of a solar distillation plant in Israel assuming the maintenance cost of the system to be constant. An economic analysis for basin and multiple-wick type solar stills has been carried out by various scientists [74,144–146]. They have done economic analysis by incorporating the effect of subsidy, rainfall collection, salvage value and maintenance cost of the system. Barrera [147] had developed a solar water still called the ‘staircase solar still’ in Mexico and presented a techno-economic analysis of the system. He stated that distilled water production for potable use might be 3.5 times more economical than chemical water acquisition.

Zein and Al-Dallal [148] performed chemical analysis to find out its possible use as potable water and results were compared with tap water. They concluded that the condensed water can be mixed with well water to produce potable water and the quality of this water is comparable with that obtained from industrial distillation plants. The tests performed also showed that impurities like nitrates, chlorides, iron, and dissolved solids in the water are completely removed by the solar still.

Although the yield of solar stills is very low, their use may prove to be economically viable if small water quantities are required and the cost of pipework and other equipment required to supply an arid area with naturally produced fresh water is high.

Solar stills can be used as desalinators for such remote settlements, where salty water is the only water available, power is scarce and demand is less than 200 m^3/day [142]. This is very feasible if setting of water pipelines for such areas is uneconomical and delivery by truck is unreliable and/or expensive. Since, other desalination plants are uneconomical for low-capacity fresh water demand, under these situations, solar stills are viewed as means to attain self-reliance and ensure a regular supply of fresh water.

In conclusion, solar stills are the cheapest, with respect to their initial cost, of all available desalination systems in use today. This is a direct collection system, which is very easy to construct and operate. The disadvantage of solar stills is the very low yield, which implies that large areas of flat ground are required. It is questionable whether solar stills can be viable unless a cheap, desert-like land is available near the sea. However, obtaining fresh water from saline or brackish water with solar stills is useful for arid and remote areas, where no other economical means of obtaining water supply is available.

5. Indirect collection systems

The operating principle of these systems involves the implementation of two separate sub-systems, a renewable energy collector (solar collector, PV, wind turbine, etc.) and a plant for transforming the collected energy to fresh water. The renewable energy sub-systems are discussed in Section 6, however, some examples employing renewable energy to power desalination plants are presented in this section. The plant sub-system is based on one of the following two operating principles:

(i) *Phase-change processes*, for which either multi-stage flash (MSF), multiple-effect boiling (MEB) or vapour compression (VC) are used.
(ii) *Membrane processes*, for which reverse osmosis (RO) or electrodialysis (ED) are applied.

The operating principle of phase-change processes entails reusing the latent heat of evaporation to preheat the feed while at the same time condensing steam to produce fresh water. The energy requirements of these systems are traditionally defined in terms of units of distillate produced per unit mass (kg or lb) of steam or per 2326 kJ (1000 Btu) heat input which corresponds to the latent heat of vaporisation at 73 °C. This dimensional ratio in kg/2326 kJ or lb/1000 Btu is known as the performance ratio PR [149]. The operating principle of membrane processes leads to the direct production of electricity from solar or wind energy, which is used to drive

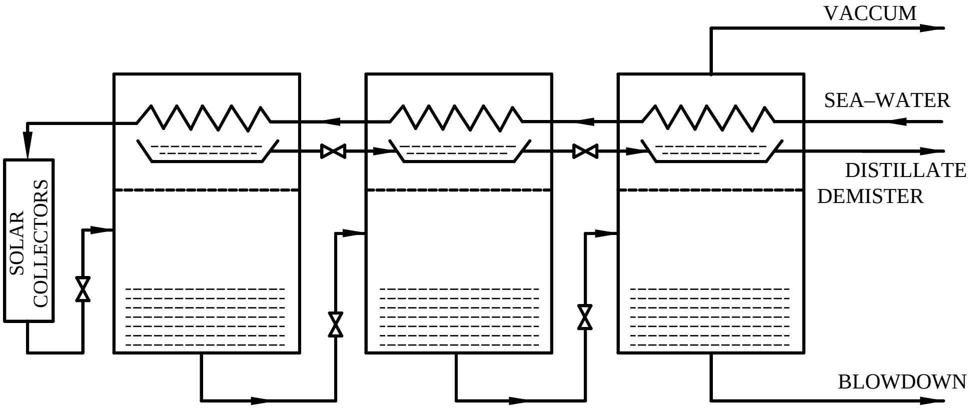


Fig. 6. Principle of operation of the multi-stage flash (MSF) system.

the plant. Energy consumption is usually expressed in kW h_e/m^3 [150].

5.1. The multi-stage flash (MSF) process

The MSF process is composed of a series of elements called stages. In each stage, condensing steam is used to preheat the seawater feed. By fractionating the overall temperature differential between the warm source and seawater into a large number of stages, the system approaches ideal total latent heat recovery. Operation of this system requires pressure gradients in the plant. The principle of operation is shown in Fig. 6. Current commercial installations are designed with 10–30 stages (2 °C temperature drop per stage).

A practical cycle representing the MSF process is shown in Fig. 7. The system is divided into heat-recovery and heat-rejection sections. Seawater is fed through the heat-rejection section, which rejects thermal energy from the plant and discharges the product and brine at the lowest possible temperature. The feed is then mixed with a large mass of water, which is recirculated around the plant. This water then passes through a series of heat exchangers to raise its temperature. The water next enters the solar collector array or a conventional brine heater to raise its temperature to nearly the saturation temperature at the maximum system pressure. The water then enters the first stage through an orifice and in so doing has its pressure reduced. Since, the water was at the saturation temperature for a higher pressure, it becomes superheated and flashes into steam. The vapour produced passes through a wire mesh (demister) to remove any entrained brine droplets and thence into the heat exchanger, where it is condensed and drips into a distillate tray. This process is repeated through the plant as both brine and distillate streams flash as they enter subsequent stages, which are at successively lower pressures. In MSF, the number of stages is not tied rigidly to the PR required from the plant. In practice, the minimum must be slightly greater than the PR, while the maximum is imposed by the boiling-point elevation. The minimum interstage temperature drop must exceed the boiling-point elevation for flashing to occur at a finite rate. This is advantageous because as the number of stages is increased, the terminal temperature difference over the heat exchangers increases and hence less heat transfer area is required with obvious savings in plant capital cost [151].

MSF is the most widely used desalination process in terms of capacity. This is due to the simplicity of the process, performance characteristics and scale control [150]. A disadvantage of MSF is that precise pressure levels are

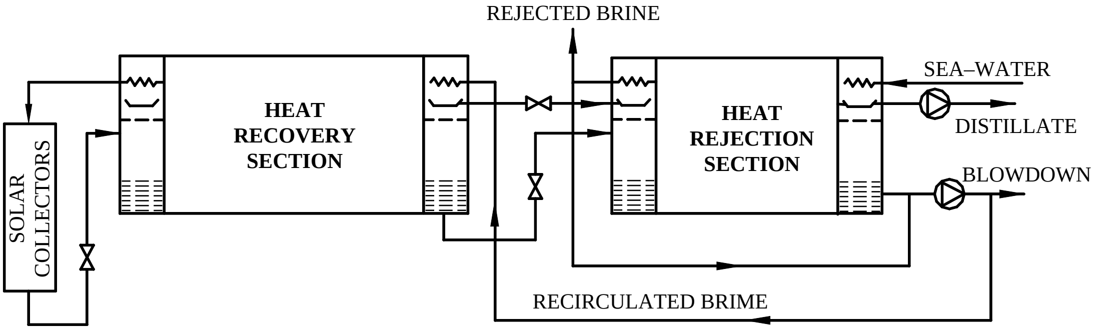


Fig. 7. A multi-stage flash (MSF) process plant.

required in the different stages and therefore some transient time is required to establish the normal running operation of the plant. This feature makes the MSF relatively unsuitable for solar energy applications unless a storage tank is used for thermal buffering [152].

For MSF system [149]:

$$\frac{M_\mathrm{f}}{M_\mathrm{d}}=\frac{L_\mathrm{m}}{c\,\Delta F}+\frac{N-1}{2N} \tag{28}$$

where $\Delta F = T_\mathrm{h}-T_\mathrm{bN}=(T_\mathrm{b1}-T_\mathrm{bN})[N/(N-1)]$.

It should be noted that the rate of external feed per unit of product $M_\mathrm{f}/M_\mathrm{d}$ is governed by the maximum brine concentration. Thus:

$$\frac{M_\mathrm{f}}{M_\mathrm{d}}=\frac{y_\mathrm{bN}}{y_\mathrm{bN}-y_\mathrm{o}} \tag{29}$$

The total thermal load per unit product obtained by adding all loads Q and approximating $(N-1)/N=1$ and is given by [149]:

$$\frac{\sum Q}{M_\mathrm{d}}=\frac{M_\mathrm{r}}{M_\mathrm{d}}c(T_\mathrm{h}-T_\mathrm{o})=L_\mathrm{m}\frac{T_\mathrm{h}-T_\mathrm{o}}{\Delta F} \tag{30}$$

Moustafa et al. [153] report on the performance of a 10 m^3/day solar MSF desalination system tested in Kuwait. The system consisted of a 220 m^2 parabolic trough collectors, 7000 l of thermal storage and a 12-stage MSF desalination system. The thermal storage system was used to level off the thermal energy supply and allowed the production of fresh water to continue during periods of low radiation and night-time. The output of the system is reported to be over 10 times the output of solar stills for the same solar collection area.

5.2. The multiple-effect boiling (MEB) process

The MEB process shown in Fig. 8 is also composed of a number of elements, which are called effects. The steam from one effect is used as heating fluid in another effect, which while condensing, causes evaporation of a part of the salty solution. The produced steam goes through the following effect, where, while condensing, it makes some of the other solution evaporate and so on. For this procedure to be possible, the heated effect must be kept at a pressure lower than that of the effect from which the heating steam originates. The solutions condensed by all effects are used to preheat the feed [50]. In this process, vapour is produced by flashing and by boiling, but the majority of the distillate is produced by boiling. Unlike an MSF plant, the MEB process usually operates as a once through system without a large mass of brine recirculating around the plant. This design reduces both pumping requirements and scaling tendencies [150].

As with the MSF plant, the incoming brine in the MEB process passes though a series of heaters but after passing through the last of these, instead of entering the brine heater, the feed enters the top effect, where the heating steam raises its temperature to the saturation temperature for the effect pressure. Further amounts of steam, either from a solar collector system or from a conventional boiler, are used to produce evaporation in this effect. The vapour then goes, in part, to heat the incoming feed and, in part, to provide the heat supply for the second effect, which is at a lower pressure and receives its feed from the brine of the first effect. This process is repeated all the way through (down) the plant. The distillate also passes down the plant. Both the brine and distillate flash as they travel down the plant due to progressive reduction in pressure [150].

There are many possible variations of MEB plants, depending on the combinations of heat-transfer configurations and flowsheet arrangements used. Early plants were of the submerged tube design and used only two to three effects. In modern systems, the problem of low evaporation rate has been resolved by making use of the thin film designs with the feed liquid distributed on the heating surface in

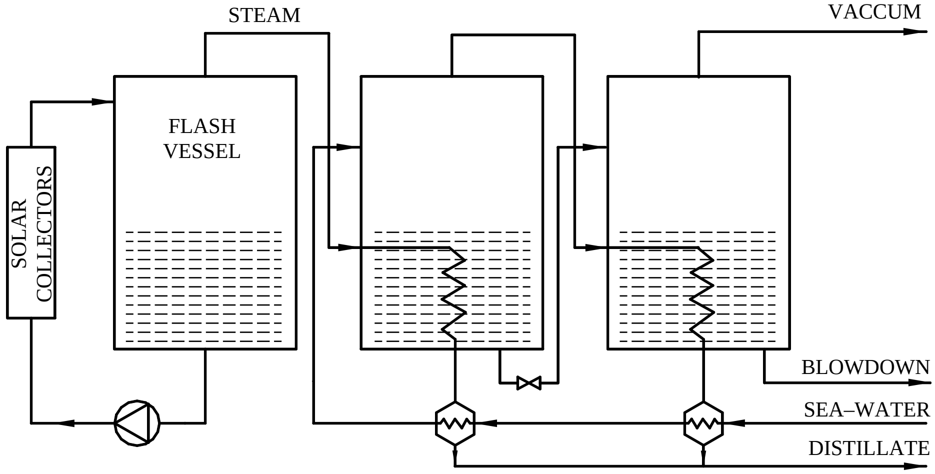


Fig. 8. Principle of operation of a multiple-effect boiling (MEB) system.

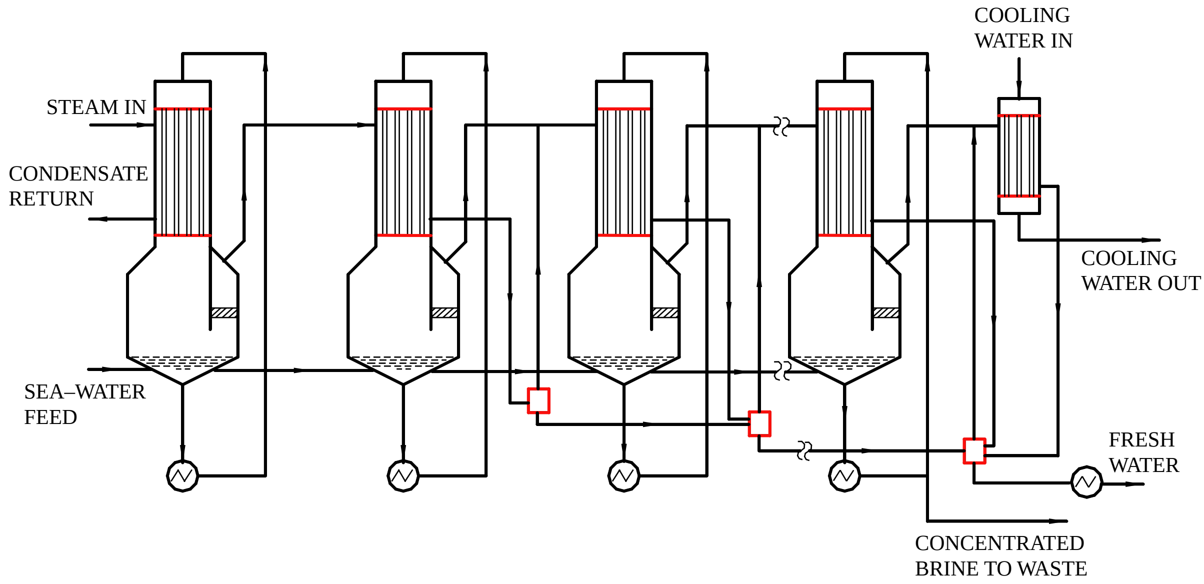


Fig. 9. Long tube vertical (LTV) MEB plant.

the form of a thin film instead of a deep pool of water. Such plants may have vertical or horizontal tubes. The vertical tube designs are of two types: climbing film, natural and forced circulation type or long tube, vertical (LTV), straight falling film type. In the LTV plants shown in Fig. 9, the brine boils inside the tubes and the steam condenses outside. In the horizontal tube, falling-film design, the steam condenses inside the tube with the brine evaporating on the outside.

With multiple evaporation, the underlying principle is to make use of the available energy of the leaving streams of a single-evaporation process to produce more distillate.

In the case of MEB system, the ratio M_f/M_d is fixed by the maximum allowable brine concentration to a value in the order of 2 and is given by [149]:

$$\frac{M_f}{M_d} = \frac{\sum_1^N f_n}{M_d}\,\frac{L_m}{cN\,\Delta t_n} + \frac{N-1}{2N} \qquad (31)$$

The total thermal load per unit product obtained by adding all loads Q and dividing by M_d is given by [149]:

$$\frac{\sum Q}{M_d} = L_m + \frac{L_m}{N} + \frac{M_f}{M_d}c(\Delta t_t + \varepsilon) + \frac{1}{2}c(T_{b1} - T_{bN}) \qquad (32)$$

Another type of MEB evaporator is the Multiple Effect Stack (MES) type. This is the most appropriate type for solar energy application. It has a number of advantages, the most important of which is its stable operation between virtually 0 and 100% output even when sudden changes are made and its ability to follow a varying steam supply without upset [154]. In Fig. 10, a four-effect MES evaporator is shown. Seawater is sprayed into the top of the evaporator and descends as a thin film over the horizontally arranged tube

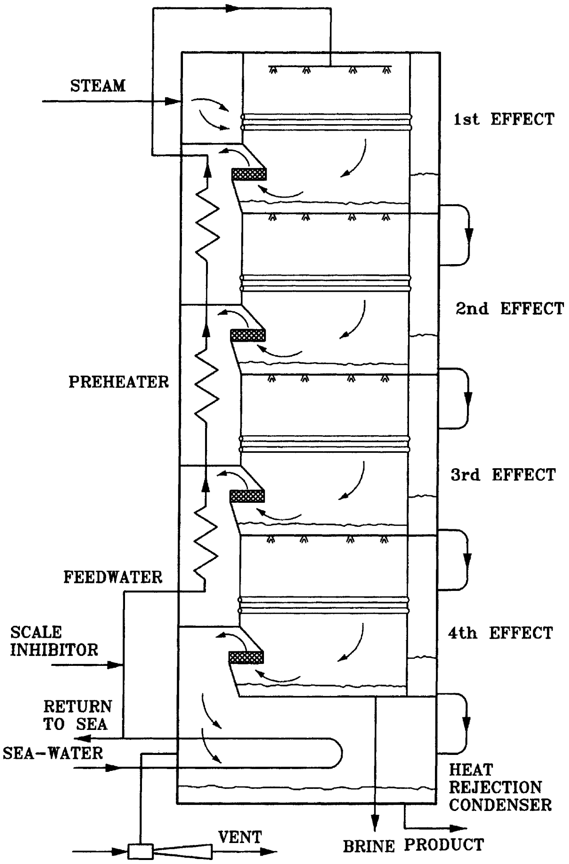


Fig. 10. Schematic of the MES evaporator.

bundle in each effect. In the top (hottest) effect, steam from a steam boiler or from a solar collector system condenses inside the tubes. Because of the low pressure created in the plant by the vent-ejector system, the thin seawater film boils simultaneously on the outside of the tubes, thus creating new vapour at a lower temperature than the condensing steam.

The seawater falling to the floor of the first effect is cooled by flashing through nozzles into the second effect, which is at a lower pressure. The vapour made in the first effect is ducted into the inside of the tubes in the second effect, where it condenses to form part of the product. Furthermore, the condensing warm vapour causes the external cooler seawater film to boil at the reduced pressure.

The evaporation–condensation process is repeated from effect to effect in the plant, creating an almost equal amount of product inside the tubes of each effect. The vapour made in the last effect is condensed on the outside of a tube bundle cooled by raw seawater. Most of the warmer seawater is then returned to the sea, but a small part is used as feedwater to the plant. After being treated with acid to destroy scale-forming compounds, the feedwater passes up the stack through a series of pre-heaters that use a little of the vapour from each effect to raise its temperature gradually, before it is sprayed into the top of the plant. The water produced from each effect is flashed in a cascade down the plant so that it can be withdrawn in a cool condition at the bottom of the stack. The concentrated brine is also withdrawn at the bottom of the stack. The MES process is completely stable in operation and automatically adjusts to changing steam conditions even if they are suddenly applied, so it is suitable for load-following applications. It is a once-through process that minimises the risk of scale formation without incurring a large chemical scale dosing cost. The typical product purity is less than 5 ppm TDS and does not deteriorate as the plant ages. Therefore, the MEB process with the MES type evaporator appears to be the most suitable for use with solar energy.

Unlike the MSF plant, the performance ratio for an MEB plant is more rigidly linked to and cannot exceed a limit set by the number of effects in the plant. For instance, a plant with 13 effects might typically have a PR of 10. However, an MSF plant with a PR of 10 could have 13–35 stages depending on the design. MSF plants have a maximum PR of approximately 13. Normally, the figure is between 6 and 10. MEB plants commonly have performance ratios as high as 12–14 [151]. The main difference between this process and the MSF is that the steam of each effect just travels to the following effect, where it is immediately used for preheating the feed. This process requires more complicated circuit equipment than the MSF; on the other hand, it has the advantage that is suitable for solar energy utilisation because the levels of operating temperature and pressure equilibrium are less critical [152].

A 14-effect MEB plant with a nominal output of 3 m^3/h and coupled with 2672 m^2 parabolic trough collectors (PTC) has been presented by Zarza et al. [155,156]. The system is installed at the plataforma solar de Almeria in Southern Spain. It also incorporates a 155 m^3 thermocline thermal storage tank. The circulated fluid through the solar collectors is a synthetic oil heat-transfer fluid (3M Santotherm 55). The PR obtained by the system varies from 9.3 to 10.7, depending on the condition of the evaporator tube-bundle surfaces. The authors estimated that the efficiency of the system can be increased considerably by recovering the energy wasted when part of the cooling water in the final condenser is rejected. Energy recovery is performed with a double-effect absorption heat pump.

El-Nashar [157] gives details of an MES system powered with 1862 m^2 evacuated tube collectors. The system is installed in Abu Dhabi, United Arab Emirates. A computer program was developed for the optimisation of the operating parameters of the plant that affect its performance, i.e. the collector area in service, the high temperature collector set-point and the heating water flowrate. The maximum daily distillate production corresponding to the optimum operating conditions was found to be 120 m^3/day, which can be obtained for 8 months of the year.

Exergy analysis, based on actual measured data of the MES plant installed in the solar plant near Abu Dhabi, is presented by El-Nashar and Al-Baghdabi [158]. The exergy destruction was calculated for each source of irreversibility. The major exergy destruction was found to be caused by irreversibilities in the different pumps with the vacuum pump representing the main source of destruction.

Major exergy losses are associated with the effluent streams of distillate, brine blow-down and seawater. Exergy destruction due to heat transfer and pressure drop in the different effects, in the preheaters and in the final condenser and in the flashing of the brine and distillate between the successive effects represents an important contribution to the total amount of exergy destruction in the evaporator.

5.3. The vapour-compression (VC) process

In a VC plant, heat recovery is based on raising the pressure of the steam from a stage by means of a compressor (see Fig. 11). The condensation temperature is thus increased and the steam can be used to provide energy to the same stage it came from or to other stages [50,159]. As in a conventional MEB system, the vapour produced in the first effect is used as the heat input to the second effect, which is at a lower pressure. The vapour produced in the last effect is then passed to the vapour compressor, where it is compressed and its saturation temperature is raised before it is returned to the first effect. The compressor represents the major energy input to the system and since the latent heat is effectively recycled around the plant, the process has the potential for delivering high PRs [151].

Parametric cost estimates and process designs have been carried out and show that this type of plant is not particularly convenient, unless it is combined with an MEB system.

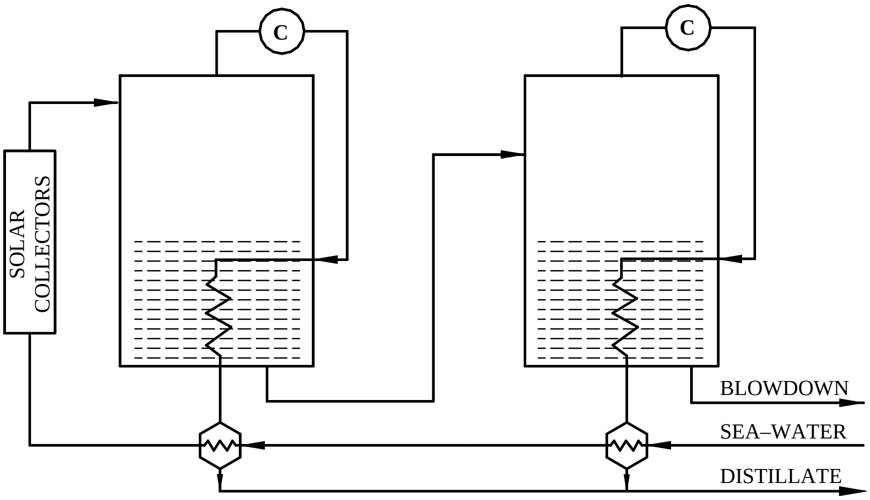


Fig. 11. Principle of operation of a vapour-compression (VC) system.

Further, it appears that the mechanical energy requirements have to be provided with a primary drive such as a diesel engine, and cooling the radiator of such an engine provides more than enough heat for the thermal requirements of the process, making the solar collector system redundant [160]. Therefore, the VC system can be used in conjunction with an MEB system and operated at periods of low solar radiation or overnight.

Vapour compression systems are subdivided into two main categories: mechanical vapour compression (MVC) and thermal vapour compression (TVC) systems. The mechanical vapour compression systems employ a mechanical compressor to compress the vapour, whereas the thermal one utilise a steam jet compressor. The main problems associated with the MVC process are [151]:

(i) Vapour containing brine is carried over into the compressor and leads to corrosion of the compressor blades.
(ii) There are plant-size limitations because of limited compressor capacities.

Thermal vapour systems are designed for projects, where steam is available. The required pressure is between 2 and 10 bar and due to the relatively high cost of the steam, a large number of evaporative-condenser heat recovery effects are normally justified.

The total thermal load per unit of distillate is simply the latent heat of vaporization and the heating of the feed all through the range T_v–T_o and is given by [149]:

$$\frac{\sum Q}{M_d} = L + \frac{M_f}{M_d} c(T_v - T_o) \tag{33}$$

Thermal performance and exergy analysis of a TVC system is presented by Hamed et al. [48] and they found that:

(1) Operational data of a four-effect, low temperature thermal vapour compression desalination plant revealed that performance ratios of 6.5–6.8 can be attained. Such ratios are almost twice those of a conventional four-effect boiling desalination plant.
(2) The performance ratios of the TVC system increase with the number of effects and with the entrainment ratio of the thermo-compressor and decrease with the top brine temperature.
(3) Exergy analysis reveals that the thermal vapour compression desalination plant (TVC) is the most exergy-efficient when compared with the mechanical vapor compression (MVC) and multi-effect boiling (MEB) ones.
(4) The sub-system most responsible for exergy destruction in all three desalination systems investigated is the first effect, because of the high temperature of its heat input. In the TVC system, this amounts to 39%, with the second highest exergy defect being that of the thermo-compressor, equal to 17%.
(5) Exergy losses can be significantly reduced by increasing the number of effects and the thermo-compressor entrainment ratio (vapour taken from evaporator and compressed by ejector), or by decreasing the top brine and first-effect heat input temperatures.

5.4. Reverse osmosis (RO)

The RO system depends on the properties of semi-permeable membranes which, when used to separate water from a salt solution, allow fresh water to pass into the brine compartment under the influence of osmotic pressure. If a pressure in excess of this value is applied to the salty solution, fresh water will pass from the brine into the water compartment. Theoretically, the only energy requirement is

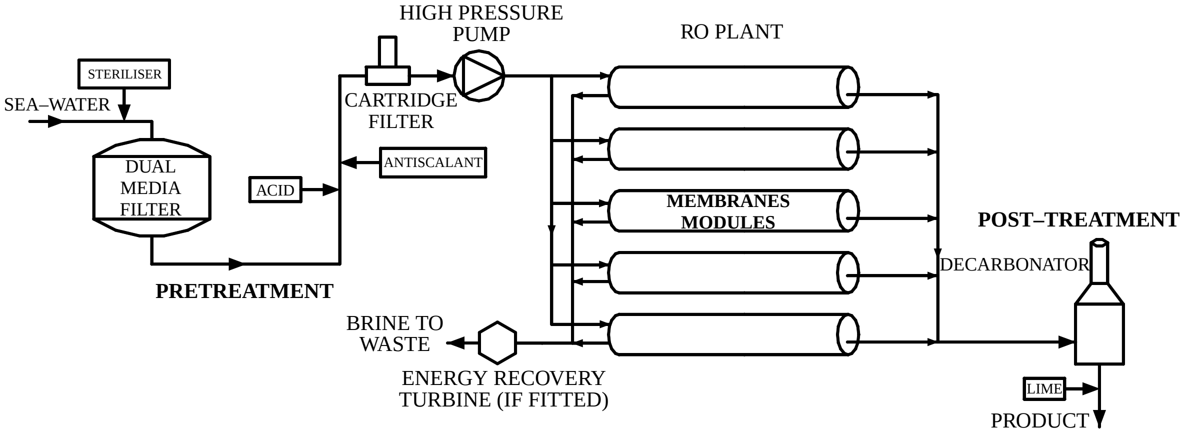


Fig. 12. Principle of operation of a reverse osmosis (RO) system.

to pump the feed water at a pressure above the osmotic pressure. In practice, higher pressures must be used, typically 50–80 atm, in order to have a sufficient amount of water pass through a unit area of membrane [161]. With reference to Fig. 12, the feed is pressurised by a high-pressure pump and made to flow across the membrane surface. Part of this feed passes through the membrane, where the majority of the dissolved solids are removed. The remainder, together with the remaining salts, is rejected at high pressure. In larger plants, it is economically viable to recover the rejected brine energy with a suitable brine turbine. Such systems are called energy recovery reverse osmosis (ER-RO) systems.

Solar energy can be used with RO systems as a prime mover source driving the pumps [162] or with the direct production of electricity through the use of photovoltaic panels [163]. Wind energy can also be used as a prime mover source. As the unit cost of the electricity produced from photovoltaic cells is high, photovoltaic-powered RO plants are equipped with energy-recovery turbines. The output of RO systems is about 500–1500 l per day per square metre of membrane, depending on the amount of salts in the raw water and the condition of the membrane. The membranes are in effect very fine filters, and are very sensitive to both biological and non-biological fouling. To avoid fouling, careful pre-treatment of the feed is necessary before it is allowed to come in contact with the membrane surface.

One method used recently for the pre-treatment of seawater before directed to RO modules is nano-filtration (NF). NF is primarily developed as a membrane softening process which offers an alternative to chemical softening. The main objectives of NF pre-treatment are [164]:

1. Minimise particulate and microbial fouling of the RO membranes by removal of turbidity and bacteria.
2. Prevent scaling by removal of the hardness ions.
3. Lower the operating pressure of the RO process by reducing the feedwater total dissolved solids (TDS) concentration.

Tabor [165] analysed a system using an RO desalination unit driven by PV panels or from a solar–thermal plant. He concluded that due to the high cost of the solar equipment the cost of fresh water is about the same as with an RO system operated from the main power supply.

Cerci [45] performed an exergy analysis of a 7250 m^3/day reverse osmosis (RO) desalination plant in California. The analysis of the system was conducted by using actual plant operation data. The RO plant is described in detail, and the exergies across the major components of the plant are calculated and illustrated using exergy flow diagrams in an attempt to assess the exergy destruction distribution. It was found that the primary locations of exergy destruction were the membrane modules in which the saline water is separated into the brine and the permeate, and the throttling valves, where the pressure of liquid is reduced, pressure drops through various process components, and the mixing chamber, where the permeate and blend are mixed. The largest exergy destruction occurred in the membrane modules, and this amounted to 74.1% of the total exergy input. The smallest exergy destruction occurred in the mixing chamber. The mixing accounted for 0.67% of the total exergy input and presents a relatively small fraction. The second law efficiency of the plant was calculated to be 4.3%, which seems to be low. It is shown that the second law of efficiency can be increased to 4.9% by introducing a pressure exchanger with two throttling valves on the brine stream, and this saved 19.8 kW of electricity by reducing the pumping power of the incoming saline water.

5.5. Electrodialysis (ED)

This system, shown schematically in Fig. 13, works by reducing salinity by transferring ions from the feed water compartment, through membranes, under the influence of an electrical potential difference. The process utilises a dc electric field to remove salt ions in the brackish water. Saline feedwater contains dissolved salts separated into positively

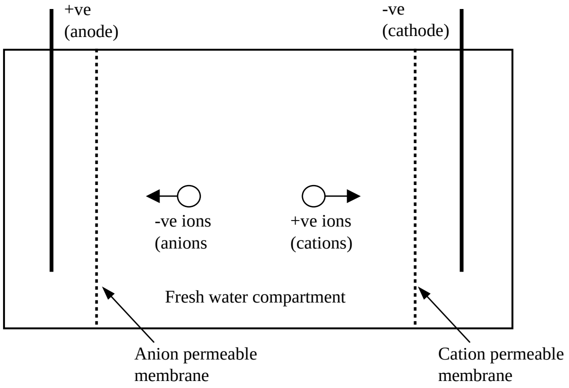


Fig. 13. Principle of operation of electrodialysis (ED).

charged sodium and negatively charged chlorine ions. These ions will move towards an oppositively charged electrode immersed in the solution, i.e. positive ions (cations) will go to the negative electrode (cathode) and negative ions (anions) to the positive electrode (anode). If special membranes, alternatively cation-permeable and anion-permeable, separate the electrodes, the centre gap between these membranes will be depleted of salts [166]. In an actual process, a large number of alternating cation and anion membranes are stacked together, separated by plastic flow-spacers that allow the passage of water. The streams of alternating flow-spacers are a sequence of diluted and concentrated water which flow in parallel to each other. To prevent scaling, inverters are used which reverse the polarity of the electric field every about 20 min.

As the energy requirements of the system are proportional to the water's salinity, ED is more feasible when the salinity of the feedwater is not more than about 6000 ppm of dissolved solids. Similarly, due to the low conductivity, which increases the energy requirements of very pure water, the process is not suitable for water of less than about 400 ppm of dissolved solids.

As the process operates with DC power, solar energy can by used with electrodialysis by directly producing the voltage difference required with photovoltaic (PV) panels.

6. Renewable energy systems

Renewable energy systems offer alternative solutions to decrease the dependence on fossil fuels. The total world-wide renewable energy desalination installations amount to capacities of less than 1% of that of conventional fossil-fuelled desalination plants [1]. This is mainly due to the high capital and maintenance costs required by renewable energy, making these desalination plants non-competitive with conventional fuel desalination plants.

This section presents a review of the possible systems that can be used for renewable energy collection and transformation into usable energy, which may be used to power desalination equipment. These cover solar energy which includes thermal collectors, solar ponds and photovoltaics, wind energy and geothermal energy. Solar energy thermal collectors include stationary and tracking collectors. Stationary collectors include the flat-plate and the evacuated tube, whereas concentrating collectors are further divided into imaging and non-imaging collectors like the parabolic trough and compound parabolic, respectively.

6.1. Solar energy systems

In this section after a brief historical introduction various solar energy systems are presented. These include solar collectors, solar ponds and photovoltaics.

6.1.1. Brief historical introduction of solar energy

Solar energy is the oldest energy source ever used. The Sun was adored by many ancient civilizations as a powerful God. The first known practical application was in drying for preserving food. The oldest large-scale application known to us is the burning of the Roman fleet in the bay of Syracuse, by Archimedes, the Greek mathematician and philosopher (287–212 BC). Scientists discussed this event for centuries. From 100 BC to 1100 AD authors made reference to this event although later it was criticized as a myth because no technology existed at that time to manufacture mirrors [34]. Nevertheless, Archimedes is the author of a book called Mirrors, which is only known from references as no copy survived. Proclus repeated Archimedes' experiment during the Byzantine period and he burned the war fleet of enemies besieging Byzance in Constantinople [34].

In his book, called Optics Vitelio, a Polish mathematician, described the burning of the Roman fleet with detail [5, 34,167,168]: "The burning glass of Archimedes composed of 24 mirrors, which conveyed the rays of the sun into a common focus and produced an extra degree of heat".

Many historians, however, believe that Archimedes did not use mirrors but the shields of the soldiers, arranged in a large parabola, for focusing the sun's rays to a common point on a ship. Although this was a military experiment, it proved that solar radiation could be a powerful source of energy. Many centuries later, scientists considered again solar radiation as a source of energy, trying to convert it into a usable form for direct utilization.

Solar energy utilization resumed during the 18th century first by the French naturalist Boufon (1747–1748), who experimented with various devices which he called 'hot mirrors burning at long distance' [1]. One of the first large-scale applications was the solar furnace built by the well-known French chemist Lavoisier who at about 1774 constructed powerful lenses to concentrate solar radiation. Between 1866 and 1878, the French engineer Mouchot constructed and tested various concentrating collectors in Europe and North Africa. One of them was presented at the 1878 International Exhibition in Paris. The solar energy gained was used to produce steam to drive a printing machine [169,170].

The efforts were continued in the USA, where John Ericsson, an American engineer developed the first steam engine driven directly by solar energy. Ericsson built eight systems having parabolic troughs by using either water or air as the working medium [171]. A complete history of these and other early applications of solar energy is given in [172] and is not repeated here.

Today, there exist many large solar plants with output in the range of MW for producing electricity or process heat. The first commercial solar plant was installed in Albuquerque, New Mexico, USA, in 1979. It consisted of 220 heliostats and had an output of 5 MW. The second was erected at Barstow, California, USA, with a total thermal output of 35 MW. Most of the solar plants produce electricity and/or process heat for industrial use and they provide superheated steam of 673 K. Thus, they can provide electricity and/or steam to drive small capacity conventional desalination plants driven by thermal or electrical energy.

A number of solar desalination plants coupled with conventional desalination systems were installed in various locations in the Middle East. The majority of these plants are experimental or demonstration scale. This is due mainly to the high capital and maintenance costs of these plants. A review of renewable energy desalination systems is given in Section 7.

6.1.2. Solar collectors

Solar energy collectors are a special kind of heat exchanger that transforms solar radiation to internal energy of the transport medium. The major component of any solar system is the solar collector. This is a device, which absorbs the incoming solar radiation, converts it into heat, and transfers this heat to a fluid (usually air, water, or oil) flowing through the collector. The solar energy thus collected is carried from the circulating fluid either directly to the hot water or space conditioning equipment, or to a thermal energy storage tank from which can be drawn for use at night and/or cloudy days.

There are basically two types of solar collectors: non-concentrating or stationary and concentrating. A non-concentrating collector has the same area for intercepting and for absorbing solar radiation, whereas a sun-tracking concentrating solar collector usually has concave reflecting surfaces to intercept and focus the sun's beam radiation to a smaller receiving area, thereby increasing the radiation flux. A large number of solar collectors are available in the market. A comprehensive list is shown in Table 3 [173].

A comprehensive review of the various types of collectors currently available is presented in [172] and may not be repeated here. The interested author is advised to refer to this publication where details of the various collectors available are described, together with their possible applications, including desalination. Also, more details of these systems can be found in numerous publications [174,175]. The rest of this section deals with collectors and renewable energy systems not covered in [172].

6.1.3. Solar ponds

A basic concept of a solar pond is to heat a large pond of water in such a way as to suppress the heat losses that would occur if less dense heated water is allowed to rise to the surface of the pond and lose energy to the environment by convection and radiation. As shown in Fig. 14, this objective can be accomplished if a stagnant, highly transparent insulating zone is created in the upper part of the pond to contain the hot fluid in the lower part of the pond. In a non-conventional solar pond, part of the incident insolation is absorbed and converted to heat, which is stored in the lower regions of the pond. Solar ponds are both solar energy collectors and heat stores. Salt gradient lakes, which exhibit an increase in temperature with depth, occur naturally. A salt-gradient non-convecting solar pond consists of three zones [176]:

1. The upper convecting zone (UCZ), of almost constant low salinity at close to ambient temperature. The UCZ, typically 0.3 m thick, is the result of evaporation,

Table 3
Solar energy collectors

Motion	Collector type	Absorber type	Concentration ratio	Indicative temperature range (°C)
Stationary	Flat plate collector (FPC)	Flat	1	30–80
	Evacuated tube collector (ETC)	Flat	1	50–200
	Compound parabolic collector (CPC)	Tubular	1–5	60–240
Single-axis tracking	Compound parabolic collector (CPC)	Tubular	5–15	60–300
	Linear Fresnel reflector (LFR)	Tubular	10–40	60–250
	Parabolic trough collector (PTC)	Tubular	15–45	60–300
	Cylindrical trough collector (CTC)	Tubular	10–50	60–300
Two-axes tracking	Parabolic dish reflector (PDR)	Point	100–1000	100–500
	Heliostat field collector (HFC)	Point	100–1500	150–2000

Note: Concentration ratio is defined as the aperture area divided by the receiver/absorber area of the collector.

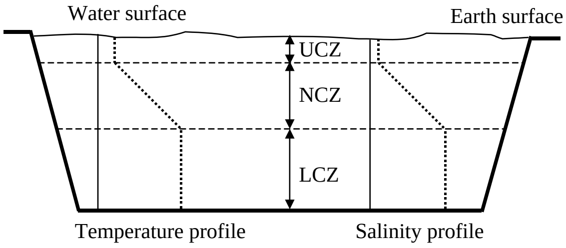


Fig. 14. Schematic vertical section through a salt-gradient solar pond.

wind-induced mixing and surface flushing. It is kept as thin as possible by the use of wave-suppressing surface meshes and placing wind-breaks near the pond.

2. The non-convecting zone (NCZ), in which both salinity and temperature increase with depth. The vertical salt gradient in the NCZ inhibits convection and thus provides the thermal insulation. The temperature gradient is formed due to the absorption of insolation at the pond base.
3. The lower convecting zone (LCZ), of almost constant, relatively high salinity (typically 20% by weight) at a high temperature. Heat is stored in the LCZ which is sized to supply energy continuously throughout the year. As the depth increases, the thermal capacity increases and annual variations of temperature decreases. However, large depths increase the initial capital expenditure and require longer start-up times.

Many techniques have been considered in order to suppress natural convection in order to create a solar pond. The most common method used is salt stratification. Salinity increases with depth in the NCZ until the LCZ is reached (see Fig. 14). Here, the solar radiation heats the high salinity water, but because of its high relative density, this hot salty water cannot rise into the lower salinity layers, thus the heat is stored and inhibited from being transferred by convection. Chemically stable salts, as well as any natural brine can be used to establish a salt-stratified solar pond. A selected salt must be safe to handle, non-toxic, cheap and readily available, should not reduce significantly the insolation transmission characteristics of water, and its solubility should be temperature dependent [176].

In evaluating a particular solar pond application, several factors need to be considered. First, since solar ponds are horizontal solar collectors, sites should be at low to moderate northern and southern latitudes, i.e. ±40°. Another important consideration is that the water table should be at least a few metres below the bottom of the bond to minimise heat losses, since the thermal conductivity of soil increases greatly with moisture content. Also the pond must not pollute the aquifers and any continuous drain of hot water will lower the pond's storage capacity and effectiveness. The next item that must be considered is the selection of a liner for the pond. Although it is possible to build a soil liner by compacting clay, in some instances the permeability may be unacceptable. Resultant loss of fluid to the soil would increase thermal losses, require replenishment of salt and water, and may present an environmental problem. All ponds constructed today have contained a liner, which is a reinforced polymer material 0.75–1.25 mm in thickness.

Surface flushing is an essential process in maintaining the pond's salt gradient. Its effect on the UCZ growth is reduced if the velocity of the surface washing water is small. Surface temperature fluctuations will result in heat being transferred upwards through the UCZ by convection, especially at night, and downward by conduction. The thickness of the UCZ varies with the intensity of the incident radiation.

Evaporation is caused by insolation and wind action. The higher the temperature of the UCZ, and the lower the humidity above the pond's surface, the greater is the evaporation rate. Excessive evaporation results in a downward growth of the UCZ [177]. Evaporation can be counterbalanced by surface water washing, which could compensate for evaporated water as well as reduce the temperature of the pond's surface especially during periods of high insolation. Reducing the wind velocity over the water's surface by using wind-breaks will reduce evaporation rates. Evaporation can be the dominant mechanism in surface-layer mixing under light-to-moderate winds. However, under strong winds it becomes of secondary importance. Wind-induced mixing can contribute significantly to the deepening of the UCZ [178]. Winds also induce horizontal currents near the top surface of the pond increasing convection in the UCZ. Wind mixing has been reduced by floating devices like plastic pipes, plastic grits, and independent rings, as well by the use of wind-breaks.

6.1.3.1. Solar ponds applications. Solar ponds can be used to provide energy for many different types of applications. The smaller ponds have been used mainly for space and water heating, while the larger ponds are proposed for industrial process heat, electric power generation, and desalination.

Although many feasibility studies have been made for the generation of electric power from solar ponds, the only operational systems are in Israel [179]. These include a 1500 m^2 pond used to operate a 6 kW Rankine cycle turbine-generator and a 7000 m^2 pond producing 150 kW peak power. Both of these ponds operate at about 90 °C.

Another use of the output from salt-gradient solar pond is to operate a low temperature distillation unit to desalt seawater. This concept has applicability in desert areas near the oceans. Solar pond-coupled desalination involves using hot brine from the pond as a thermal source to evaporate the water to be desalted at low pressure in a multiple effect boiling (MEB) evaporator.

Matz and Feist [180] propose solar ponds as a solution of brine disposal at inland ED plants as well as a source of thermal energy to heat the feed of an ED plant which can increase its performance.

6.1.4. Photovoltaics

Becquerel had discovered the photovoltaic effect in selenium in 1839. The conversion efficiency of the 'new' silicon cells developed in 1958 was 11% although the cost was prohibitively high ($1000/W) [181]. The first practical application of solar cells was in space, where cost was not a barrier as no other source of power is available.

The photovoltaic (PV) process converts sunlight, the most abundant energy source on the planet, directly into electricity. PV equipment has no moving parts and as a result requires minimal maintenance and has a long life. It generates electricity without producing emissions of greenhouse or any other gases, and its operation is virtually silent.

A PV cell consists of two or more thin layers of semiconducting material, most commonly silicon. When the silicon is exposed to light, electrical charges are generated and this can be conducted away by metal contacts as direct current (DC). The electrical output from a single cell is small, so multiple cells are connected together and encapsulated (usually glass covered) to form a module (also called a 'panel').

The PV panel is the principle building block of a PV system and any number of panels can be connected together to give the desired electrical output. This modular structure is a considerable advantage of the PV system, where further panels can be added to an existing system as required.

Photovoltaic (PV) cells are made of various semiconductors, which are materials that are only moderately good conductors of electricity. The materials most commonly used are silicon (Si) and compounds of cadmium sulphide (CdS), cuprous sulphide (Cu_2S), and gallium arsenide (GaAs). These cells are packed into modules which produce a specific voltage and current when illuminated. A comprehensive review of cell and module technologies is given by Kazmerski [182]. PV modules can be connected in series or in parallel to produce larger voltages or currents. Photovoltaic systems can be used independently or in conjunction with other electrical power sources. Applications powered by PV systems include communications (both on earth and in space), remote power, remote monitoring, lighting, water pumping and battery charging. The global installed capacity of photovoltaics at the end of 2002 was near 2 GW_p [183].

6.1.4.1. Types of PV technology. Monocrystalline silicon cells. These cells are made from very pure monocrystalline silicon. The silicon has a single and continuous crystal lattice structure with almost no defects or impurities. The principle advantage of monocrystalline cells is their high efficiency, typically around 15%, although the manufacturing process required to produce monocrystalline silicon is complicated, resulting in slightly higher costs than other technologies.

Multicrystalline silicon cells. Multicrystalline cells are produced using numerous grains of monocrystalline silicon. In the manufacturing process, molten polycrystalline silicon is cast into ingots; these ingots are then cut into very thin wafers and assembled into complete cells. Due to the simpler manufacturing process, multicrystalline cells are cheaper to produce than monocrystalline ones. However, they tend to be slightly less efficient, with average efficiencies of around 12%.

Amorphous silicon. Amorphous silicon cells are composed of silicon atoms in a thin homogenous layer rather than a crystal structure. Amorphous silicon absorbs light more effectively than crystalline silicon, so the cells can be thinner. For this reason, amorphous silicon is also known as a 'thin film' PV technology. Amorphous silicon can be deposited on a wide range of substrates, both rigid and flexible, which makes it ideal for curved surfaces and 'fold-away' modules. Amorphous cells are, however, less efficient than crystalline based cells, with typical efficiencies of around 6%, but they are easier and therefore cheaper to produce. Their low cost makes them ideally suited for many applications, where high efficiency is not required and low cost is important.

Amorphous silicon (a-Si) is a glassy alloy of silicon and hydrogen (about 10%). Several properties make it an attractive material for thin-film solar cells:

1. Silicon is abundant and environmentally safe.
2. Amorphous silicon absorbs sunlight extremely well, so that only a very thin active solar cell layer is required (about 1 μm as compared to 100 μm or so for crystalline solar cells), thus greatly reducing solar-cell material requirements.
3. Thin films of a-Si can be deposited directly on inexpensive support materials such as glass, sheet steel, or plastic foil.

Other thin films. A number of other promising materials such as cadmium telluride (CdTe) and copper indium diselenide ($CuInSe_2$) are now being used for PV modules. The attraction of these technologies is that they can be manufactured by relatively inexpensive industrial processes, in comparison to crystalline silicon technologies, yet they typically offer higher module efficiencies than amorphous silicon.

6.1.4.2. Photovoltaic panels. PV modules are designed for outdoor use in such a harsh conditions as marine, tropic, arctic, and desert environments. The choice of the photovoltaically active material can have important effects on system design and performance. Both the composition of the material and its atomic structure are influential. The atomic structure of a PV cell can be single-crystal (monocrystalline), multicrystalline, or amorphous. The most commonly produced PV material is crystalline silicon, either polycrystalline or in single-crystals.

A module is a collection of PV cells that protects the cells and provides a usable operating voltage. PV cells can be fragile and susceptible to corrosion by humidity or fingerprints and can have delicate wire leads. Also, the operating voltage of a single PV cell is less than 1 V, making it unusable for many applications. Depending on the manufacturer and the type of PV material, modules have different appearances and performance characteristics. Also, modules may be designed for specific conditions, such as hot and humid climates. Nowadays, the panels come in a variety of shapes like roof-tiles made from amorphous silicon solar cells.

Usually, the cells are series-connected to other cells to produce an operating voltage around 14–16 V. These strings of cells are then encapsulated with a polymer, a front glass cover, and a back material. Also, a junction box is attached at the back of the module for convenient wiring to other modules or other electrical equipment.

Cells made of amorphous silicon, cadmium telluride, or copper indium diselenide are manufactured on large pieces of material that become either the front or the back of the module. A large area of PV material is divided into smaller cells by scribing or cutting the material into electrically isolated cells.

6.1.4.3. PV applications. Stand-alone applications. Stand-alone PV systems are used in areas that are not easily accessible or have no access to main electricity. A stand-alone system is independent of the electricity grid, with the energy produced normally being stored in batteries. A typical stand-alone system would consist of PV module or modules, batteries and charge controller. An inverter may also be included in the system to convert the direct current (DC) generated by the PV modules to the alternating current form (AC) required by normal appliances. A photograph of a stand-alone system is shown in Fig. 15.

Grid-connected systems. Nowadays, it is usual practice to connect PV systems to the local electricity network. This means that during the day, the electricity generated by the PV system can either be used immediately (which is normal for systems installed in offices, other commercial buildings and industrial applications), or can be sold to one of the electricity supply companies (which is more common for domestic systems, where the occupier may be out during the day). In the evening, when the solar system is unable to provide the electricity required, power can be bought back from the network. In effect, the grid is acting as an energy storage system, which means the PV system does not need to include battery storage.

6.1.4.4. PV system configuration. The PV array consists of a number of individual photovoltaic modules connected together to give a suitable current and voltage output. Common power modules have a rated power output of around 50–80 W each. As an example, a small system of 1.5–2 kW_p may therefore comprise some 20–30 modules covering an area of around 15–25 m^2, depending on the technology used and the orientation of the array with respect to the sun.

Most power modules deliver direct current (DC) electricity at 12 volts (V), whereas most common household appliances and industrial processes operate with alternating current (AC) at 240 or 415 V (120 V in the United States). Therefore, an inverter is used to convert the low voltage DC to higher voltage AC. Numerous types of inverters are available, but not all are suitable for use when feeding power back into the mains supply.

Other components in a typical grid-connected PV system are the array mounting structure and the various cables and switches needed to ensure that the PV generator can be isolated.

6.2. Wind energy

Wind is generated by atmospheric pressure differences, driven by solar power. Of the total 173,000 TW of solar power reaching the earth, about 1200 TW (0.7%) is used to drive the atmospheric pressure system. This power generates a kinetic energy reservoir of 750 EJ with a turnover time of 7.4 days [184]. This conversion process mainly takes place in the upper layers of the atmosphere, at around 12 km height (where the ‘jet streams’ occur). If it is assumed that about 1% of the kinetic power is available in the lowest strata of the atmosphere, the world wind potential is of the order of 10 TW. Therefore, it can be concluded that, purely on a theoretical basis, and disregarding the mismatch between supply and demand, the wind could supply an

Fig. 15. A photograph of a stand-alone PV application.

amount of electrical energy equal to the present world electricity demand.

As a consequence of the on-linear relationship between wind speed and the power (and hence the energy) of the wind, one should be careful in using average wind speed data (m/s) to derive wind power data (W/m^2). Local geographical circumstances may lead to mesoscale wind structures which have a much higher energy content than one would calculate from the most commonly used wind speed frequency distribution (Rayleigh). Making allowances for the increase of wind speed with height, it follows that the energy available at, say 25 m varies from around 1.2 MW h/m^2/yr to around 5 MW h/m^2/yr in the windiest regions. Higher energy levels are possible if hilly sites are used, or if local topography funnels a prevailing wind through valleys.

6.2.1. Brief historical introduction into wind energy

After solar energy, wind energy is the most widely used energy source for small capacity desalination plants, mainly of the reverse osmosis type. Many wind farms exist which produce electricity and some are connected to desalination plants. Wind energy is, in fact, an indirect activity of the sun. Its use as energy goes as far back as 4000 years, during the dawn of historical times. It was adored, like the sun, as God. For the Greeks, wind was the god Aeolos, the ‘flying man’. After this god’s name, wind energy is sometimes referred to as Aeolian energy [1].

In the beginning, about 4000 years ago, wind energy was used for the propulsion of sailing ships. In antiquity this was the only energy available to drive ships sailing in the Mediterranean Basin and other seas, and even today it is used for sailing small leisure boats. At about the same period windmills appeared which were used mainly to grind various crops.

It is believed that the genesis of windmills, though not proved, originated from the prayer mills of Tibet. The first, very primitive windmills have been found at Neh, eastern Iran and on the Afghanistan borders [2]. Many windmills have been found in Persia, India, Sumatra and Bactria. It is believed in general that many of the windmills were constructed by the Greeks, who immigrated to Asia with the troops of Alexander the Great [1]. The earliest written document known to us about windmills is in a Hindu book of about 400 BC, called Arthasastra of Kantilys [185], where there is a suggestion for the use of windmills to pump water. In Western Europe windmills came later, during the 12th century, with the first written reference in the 1040–1180 AD time frame [186].

The famous Swiss mathematician, Euler, developed the wind wheel theory and related equations, which are, even today, the most important principles for turbogenerators. The ancestor of today’s vertical axis wind turbines were developed by Darrieus [187] but it took about 50 years to be commercialized in the 1970s. Scientists in Denmark first installed wind turbines during World War II to increase the electrical capacity of their grid. They installed 200 kW Gedser mill turbines, which were in operation until the 1960s [188].

Wind farms or individual wind generators are used today to produce electricity for reverse osmosis desalination units in order to provide fresh water to small communities in isolated and remote locations having sufficient wind energy sites.

6.2.2. Wind turbines

The theoretical maximum aerodynamic conversion efficiency of wind turbines, from wind to mechanical power is 59%. However, the fundamental properties of even the most efficient of modern aerofoil sections, used for blades of large and medium size wind turbines, limit the peak achievable efficiency to around 48%. In practice the need to economize on blade costs tends to lead to the construction of slender bladed, fast running wind turbines with peak efficiencies a little below the optimum, say 45%. The average, year-round efficiency of most turbines is about half this figure. This is due to the need to shut down the wind turbine in low or high winds and to limit the power once the rated level is reached. Further, a reduction of the average efficiency is caused by generator (and gearbox) losses and by the fact that the machine does not always operate in its optimum working point [189].

Wind turbines represent a mature technology for power production and they are commercially available on a wide range of nominal power. A valuable review of wind technology was presented by Ackermann and Soder [190]. In spite of its maturity, new control strategies and improved energy storage systems may increase the production of wind turbines.

6.2.3. Economy

In many countries, wind power is already competitive with fossil and nuclear power when external/social costs are included. The often-perceived disadvantage of wind energy (and solar energy) that, being an intermittent (stochastically varying) source, not representing any capacity credit, which makes the resource of uncertain value for large scale electricity production, is not true. Utility studies have shown that wind energy does represent a certain capacity credit, though a factor 2–3 lower than the value for nuclear and fossil fuel fired plants. Thus wind energy replaces fossil fuels and saves capacity of other generating plants.

The growth of the installed wind power is hampered by a number of barriers. These are public acceptance, land requirements, visual impact, audible noise, telecommunication interference and various impacts on natural habitat and wild life. Most of these problems, however, are solved by the installation of offshore wind parks.

6.2.4. Wind turbine system technology

Wind energy can compete with energy from other sources (coal, oil and nuclear) only under favourable wind

Fig. 16. A photograph of a wind park.

and grid conditions. Further decrease of cost will extent the market potential for wind turbine systems considerably. Decrease of the cost of wind energy can be achieved by reducing the relative investment cost, introducing reliability design methods, and exploiting the best available wind sites.

The exploitation of wind energy today uses a wide range of machine sizes and types giving a range of different economic performances. These are the small machines up to about 300 kW and the large capacity ones which are in the MW range. A photograph of a wind park is shown in Fig. 16.

The technology of the wind turbine generators currently in use is only 25 years old, and investment in it has so far been rather modest, as compared with other energy sources. The worldwide installed wind capacity at the end of 2003 was 30.6 GW_e [191] with an increase of about 30% per year. Nearly, all the wind turbines manufactured by industry are of the horizontal axis type and most of them have a three bladed rotor. However, for some years now, machines have been constructed with two blades to reduce the costs and prolong the life of machines by making them lighter and more flexible by reducing the number of high technology components.

6.3. Geothermal energy

Measurements show that the ground temperature below a certain depth remains relatively constant throughout the year. This is due to the fact that the temperature fluctuations at the surface of the ground are diminished as the depth of the ground increases because of the high thermal inertia of the soil.

Popiel et al. [192] present the temperature distributions measured in the ground for the period between summer 1999 to spring 2001. The investigation was carried out in Poland. From the point of view of the temperature distribution, they distinguish three ground zones:

1. *Surface zone* reaching a depth of about 1 m, in which the ground temperature is very sensitive to short time changes of weather conditions.
2. *Shallow zone* extending from the depth of about 1–8 m (for dry light soils) or 20 m (for moist heavy sandy soils), where the ground temperature is almost constant and close to the average annual air temperature; in this zone the ground temperature distributions depend mainly on the seasonal cycle weather conditions.
3. *Deep zone* below the depth of the shallow zone, where the ground temperature is practically constant (and very slowly rising with depth according to the geothermal gradient).

There are different geothermal energy sources. They may be classified in terms of the measured temperature as low (<100 °C), medium (100–150 °C) and high temperature (>150 °C). The thermal gradient in the Earth varies between 15 and 75 °C per kilometre depth nevertheless, the heat flux is anomalous in different continental areas. Moreover, there are local centres of heat, between 6 and 10 km deep, created due to the disintegration of radioactive elements. Barbier [193,194] presented a complete overview of geothermal energy technology. Baldacci et al. [195] reported that the cost of electrical energy is generally competitive, 0.6–2.8 US¢/MJ (2–10 US¢/kW h) and that 0.3%, i.e. 177.5 billion MJ/yr (49.3 billion kW h/yr), of the world total electrical energy is generated in year 2000 from geothermal resources. Geothermal energy can be used as a power input for desalination. A number of applications are given in Section 7.5.

Energy from the earth is usually extracted with ground heat exchangers. These are made of a material that is extraordinarily durable but allows heat to pass through efficiently. Ground heat exchanger manufacturers typically use high-density polyethylene which is a tough plastic, with heat fuse joints. This material is usually warranted for as much as 50 years. The fluid in the loop is water or an environmentally safe antifreeze solution. Other types of heat exchangers utilise copper piping placed underground. The length of the loop depends upon a number of factors such as the type of loop configuration, the thermal load, the soil conditions, local climate and many others. A review of ground heat exchangers is given in [196].

7. Review of renewable energy desalination systems

7.1. Solar thermal energy

Solar thermal energy is one of the most promising applications of renewable energy to seawater desalination. A solar distillation system may consist of two separated devices, the solar collector and the conventional distiller (indirect solar desalination). Indirect solar desalination systems usually consist of a commercial desalination plant that is connected to commercial or special solar thermal collectors. With respect to special solar thermal collectors, Rajvanshi [197] designed such a solar collector to be connected to a MSF distillation plant. Hermann et al. [198] report the design and test of a corrosion-free solar collector for driving a multieffect humidification process. The pilot plant was installed at Pozo Izquierdo (Gran Canaria, Spain) [199]. Details of the solar collectors are given in [200,201].

Ajona [202] give details of the ACE-20 parabolic trough collector that is optimised for driving a solar MEB plant coupled to a double effect absorption heat pump installed at the solar research centre in Plataforma Solar de Almeria, Spain.

There are also special designs of distillation devices which can be coupled to solar thermal collectors. One such application is presented by Miyatake et al. [203], who show a prototype distiller design which uses the steam generated in the desalination process for driving another process.

Since, the standard MSF process is not able to operate with variable heat source, the company ATLANTIS developed an adapted MSF system that is called ‘Autoflash’ which can be connected to a solar pond [204]. With regard to pilot desalination plants coupled to salinity gradient solar ponds the seawater or brine preheated by the desalination plant absorbs the thermal energy delivered by the heat storage zone of the solar pond [205].

Different plants were implemented coupling a solar pond to an MSF process:

- Margarita de Savoya, Italy: Plant capacity 50–60 m^3/day [206].
- Islands of Cape Verde: Atlantis ‘Autoflash’, plant capacity 300 m^3/day [204].
- Tunisia: a small prototype at the laboratoire of thermique Industrielle; a solar pond of 1500 m^2 drives an MSF system with capacity of 0.2 m^3/day [207].
- El Paso, Texas: plant capacity 19 m^3/day [208].

There are also solar pond-powered MEB plants:

- University of Ancona, Italy: a hybrid plant with capacity of 30 m^3/day [209].
- Near Dead Sea: plant capacity 3000 m^3/day [210].

Several other researchers [196,211] selected solar pond-powered desalination as one of the most cost-effective systems. Tleimat and Howe [212] analysed an MEB plant driven by a solar pond. Hoffman [213] proposed solar pond-driven MEB plants as the most cost-effective solar MEB process, competitive with the use of fossil fuel.

Thermal energy delivered by a salinity-gradient solar pond has been used in seawater and brackish water RO desalination [214]. Lu et al. [208] describe a solar pond-powered desalination plant at El Paso (USA) in which the solar pond drives both, thermal and RO plants. Safi and Korchani [215] analyse the cost of dual purpose plants connected to a solar pond.

Rheinlander and Lippke [216] analysed a cogeneration system in which a MEB plant is coupled to a solar tower power plant. Glueckstern [217] presented a detailed analysis of dual-purpose solar plants. A hybrid MSF-RO system driven by a dual purpose solar plant was installed at Kuwait [206]. The desalination system consists of a 25 m^3/day MSF plant and a 20 m^3/day RO plant.

Other indirect solar desalination pilot plants are implemented at different locations:

- Safat, Kuwait: a 10 m^3/day-MSF driven by solar collectors [210].
- Takami Island, Japan: a 16 effect-ME, plant capacity, 16 m^3/day; solar collectors, flat plate [206].
- Abu Dhabi, UAE: ME-18 effects with plant capacity of 120 m^3/day driven by evacuated tube collectors [218].
- Al-Ain, UAE: the plant consists of a hybrid distillation system (ME-55 stages, MSF-75 stages) with capacity of 500 m^3/day driven by parabolic trough collectors [219].
- Arabian Gulf: an MEB plant with capacity of 6000 m^3/day driven by parabolic trough collectors [206].
- Al Azhar University in Gaza: small experimental pilot plant consisting of an MSF of 4-stages driven by solar thermal collectors and PV cells to drive the auxiliary equipment. The tests performed show the maximum daily production of 0.2 m^3/day [220].
- Almeria, Spain, at the Plataforma Solar de Almeria (PSA): a parabolic trough solar field was connected to a 14 effect-MED-TVC plant with capacity of 72 m^3/day [221]. On a second phase of the project, a double-effect absorption heat pump (HP) was coupled to the solar desalination plant [222].
- Berken, Germany: an MSF with capacity of 10 m^3/day [223].
- Hzag, Tunisia: a distillation plant with capacity range of 0.1–0.35 m^3/day driven by solar collector [210].
- Gran Canaria, Spain: a 10 m^3/day-MSF plant driven by low concentration solar collectors [224].
- La Desired Island, France: an ME-14 effects, with capacity of 40 m^3/day driven by evacuated tube collectors [225].
- Lampedusa Island, Italy: a 0.3 m^3/day-MSF plant driven by low concentration solar collectors [226].
- Kuwait: an autoregulated MSF with capacity of 100 m^3/day driven by parabolic trough collectors [206].
- La Paz, Mexico: an MSF with 10 stages and plant capacity of 10 m^3/day driven by flat plate and parabolic trough collectors [227].

Another way of using solar energy is by coupling the shaft power produced from solar thermal energy to drive a RO process or a MVC. A prototype of a RO plant of 300 m^3/day was implemented with flat plate collectors using Freon as the working fluid [228]. Also, Childs et al. [229] presented a system that is able to be connected to solar thermal collectors and a RO plant.

7.2. Solar photovoltaics

The photovoltaic technology can be connected directly to a RO system, the main problem, however, is the currently high cost of PV cells. The extent at which the PV energy is competitive with conventional energy depends on the plant capacity, on the distance to the electricity grid and on the salt concentration of the feed. Kalogirou [230] and Tzen et al. [231] analysed the cost of PV-RO desalination systems. Al Suleimani and Nair [232] presented a detailed cost analysis of a system installed in Oman. Thomson and Infield [233] presented the simulation and implementation of a PV-driven RO for Eritrea with variable flow that is able to operate without batteries. The production capacity of the system was 3 m^3/day with a PV array of 2.4 kW_p. The model was validated with laboratory tests. The Canary Islands Technological Institute (ITC) developed a stand alone system (DESSOL) with capacity of 1–5 m^3/day of nominal output.

In Riyadh, Saudi Arabia, a PV-RO brackish water desalination plant was installed. It is connected to a solar still with a production of 5 m^3/day. The feed water of the solar still is the blowdown of the RO unit (10 m^3/day) [234].

Another way of using PV is in combination with ED. ED process is more suitable than RO for brackish water desalination in remote areas. Several pilot plants of ED systems connected to photovoltaic cells by means of batteries have been implemented. Gomkale [60] analysed solar desalination for Indian villages and concluded that solar-cell-operated ED seems to be more advantageous for desalting brackish water than conventional solar still. A PV-driven ED plant was installed at the Spencer Valley, in New Mexico. It was developed by the Bureau of Reclamation (United States) [210,235]. Experimental research in PV-ED was also performed at Laboratory for Water Research, University of Miami, Miami, FL, USA [236] and at the University of Bahrain [237].

Some other PV-ED systems installed are as follows:

- Thar desert, India: 0.120 m^3/h, brackish water, 450 W_p [238].
- Spencer Valley, New Mexico: 2.8 m^3/day, brackish water [210].
- Ohsima Island, Nagasaki, Japan: 10 m^3/day, seawater [239].
- Fukue city, Nagasaki, Japan: 8.33 m^3/h, brackish water [240].

7.3. Wind power

Since, RO is the desalination process with the lowest energy requirements (see Section 8) and coastal areas present a high availability of wind power resources [241], wind powered desalination is one of the most promising alternatives of renewable energy desalination. A preliminary cost evaluation of wind-powered RO is presented by Garcıa-Rodrıguez et al. [242]. In particular, the influence of climatic conditions and plant capacity on product cost is analysed for seawater RO driven by wind power. Additionally, the possible evolution of product cost due to possible future changes in wind power and RO technologies is evaluated. Finally, the influence on the competitiveness of wind-powered RO versus conventional RO plants due to the evolution of financial parameters and cost of conventional energy is pointed out.

Kiranoudis et al. [243] performed a detailed analysis of a wind-powered RO plant by considering both different wind turbines and membranes. Design parameters selection and operation aspects were considered as well as the use of seawater and brackish water feed.

Habali and Saleh [244] presented a study of a wind-powered brackish water RO plant for Jordan. The reported product cost is lower than that obtained by using conventional diesel engines.

Heukelom et al. [245] reported on a wind-powered RO plant with possible combinations of autonomous diesel operation. The system is using a relatively cheap wind energy and when combined with a diesel generator set, a reliable energy system for water desalination is provided.

Gonzalez [246] gives details of a wind driven seawater desalination system installed at Pajara (Fuerteventura Island, Spain). It is a RO plant with capacity of 56 m^3/day driven by a hybrid diesel-wind system. It consists of two diesel engines and a wind turbine of 225 kW. Such hybrid system provides the energy requirements of a village of 300 people.

Ehmann and Cendagorta [247] report a RO system with variable load connected to a wind turbine. It was installed at the ITC (Canary Islands Technological Institute), located at Pozo Izquierdo, Gran Canaria, Spain.

Another pilot plant in which the RO system is able to adapt to the variable wind energy available is described by Miranda and Infield [248]. Robinson et al. [249] described a wind-RO brackish water desalination system which was designed for small remote communities in Australia.

The Canary Islands Technological Institute also developed a stand-alone system with capacities between 5 and 50 m^3/day, known as AEROGEDESA [250,251]. The average production claimed is 11 m^3/day for a plant with nominal output of 13 m^3/day for an annual average wind speed of 7 m/s.

Other wind-driven RO systems are as follows:

- In Drepanon, Achaia, near Patras (Greece) a wind powered RO system was set in operation in 1995 [252].
- A 25 m^3/day RO plant connected to a hybrid wind-diesel system is installed in the Middle East [253].
- A RO system driven by a wind power plant, in Island of the County Split and Dalmatia [254].

Another area of interest is the direct coupling of a wind energy system and a RO unit by means of shaft power.

Research in this field has been carried out at the Canary Islands Technological Institute [255]. In Coconut Island off the northern coast of Oahu, Hawai, a brackish water desalination wind-powered RO plant was installed. The system is using directly the shaft power production of a windmill with the high pressure pump and RO. In particular a constant fresh water production of 13 l/min can be maintained for wind speed of 5 m/s [256].

Another possibility investigated is the use of wind power directly with an MVC. A detailed analysis of the influence of the main parameters of such systems was performed by Karameldin et al. [257]. In Borkum Island, in the North Sea a pilot plant was erected with a fresh water production of about 0.3–2 m^3/h [210,258]. In Ruegen Island (Germany), another pilot plant was installed with a 300 kW wind energy converter and 120–300 m^3/day fresh water production [210,259].

Finally, another possibility investigated is the use of wind power with ED. Modelling and experimental tests results of one such system with a capacity range of 192–72 m^3/day, installed at the ITC, Gran Canaria, Spain is presented by Veza et al. [260].

7.4. Hybrid solar PV-wind power

The complementary features of wind and solar resources make the use of hybrid wind–solar systems to drive a desalination unit a promising alternative as usually when there is no sun the wind is stronger and vice versa. Manolakos et al. [261] presented a useful software for simulation of hybrid wind-PV RO systems. The Cadarache Centre in France designed a pilot unit that was installed in 1980 at Borj–Cedria of Tunisia [235]. The system consists of a 0.1 m^3/day-compact solar distiller, a 0.25 m^3/h RO plant and an ED plant for 4000 ppm brackish water. The energy supply system consists of a photovoltaic field with a capacity of 4 kW peak and two wind turbines. Other systems that have been designed and implemented are as follows:

- Two RO-desalination plants supplied by a 6 kW wind energy converter and a 2.5 kW solar generator for remote areas [262].
- A 3 m^3/day-plant for brackish water installed in Israel [263].
- A system with a capacity of 1 m^3/h in Oman [264].

7.5. Geothermal energy

Low temperature geothermal waters in the upper 100 m may be a reasonable energy source for desalination [228]. Ophir [265] gave an economic analysis of geothermal desalination in which sources of 110–130 °C were considered. He concludes that the price of geothermal desalination is as low as the price of large multi-effect dual purpose plants.

Possibly, the oldest paper found regarding desalination plants assisted by geothermal energy was authored by Awerbuch et al. [266]. They reported that the Bureau of Reclamation of the US Department of the Interior investigated a geothermal powered desalination pilot plant near Holtville, California, USA in 1972. Boegli et al. [267] from the same department, reported experimental results of geothermal fluids desalination at East Mesa Test Site. The processes analysed included MSF distillation and high-temperature ED as well as different evaporation tubes and membranes.

Karytsas [268,269] performed a technical and economic analysis on the use of geothermal sources between 75 and 90 °C with MEB. One such plant was planned to be installed in Cyclades Islands, Greece.

Two geothermal-powered distillation plants were installed one in France [270] and one in the south of Tunisia [271]. Both of them use evaporators and condensers made from polypropylene at an operation temperature range of 60–90 °C [272]. Bouchekima [273] also analysed the performance of a solar still in which the feed water is brackish underground geothermal water.

Another possibility which can be investigated is the use of high-pressure geothermal power directly as shaft power on desalination. Moreover, there are commercial membranes that withstand temperatures up to 60 °C, which permits the direct use of geothermal brines for desalination [274].

8. Process selection

During the design stage of a renewable energy powered desalination system, the designer will need to select a process suitable for a particular application. The factors that should be considered for such a selection are the following [150]:

(i) Suitability of the process for renewable energy application.
(ii) The effectiveness of the process with respect to energy consumption.
(iii) The amount of fresh water required in a particular application in combination with the range of applicability of the various desalination processes.
(iv) The seawater treatment requirements.
(v) The capital cost of the equipment.
(vi) The land area required or could be made available for the installation of the equipment.

Before any process selection can start, a number of basic parameters should be investigated. The first is the evaluation of the overall water resources. This should be done both in terms of quality and quantity (for brackish water resource). Should brackish water be available then this may be more attractive as the salinity is normally much lower (< 10,000 ppm), and hence the desalination of the brackish water should be the more attractive option. In inland sites, brackish water may be the only option. On a coastal site seawater is normally available. The identification and evaluation of the renewable energy resources in the area, completes the basic steps to be performed towards the design of a RES driven desalination system. Renewable energy driven desalination technologies mainly fall into two categories. The first category includes distillation desalination technologies driven by heat produced by RES, while the second includes membrane and distillation desalination technologies driven by electricity or mechanical energy produced by RES. Such systems should be characterized by robustness, simplicity of operation, low maintenance, compact size, easy transportation to site, simple pretreatment and intake system to ensure proper operation and endurance of a plant at the difficult conditions often encountered in remote areas. Concerning their combination, the existing experience has shown no significant technical problems [43].

Water production costs generally include the following items [275]:

- fixed charges, which depend on the capital cost and depreciation factor (determined from both plant life and financial parameters and consequently varying for each country);
- variable charges, which depend on the consumption and cost of energy (related to the source employed and location selected), operational (manpower) and maintenance cost (varying for each country), consumption and cost of chemicals used for pre- and post-treatment of water (especially in RO plants) and the rate at which the membranes are to be replaced in RO plants (these factors are both site related).

Generally, the percentage of TDS in seawater has practically no effect in thermal processes, but has a remarkable effect in reverse osmosis, where the energy demand increases linearly at a rate of more than 1 kW h/m^3 per 10,000 ppm [275]. If, however, the input pressures are left unchanged, the percentage of salts in the water produced could be intolerably high. Normally, this value for the RO process is expected to be around 300 ppm. The value, though lying well within the limit of 500 ppm (fixed by the WHO for the drinking water), still results in being at least one order of magnitude higher than the salinity of water produced from thermal processes. Also for high salinity concentration the use of RO technology is very problematic.

Renewable energy sources can provide thermal energy (solar collectors, geothermal energy), electricity (photovoltaics, wind energy, solar thermal power systems) or mechanical energy (wind energy). All these forms of energy can be used to power desalination plants.

Solar energy can generally be converted into useful energy either as heat, with solar collectors and solar ponds, or as electricity, with photovoltaic cells and solar thermal power systems. As was seen in Section 7, both methods have been used to power desalination systems. The direct collection systems can only utilise solar energy whenever it is available, and their collection is inefficient. Alternatively, in the indirect collection systems, solar energy is collected by more efficient solar collectors, in the form of hot water or steam. It should be noted, however, that solar energy is only available for almost half of the day. This implies that the process operates for only half the time available unless some storage device is used. The storage device, which is usually expensive, can be replaced by a back-up boiler or electricity from the grid in order to operate the system during low insolation and night-time. When such a system operates without thermal buffering, the desalination sub-system must be able to follow a variable energy supply, without upset. In all solar energy desalination systems an optimum PR has to be calculated based on the solar energy collectors cost, storage devices cost (if used), and the cost of the desalination plant [150]. Probably, the only form of stable energy supply is the solar pond, which due to its size, it does not charge/discharge easily, and thus is more insensitive to variations in the weather.

Wind energy is also a highly variable source of supply, with respect to both wind speed and frequency. When wind energy is used for electricity generation the variation of the wind source can be balanced by the addition of battery banks, which act in a similar way to a storage tank in solar thermal systems, i.e. the batteries charge when wind is available and discharge to the load (desalination plant) when required. In the case of mechanical energy production from wind, the desalination plant can operate only when there is wind. In this case, the desalination plant is usually oversized with respect to water demand, and instead of storing the energy, the water produced when wind is available is stored.

Concerning the technologies selection another parameter to be considered is the type of connection of the two technologies. A RO renewable desalination plant can be designed to operate coupled to the grid or off-grid (stand-alone-autonomous system). When the system is grid connected, the desalination plant can operate continuously as a conventional plant and the renewable energy source merely acts as a fuel substitute. Where no electricity grid is available, autonomous systems have to be developed which allow for the intermittent nature of the renewable energy source. Desalination systems have traditionally been designed to operate with a constant power input [276]. Unpredictable and non-steady power input, force the desalination plant to operate in non-optimal conditions and may cause operational problems [43]. Each desalination system has specific problems when it is connected to a variable power system. For instance, the reverse osmosis (RO) system has to cope with the sensitivity of the membranes regarding fouling, scaling, as well as unpredictable phenomena due to start-stop cycles and partial load operation during periods of oscillating power supply. On the other hand, the vapour compression system has considerable thermal inertia and requires considerable energy to get to

Table 4
Energy consumption of desalination systems

Process	Heat input (kJ/kg of product)	Mechanical power input (kW h/m^3 of product)	Prime energy consumption (kJ/kg of product)[a]
MSF	294	2.5–4 (3.7)[b]	338.4
MEB	123	2.2	149.4
VC	–	8–16 (16)	192
RO	–	5–13 (10)	120
ER-RO	–	4–6 (5)	60
ED	–	12	144
Solar still	2330	0.3	2333.6

[a] Assumed conversion efficiency of electricity generation of 30%.

[b] Figure used for the prime energy consumption estimation shown in last column.

the nominal working point. Thus, for autonomous systems a small energy storage system, batteries or thermal stores, should be added to offer stable power to the desalination unit. Any candidate option resulting from the previous parameters should be further screened through constraints such as site characteristics (accessibility, land formation, etc.) and financial requirements [43].

The energy required for various desalination processes, as obtained from a survey of manufacturers' data is shown in Table 4. It can be seen from Table 4 that the process with the smallest energy requirement is RO with energy recovery. But this is only viable for very large systems due to the high cost of the energy-recovery turbine. The next lowest is the RO without energy recovery and the MEB. A comparison of the desalination equipment cost and the seawater treatment requirement, as obtained from a survey of manufacturers' data, is shown in Table 5. The cheapest of the systems considered is the solar still. This is a direct collection system, which is very easy to construct and operate. The disadvantage of this process is the very low yield, which implies that large areas of flat ground are required. It is questionable whether such process can be viable unless a cheap, desert-like land is available near the sea. The MEB is the cheapest of all the indirect collection systems and also requires the simplest seawater treatment. RO although requiring a smaller amount of energy is expensive and requires a complex seawater treatment.

Due to the development of RO technology, the energy consumption values of more than 20 kW h/m^3 during the year 1970 have been reduced today to about 5 kW h/m^3 [275]. This is due to improvements that were made in RO membranes. Research in this sector is ongoing worldwide and we may see further reductions in both energy requirements and costs in the coming years. It should be noted that nearly 3 kg of CO_2 are generated for each cubic metre of water produced (at an energy consumption rate of 5 kW h/m^3 with the best technology currently used on large scale) which could be avoided if the conventional fuel is replaced by a renewable one.

One alternative, which is usually considered for solar-powered desalination, is to use an RO system powered with photovoltaic cells. This is more suitable for intermittent operation than conventional distillation processes and has higher yields per unit of energy collected. According to Zarza et al. [156] who compared RO with photovoltaic generated electricity with an MEB plant coupled to parabolic trough collectors, the following apply:

(i) The total cost of fresh water produced by an MEB plant coupled to parabolic trough collectors is less than that of the RO plant with photovoltaic cells due to the high cost of the photovoltaic-generated electricity.
(ii) The highly reliable MEB plant operation makes its installation possible in countries with high insolation levels but lacking in experienced personnel. Because any serious mistake during the operation of a RO plant can ruin its membranes, these plants must be operated by skilled manpower.

Also, since renewable energy is expensive to collect and store, an energy-recovery turbine is normally fitted to recover energy from the rejected brine stream, which increases the RO plant cost considerably. Additionally, in polluted areas, distillation processes are preferred for desalination because water is boiled, which ensures that the distilled water does not contain any micro-organisms [150]. Specific water quality problems include in addition to the high salinity manganese, fluoride, heavy metals, bacterial contamination and pesticide/herbicide residues. In all these cases, thermal processes are preferred to the membrane ones. Even the simple solar still can provide removal efficiencies in the order of 99% [277].

Table 5
Comparison of desalination plants

Item	MSF	MEB	VC	RO	Solar still
Scale of application	Medium–large	Small–medium	Small	Small–large	Small
Seawater treatment	Scale inhibitor anti-foam chemical	Scale inhibitor	Scale inhibitor	Sterilizer coagulant acid deoxidiser	–
Equipment price (Euro/m^3)	950–1900	900–1700	1500–2500	900–2500 membrane replacement every 4–5 yr	800–1000

Low figures in equipment price refer to bigger size in the range indicated and vice versa.

If both RO and thermal processes are suitable for a given location, the renewable energy available and the energy required electrical/mechanical/thermal by the process limit the possible selection. Finally, the required plant capacity, the annual and daily distribution of the fresh water demand, the product cost, the technology maturity and any problems related to the connection of the renewable energy and the desalination systems are factors which influence the selection.

If thermal energy is available, it can be used directly to drive a distillation process such as MSF, MEB or TVC. MEB plants are more flexible to operate at partial load, less sensible to scaling, cheaper and more suitable for limited capacity than MSF plants. TVC have lower performance than MEB and MSF. Besides that, the thermomechanical conversion permits the indirect use of thermal energy to drive RO, ED or MVC processes.

If electricity or shaft power can be obtained from the available energy resources, RO, ED or MVC can be selected. Fluctuations of the available energy would ruin the RO system. Therefore, an intermediate energy storage would be required, but it would reduce the available energy and increase the costs. In remote areas, the ED is most suitable for brackish water desalination because it is more robust and its operation and maintenance are simpler than RO systems. In addition, ED process is able to adapt to changes of available energy input. On the other hand, although MVC consumes more energy than RO, it presents fewer problems due to the fluctuations of the energy resource than RO. MVC systems are more suitable for remote areas since they are more robust, they need fewer skilled workers and fewer chemicals than RO systems [40]. In addition, they need no membrane replacement and offer a better quality product than RO. Moreover, in case of polluted waters, the distillation ensures the absence of micro-organisms and other pollutants in the product.

It is believed that solar energy is best and most cheaply harnessed with thermal energy-collection systems. Therefore, the two systems that could be used are the MSF and the MEB plants. As can be seen from Section 7, both systems have been used with solar energy collectors in various applications. According to Tables 4 and 5, the MEB process requires less specific energy, is cheaper and requires only a very simple seawater treatment. In addition, the MEB process has advantages compared to other distillation processes. According to Porteous [278], these are as follows:

(i) Energy economy because the brine is not heated above its boiling point as is the case for the MSF process. The result is less irreversibility in the MEB process since the vapour is used at the temperature at which it is generated.
(ii) The feed is at its lowest concentration at the highest plant temperature so that scale-formation risks are minimised.
(iii) The feed flows through the plant in series and the maximum concentration occurs only in the last effect; therefore, the worst boiling-point elevation is confined to this effect.
(iv) The other processes have a high electrical demand because of the recirculation pump in the MSF or the vapour compressor in the VC systems.
(v) MSF is prone to equilibrium problems, which are reflected by a reduction in PR. In MEB plants, the vapour generated in one effect is used in the next and PR is not subject to equilibrium problems.
(vi) Plant simplicity is promoted by the MEB process because fewer effects are required for a given PR.

Of the various types of MEB evaporators, the Multiple Effect Stack (MES) type is the most appropriate for solar energy application. There are a number of advantages, the most important of which is stable operation between virtually zero and 100% output even when sudden changes are made and the ability to follow a varying steam supply without upset [154]. For this purpose, collectors of proven technology like the parabolic trough can be used to produce the input power to the MES system in the form of low-pressure steam. The temperature required for the heating medium is between 70 and 100 °C, which can be produced with such collectors with an efficiency of about 65% [154].

9. Conclusions

In this paper, a review of the various renewable energy desalination systems is presented together with a review of a number of pilot systems erected in various parts of the world. The selection of the appropriate RES desalination technology depends on a number of factors. These include, plant size, feed water salinity, remoteness, availability of grid electricity, technical infrastructure and the type and potential of the local renewable energy resource. Among the several possible combinations of desalination and renewable energy technologies, some seem to be more promising in terms of economic and technological feasibility than others. However, their applicability strongly depends on the local availability of renewable energy resources and the quality of water to be desalinated. In addition to that, some combinations are better suited for large size plants, whereas some others are better suited for small scale applications.

The most popular combination of technologies is MEB with thermal collectors and reverse osmosis with PV. PV is particularly good for small applications in sunny areas. For large units, wind energy may be more attractive as it does not require anything like as much ground. This is often the case on islands, where there is a good wind regime and often very limited flat ground. With distillation processes, large sizes are more attractive due to the relatively high heat loses from small units. Energy cost is one of the most important elements in determining water costs when water is produced from desalination plants.

The worlds water needs are increasing dramatically. Wind, solar and other renewable technologies that can be used for desalination are rapidly emerging with the promise of economic and environmental viability on a large scale. There is a need to accelerate the development of novel water production systems from renewables. Keeping in mind the climate protection targets and strong environmental concerns, future water desalination around the world should be increasingly powered by solar, wind and other clean natural resources. Such environmentally friendly systems should be potentially available at economic costs.

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