

RENEWABLE ENERGY POWERED DESALINATION SYSTEMS: TECHNOLOGIES AND ECONOMICS-STATE OF THE ART

Mohamed A. Eltawil^{1,2}, Zhao Zhengming¹ and Liqiang Yuan¹

¹ The State Key Laboratory of Power System, Department of Electrical Engineering,
Tsinghua University, Beijing, 100084, China

² Agricultural Engineering Department, Kafrelsheikh University, Box 33516, Egypt
E-mail: eltawil69@yahoo.co.in

ABSTRACT

Energy resources and their utilization intimately relate to sustainable development. In attaining sustainable development, increasing the energy efficiencies of processes utilizing sustainable energy resources plays an important role. The utilization of renewable energy offers a wide range of exceptional benefits. In this paper an attempt has been made to present a review, in brief, work of the highlights that have been achieved during the recent years world-wide and the state-of-the-art for most important efforts in the field of desalination by renewable energies, with emphasis on technologies and economics. The review also includes water sources, demand, availability of potable water and purification methods. The classification of distillation units has been done on the basis of literature survey till today. A comparative study between different renewable energy technologies powered desalination systems as well as economics have been done. The real problem in these technologies is the optimum economic design and evaluation of the combined plants in order to be economically viable for remote or arid regions. Conversion of renewable energies, including solar, requires high investment cost and though the intensive R&D effort technology is not yet enough mature to be exploited through large-scale applications. Desalination is economically feasible with the cost of water produced from desalination processes being directly related to the salt concentration of the source water. Reverse osmosis is becoming the technology of choice with continued advances being made to reduce the total energy consumption and lower the cost of water produced. Also, the environmental issues are associated with brine concentrate disposal, energy consumption and associated greenhouse gas production

1. INTRODUCTION

Water has been recognized as a basic human right. Large quantities of fresh water are required in many parts of the world for agricultural, industrial and domestic uses. As of today, nearly one fourth of mankind is suffering from inadequate fresh water supply [1]. Owing to the foreseen growth of population worldwide (especially in the developing countries), the above mentioned situation will be more and more critical over the next two decades or so.

Drought and desertification are increasing significantly, involving wider and wider areas of the planet. More than two-third of the earth's surface is covered with water. Water availability will remain constant in the near future. Most of the available water is either present as seawater or icebergs in the Polar Regions. About 97% of the earth's water is salty and rest is fresh water. Less than 1% fresh water is within human reach. Despite, technological progress, renewable fresh water reserves on earth will be only 0.3% of the world water. Agriculture uses two-third of available fresh water. The proportion of irrigated surface should increase by 1/3 in 2010 and by 50% in 2025. Industrial and domestic water use increases at twice the rate of population increase. Water consumption increased seven fold since 1900. In total, water demand doubles every 20 year. Fresh water resources are almost completely exhausted in many middle-east countries [2].

It is estimated that the population will increase over the next 20 years (2000–2020) with about 50% in Africa, 25% in Asia, 14% in the USA and, surprisingly, 2% negative, in Europe. It is obvious that a considerable increase in the world population (over the next decade or so) will be concentrated mainly in most of the developing countries and particularly in Africa, causing severe water shortages [3]. As a result, 40% of the world population is struggling with serious water shortages, with the majority of this burden falling on people who live in remote rural areas and rapidly expanding urban areas [4].

The water emergency situation is certainly very alarming, especially in countries located within the southern Mediterranean belt also, the countries from southern Europe are partially affected by the lack of drinking water, and it is advisable to take appropriate actions to avoid serious negative impacts in the very near future.

World Water challenges for the 21st century are water scarcity, lack of accessibility, water quality deterioration, world peace and security, awareness by decision makers and the public, decline of financial resources allocation and fragmentation of water management.

Most of the water available on earth has the salinity up to 10,000 ppm whereas seawater normally has salinity in the range of 35,000–45,000 ppm in the form of total dissolved salts. According to World Health Organization (WHO), the permissible limit of salinity in water is 500 ppm and for special cases goes up to 1000 ppm. Excess brackishness causes the problem of health. The annual water availability of 1000 m³ per capita constitutes the limit below which it will not be possible to guarantee an acceptable living standard as well as economic development [5]. One of the control measures includes supply of water with total dissolved solids within permissible limits of 500 ppm or less. This is accomplished by several water desalination and purification methods.

Renewable energies are expected to have a flourishing future and an important role in the domain of brackish and seawater desalination in developing countries. Many industrial countries are already initiating a transition of their electricity supply

schemes to higher renewable energy shares, by supporting market introduction and expansion of those technologies. The European Union has set a goal to double its renewable energy share until 2010, and the intergovernmental panel on climate change recommends a world wide reduction of 75% of carbon emissions by the end of this century in order to avoid dangerous, uncontrolled effects on climate and on the world's economy.

The sustainable energy systems should take into consideration the environmental impact, technical, social and economical point of view. Solar thermal power generation is playing an important role in a well-balanced mix of renewable energy sources (RES), efficient power technologies and rational use of energy.

Throughout the world a trend to intensified use of desalination as a means to reduce current or future water scarcity can be observed. Water scarcity, which occurs not only in arid regions, may be characterized as a mismatch between water supply and water demand. Over a billion people worldwide lack access to sufficient water of good quality. Most of these people live in Asia and Africa. The growing population causes a steady rise in the living standards leads to increase the specific water consumption per capita.

The lack of potable water poses a big problem in remote and arid regions. Pollution and exploitation of groundwater aquifers and surface water have led to a decrease of quantity and/or quality of available natural water resources in many regions.

The dramatic increase in desalinated water supply will create a series of problems, the most significant of which are those related to energy consumption. It has been estimated that a production of 13 million m³ of portable water per day requires 130 million tons of oil per year [17]. Given the current understanding of the greenhouse effect and the importance of CO₂ levels, this use of oil is debatable. Thus, apart from satisfying the additional energy-demand, environmental pollution would be a major concern. CO₂ emissions can be greatly reduced through the application of renewable energy technologies, which are already cost competitive with fossil fuels in many situations.

If desalination is accomplished by conventional technology, then it will require the 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 used. Fortunately, countries which lie in high solar insolation band and the vast solar potential can be exploited to convert saline water to potable water. Where the demand for fresh water exceeds the amount that fresh water sources can meet, desalination of lower quality water provides a reasonable new fresh water source. Desalination (desalting) of brackish water and seawater to provide the needed drinking water fulfills a basic social need and, in general, it does this without any serious impact on the environment. Nowadays, desalination has become a very affordable solution to cope with fresh water shortage typically in tropical as well as of off-shore areas.

Factors that have the largest effect on the cost of desalination are feed water quality (salinity levels), product water quality, energy costs as well as economies of scale [6,7]. Seawater desalination is being applied at 58% of installed capacity worldwide, followed by brackish water desalination accounting for 23% of installed capacity [8,9]. Fig. 1 outlines the global desalting capacity by feed water sources.

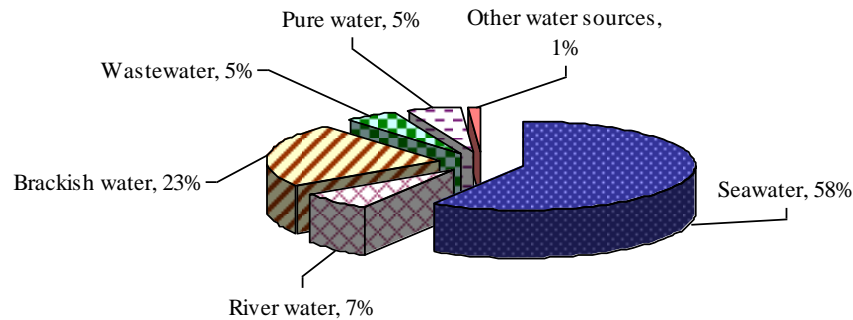


Fig. 1. Global installed desalination capacity by feed water sources [10].

Since 1950, global water use has tripled and in the next 20 years, it is estimated that humans will require 40% more water than is currently being used [4]. Meanwhile, the existing supply of natural water resources is declining as a result of increasing water pollution (90% of wastewater in developing countries is released directly into rivers and streams without treatment) and overexploitation of groundwater sources (groundwater currently supplies 50% of drinking water, 40% of industrial water and 20% of agricultural water globally) [11]. Finally, climate change may disrupt current rainfall patterns and regional water cycles around the globe.

The costs of water produced by desalination have dropped considerably over the years as a result of reductions in price of equipment, reductions in power consumption and advances in system design and operating experiences. As the conventional water supply tends to be more expensive due to over-exploitation of aquifers and increasing contaminated water resources, desalted water becomes a viable alternative water source.

Unprecedented commitment on a global scale to innovate new water technologies and management systems will be required to: 1) preserve the quality of our current supplies, 2) reduce the demand for water through gains in efficiency, and 3) increase the overall quantity of freshwater available.

This paper seeks to address the third intervention described above, by exploring the global potential for integrating renewable energy sources (RES) and desalination technologies aiming to light up their prospective characteristics and increase water supplies. Desalination processes are used to convert abundant salty water to relatively scarce freshwater and therefore represent great potential for water scarcity alleviation. The major limitation of desalination is its high energy requirements, and therefore it is

useful to explore how RES can be linked into desalination systems for sustainable freshwater production into the future, considering the technological advancements and costs.

2. RENEWABLE ENERGY COUPLING TO DESALTING TECHNOLOGIES

Renewable energies for use in desalination processes include wind, solar thermal, photovoltaic and geothermal. Renewable energy driven desalination systems fall into two categories. The first category includes distillation processes driven by heat produced by the renewable energy systems, while the second includes membrane and distillation processes driven by electricity or mechanical energy produced by RES.

The most investigated mode of coupling between RES and desalination processes is the use of direct sun rays to produce fresh water by means of solar stills. Numerous attempts to harness solar thermal energy for water distillation have been carried out in many places worldwide [12, 13]. Belessiotis and Delyannis [14], Delyannis and Belessiotis [15], Mathioulakis et al. [16] and Garcia-Rodriguez [17] presented valuable reviews of renewable energy systems. Also, there are other general reviews of renewable energy-powered desalination are, among others: Baltas et al. [18] Belessiotis and Delyannis [19], Garcia-Rodriguez [20], or Rodriguez-Girones et al. [21]. Voivontas et al. [22] developed software about alternative renewable-energy-powered desalination that includes costs analysis. Since solar desalination is one of the most promising technologies there are many reviews in the literature as follows: Delyannis [12], Delyannis and Belessiotis [15], or Garcia-Rodriguez and Gomez-Camacho [13]. Interesting comparisons of such system are given in El-Nashar [23], Kalogirou [24], Garcia-Rodriguez and Gomez Camacho [25]. While, the present status and economics of solar desalination are given in Al-Shammiri and Safar [26], Goosen et al. [27], Kamal et al. [28], Mohsen and Al-Jayyousi [29] and Rognoni and Trezzi [30].

Many studies have investigated the effect of different design parameters on the overall performance of solar stills, for example: Garg and Mann [31] Rajvanshi [32], Tiwari et al. [33,34], Zaki et al. [35], Al-Hussaini and Smith [36] and Singh et al. [37]. In this context, Tunisia has been a pioneer in exploring the possibility of water desalination through single basin solar stills. A number of desalination plants consisting of glass covered solar stills have been constructed in many parts of the country in the late 1960's [38].

Numerous attempts and experiments have been carried out throughout the world in an attempt to find suitable coupling procedures between desalination processes and RES. The suitability of a given renewable energy source for powering certain desalting processes depends on both the requirements of such processes and the form of energy that can be obtained from the considered source. Different plausible combinations between renewable energy sources and desalination technologies can be envisaged

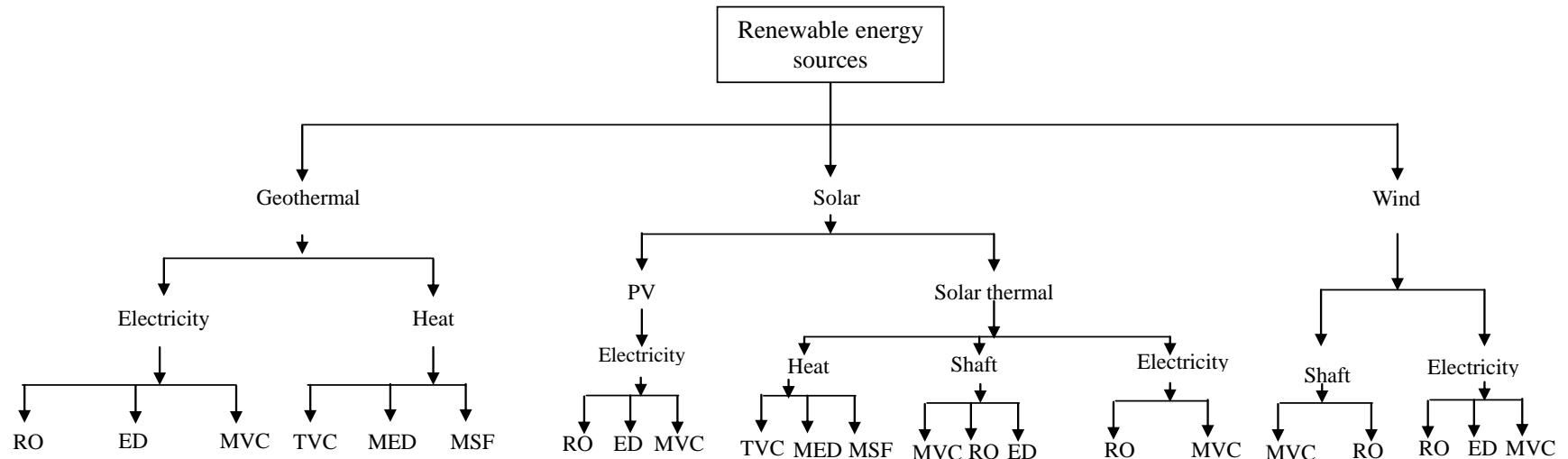
[39]. The interface between the renewable energy system and the desalination system is met at the place/subsystem where the energy generated by the RE system is promoted to the desalination plant. This energy can be in different forms such as thermal energy, electricity or shaft power. Fig. 2 shows the possible combinations [11,40]. Fig. 3 presents the algorithm for the design of the appropriate RES/desalination plant [41].

Recently, there is a significant increase in efficiency and reduction of cost due to the intensive R&D efforts and operation experience gained, advances in conventional desalination plants, steam or electrically driven [42,43].

There are numerous renewable energy sources (RES)-desalination combinations have been identified and tested in the framework of ongoing research for innovative desalination processes [39, 44- 47]. Detailed assessments of available and exploitable water resources and water needs have been carried out in the framework of research programs [48-50] taking into account current and future trends of economic development and environmental and socioeconomic factors. Moreover, the market potential for RES desalination in specific regions has been identified, based on the combined evaluation of water shortage problems and RES potential with the objective to determine economically competitive options for RES-powered desalination [51,52]. Since there are many influential criteria for determining the best combination of RES and desalination technologies, there is a broad range of existing installations of RES desalination facilities. Fig. 4 shows the distribution of renewable energy powered desalination technologies [40].

Renewable energy represents the best energy supply option for autonomous desalination systems, especially in arid and coastal areas where the conventional energy supply is shortage. Self-sufficiency and local support can be achieved by both of renewable energy systems and desalination. Climatic reasons lead to remarkable agreement on a time-basis, between the availability of RES, especially when referring to solar energy, and the intensive demand of water. The operation and maintenance of RES in remote areas are often easier than conventional energy ones. Renewable energies allow diversification of energy resources and help to avoid external dependence on energy supply. Seawater desalination processes are strongly energy consuming. Therefore, the environmental effects (Environmental impact) of the fossil fuels consumed are important. Note that total world-wide capacity of desalted water is about $23 \times 10^6 \text{ m}^3/\text{d}$ [53]. The cost reduction of renewable energy systems has been significant during the last decades. Therefore, future reductions as well as the rise of fossil fuel prices could make possible the competitiveness of seawater desalination driven by renewable energies.

Table 1 shows the relationship between various energy inputs and criteria for desalination technologies. While Table 2 shows the recommended renewable energy–desalination combinations.



PV= Photovoltaic, RO= Reverse osmosis, ED= Electrodialysis, MVC= Mechanical vapor compression, MED= Multi effect distillation, MSF= Multi stage flash distillation, TVC= Thermal vapor compression

Fig. 2. Combinations technologies of RES and desalination methods.

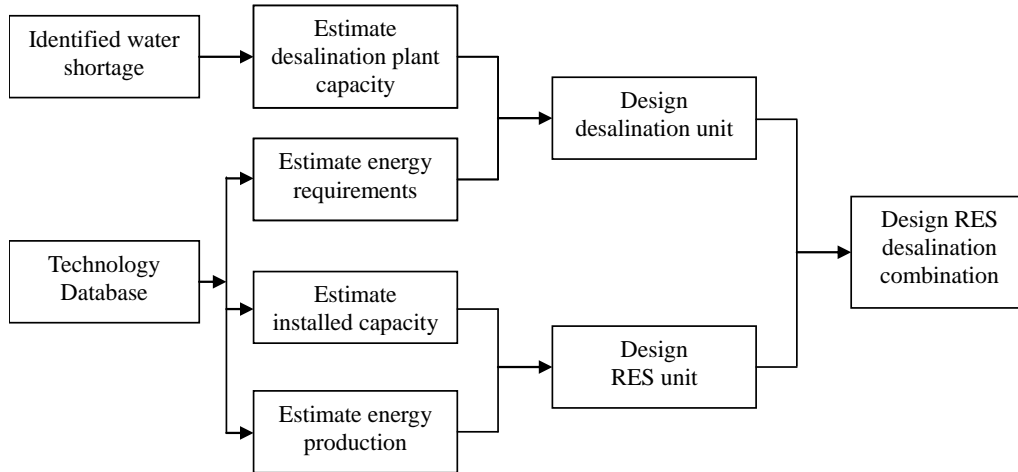


Fig. 3. Design of the appropriate RES/desalination plant.

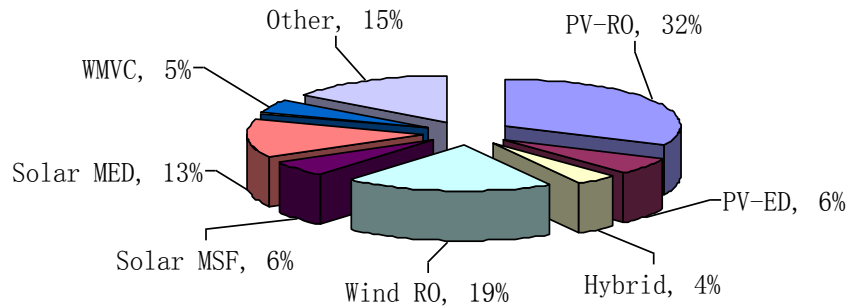


Fig. 4. Distribution of renewable energy powered desalination technologies.

Table 1. Evaluation of renewable energy technologies [54].

Criterion	Solar thermal energy	Photovoltaic	Wind energy	Geothermal energy
Suitability for powering desalination plants	Well suited for desalination plants requiring thermal power (3)	Well suited for desalination plants requiring electrical power (3)	Well suited for desalination plants requiring electrical power (3)	Well suited for desalination plants requiring thermal power (3)
Site requirements and resources availability	Typically good match with need for desalination (3)	Typically good match with need for desalination (3)	Resources is location-dependent (2)	Resources is limited to certain location (1)
Continuity of power output	Output is intermittent (energy storage required) (1)	Output is intermittent (energy storage required) (1)	Output is intermittent (energy storage required) (1)	Continuous power output (3)
Predictability of power output	Output is relatively unpredictable (2)	Output is relatively unpredictable (2)	Output is very unpredictable/fluctuates (1)	Output is predictable (3)

Note: 3 = excellent compliance with criterion; 2 = good compliance with criterion; 1 = poor compliance with criterion.

Table 2. Recommended renewable energy–desalination combinations [54].

Feed water available	Product water	RE resources available	System size			Suitable RE-Desalination combination
			Small, 1-50 m ³ /d	Medium, 50-250 m ³ /d	Large, >250 m ³ /d	
Brackish water	Desalinate	Solar	*			Solar distillation
	Potable	Solar	*			PV-RO
	Potable	Solar	*			PV-ED
	Potable	Wind	*	*		
	Potable	Wind	*	*		
Sea water	Desalinate	Solar	*			Solar distillation
	Desalinate	Solar		*	*	Solar thermal-MED
	Desalinate	Solar			*	Solar thermal-MSF
	Potable	Solar	*			PV-RO
	Potable	Solar	*			PV-ED
	Potable	Wind	*	*		Wind-RO
	Potable	Wind	*	*		Wind-ED
	Potable	Wind		*	*	Wind-VC
	Potable	Geothermal		*	*	Geothermal-MED
	Potable	Geothermal			*	Geothermal-MSF

In spite of the above mentioned advantages of RES which can be used to drive the desalination systems, but the current installed systems of RES- desalination are scarce and limited of about 0.02% of the total desalination capacity [55]. The reasons for this are related to various, often correlated, aspects such as: i) Availability, where the geographical distribution of RES potential does not always comply with the water stress intensity at a local level. ii) Costs, where the initial capital instillation costs and various system components are still expensive. Even though prices decrease continuously still in many cases they are prohibiting for commercialization. iii) Technologies, which imposes the combination of energy conversion and the desalination systems. A real challenge for these technologies would be the optimum technological design of combined plants which increase the efficiency as well as volume and decrease costs. iv) Sustainability, where in most of the cases, the maturity of the associated technologies does not match the low level of infrastructures which often characterizes places with severe water stress. Experience has shown that several attempts to integrate advanced desalination solutions in isolated areas failed due to lack of reliable technical support [adapted from 16].

2.1. Selection of desalination-process

Renewable energies may be used in desalination processes and include wind, solar thermal, photovoltaic and geothermal. Matching renewable energies with desalination units, however, requires a number of important factors to be considered. Not all the combinations of RES-driven desalination systems are practicable, since many of these

possible combinations may not be viable under certain circumstances. The optimum or just simple specific technology combination must be studied in connection to various local parameters as geographical conditions, topography of the site, capacity and type of energy available in low cost, availability of local infrastructures (including electricity grid), plant size and feed water salinity.

There are several factors to be considered for selecting desalination process suitable for a particular application, such as [adapted from 24]:

- i. The amount of fresh water required in a particular application in combination with the range of applicability of the various desalination-processes.
- ii. The effectiveness of the process with respect to energy consumption.
- iii. Suitability of the process for solar-energy application.
- iv. The sea-water 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.
- v. Robustness criteria and simplicity of operation,
- vi. Low maintenance, compact size and easy transportation to site.

3. DESALINATION TECHNOLOGIES

A desalting device essentially separates saline water into two streams: one with a low concentration of dissolved salts (the fresh water stream) and the other containing the remaining dissolved salts (the concentrate or brine stream). The device requires energy to operate and can use a number of different technologies for the separation. There are two basic technologies are utilized to remove the salts from ocean water: thermal distillation and membrane separation. Industrial desalination technologies use semipermeable membranes to separate the solvent or some solutes, or involve phase changes. All processes require a chemical pretreatment of raw brackish water to avoid scaling, foaming, corrosion, biological growth, and fouling and also it require a chemical post treatment of the processed water. The categorization of desalination technologies are shown in Fig. 5.

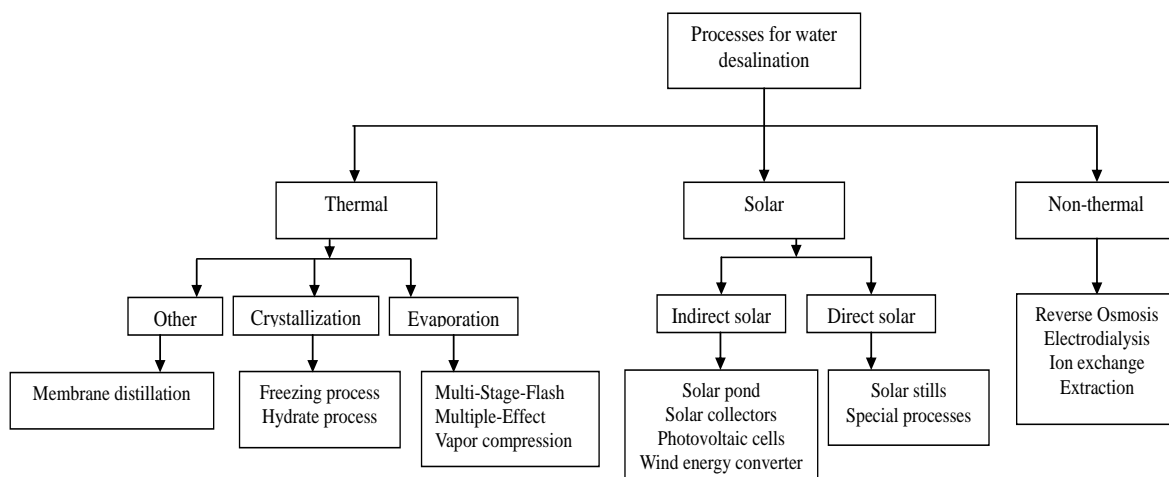


Fig. 5. Categories of desalination processes [adapted from 54].

3.1. Thermal processes

Commercial desalination processes or conventional technologies to treat impaired or marginal quality waters consist of separating fresh water from saline water, simple settling, and disinfection with chlorine or iodine. This is including multi stage flash (MSF), multiple effect (ME), vapor compression (VC) which can be thermal (TVC) or mechanic (MVC), reverse osmosis (RO), ion exchange, electrodialysis, phase change and solvent extraction. These technologies are expensive especially for the production of small amount of fresh water. On the other hand, the use of conventional energy sources (hydrocarbon fuels) to drive these technologies has a negative impact on the environment. Several other membrane technologies are available for treatment of water to varying degrees. Those used in pre-treatment of desalination plants such as [56]:

- Microfiltration (MF);
- Ultrafiltration (UF); and
- Nanofiltration (NF).

About 80% of the world's desalination capacity is provided by two technologies: Multi-stage flash (MSF), and reverse osmosis (RO). MSF units are widely used in the Middle East (particularly in Saudi Arabia, the United Arab Emirates, and Kuwait) and they account for over 40% of the world's desalination capacity [57].

MSF and MED 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 to an evacuated chamber. The process is repeated stage by stage at successively decreasing pressure (Fig. 6). This process requires an external steam supply, normally at 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. A key design feature of MSF systems is bulk liquid boiling. This alleviates problems with scale formation on heat transfer tubes.

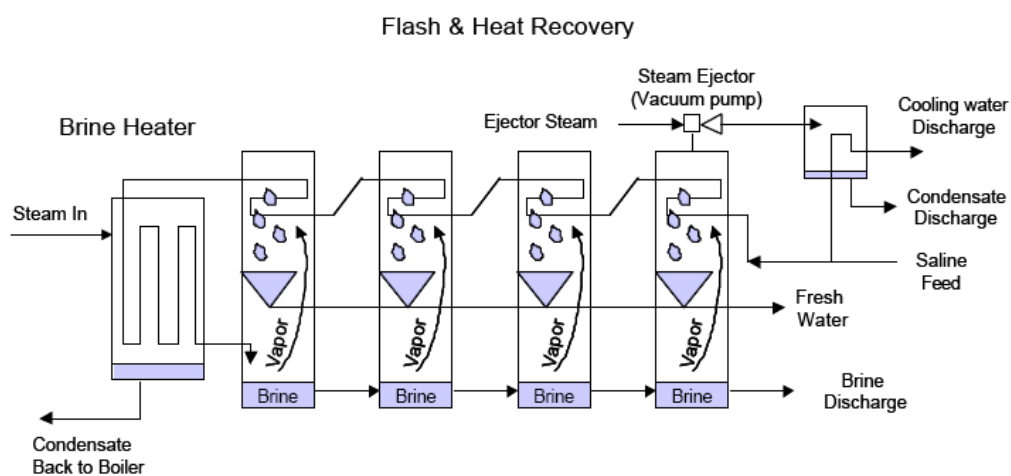


Fig. 6. Schematic diagram of a basic multi-stage flash (MSF) desalination process [58].

On MED, vapors 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 next stage is at lower temperature and pressure. The performance of the process is proportional to the number of stages or effects (Fig. 7). MED plants normally use an external steam supply at low temperature of about 70°C. The low temperature MED is gaining more acceptance for low and medium capacity desalination plants, owing to following advantages:

- Lower energy consumption;
- Higher heat transfer coefficient;
- Compactness;
- High product water quality; and
- Reduced pre-treatment.

These newer LT-MED systems have also been studied in combination with solar energy input as small-scale desalination plants for remote areas [59].

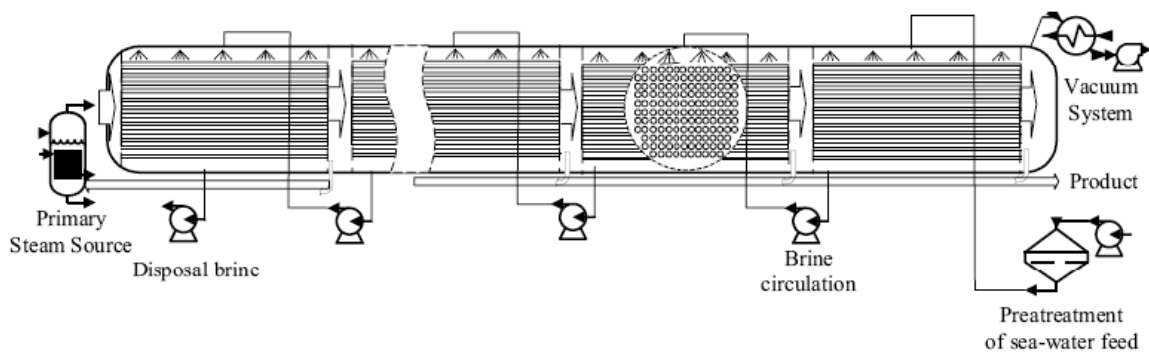


Fig. 7. Schematic presentation of horizontal tubes multi-effect distillation (MED) plant [60].

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 process. Figure 8 provides a schematic illustration of the process. Low temperature VCD is a simple, reliable process and produces high quality product water (5–25 mg/L TDS). A number of desalination plants are installed worldwide for producing good quality water from saline water for industrial and municipal use. However, VCD plants have the disadvantage of restricted plant capacity due to scale limitations for large size vapour compressors [61]. Also, freezing desalination exhibits some technical problems which limit its industrial development.

On the other hand, other desalination processes do not involve phase changes. They are membrane processes, reverse osmosis (RO) and electro dialysis (ED)/electrodialysis reversal (EDR). It is forecast that membrane processes, and in particular RO, will continue to take market share from thermal desalination, with 59% of the total new build capacity being membrane based [62].

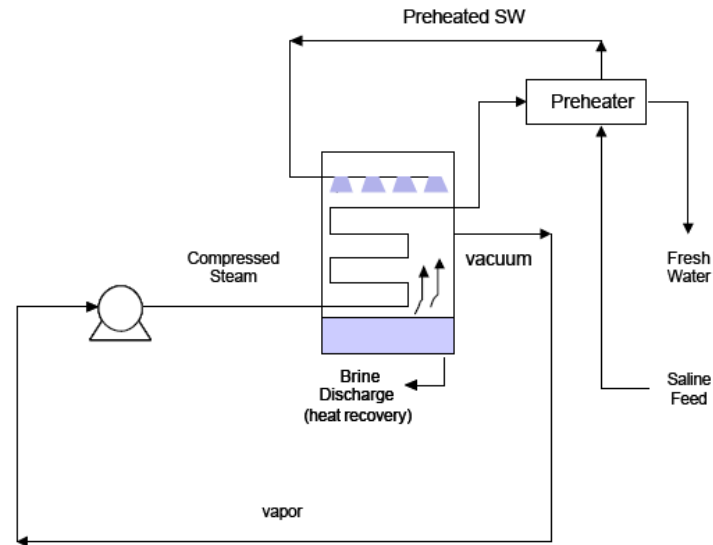


Fig. 8. Schematic diagram of a single stage mechanical vapor compression desalination process [58].

Both processes (RO and ED/EDR) require energy inputs to overcome the existing osmotic pressure between fresh water and saltwater. ED technology is usually limited to brackish feed water, while RO technologies can be used with brackish waters or seawater. Electrodialysis (ED) was developed about 10 years before RO and uses electric currents to draw salts through a selective membrane, leaving behind a freshwater effluent. Reverse Osmosis (RO) relies on forcing salt water against membranes (usually made of cellulose acetate or aromatic polyamide) at high pressure, so that water molecules can pass through membranes and the salts are left behind as a briny concentrate [54].

The dominant processes of MSF and RO are 44 and 42% of worldwide capacity, respectively. The MSF process represents more than 93% of the thermal process production, while RO process represents more than 88% of membrane processes production [17,58]. The schematic representations of these two types of membrane technologies (ED and RO) are shown in Figs. 9 and 10. Table 3 provides an overview of removal capabilities of each of membrane process. In water desalination, ED is competing directly with RO distillation and more recently NF.

The use of both renewable energy (i.e. solar and wind power) and desalination technologies are growing in absolute terms, as well as geographically. Meanwhile, the cost of implementing both of these technologies is decreasing. Additionally, the global population continues to grow, creating increased demand for both energy and water resources. Assuming all of these trends continue, it is likely that the integration of these two technologies will become an attractive option for increasing regional water supplies by producing freshwater from seawater.

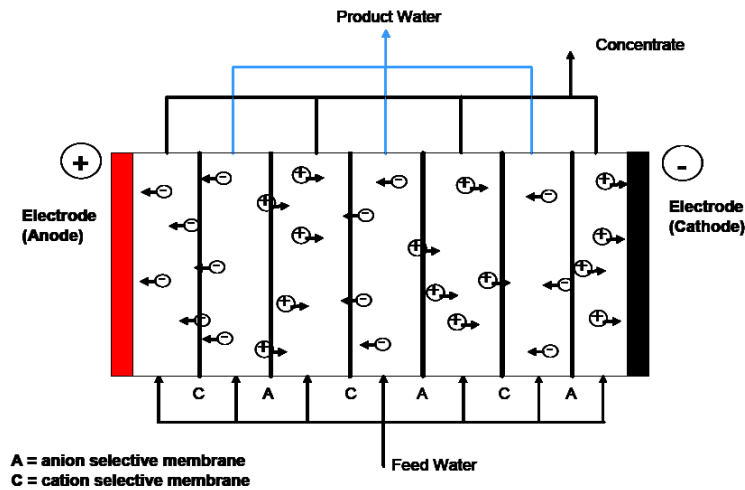


Fig. 9. Principle of electrodesalination under constant DC current field [56].

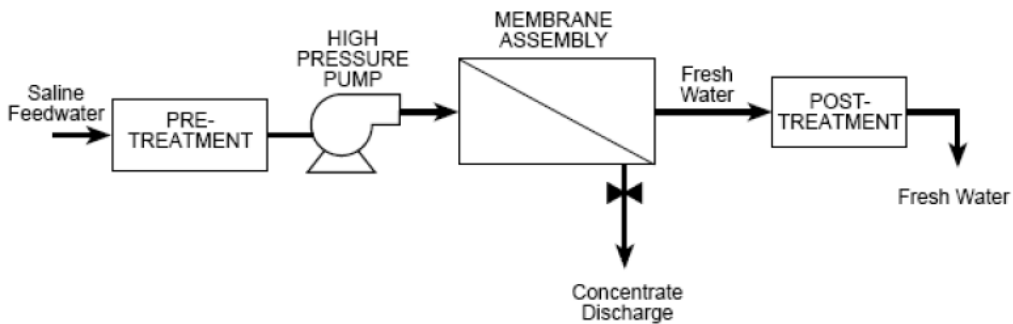


Fig. 10. Schematic of a simple reverse osmosis (RO) system [63].

Table 3: Overview of typical particle removal achieved by membrane processes with application to potable water [64,65].

Process	Operating pressure (kPa)	Pore size (µm)	Approximate particle size removed
RO	1000-5000	≥ 0.0001	Metal ions (monovalent), aqueous salts
ED/EDR	-	-	Metal ions, aqueous salts
NF	500-1000	≥ 0.001	Metal ions (divalent) organic chemicals (humus), hardness, synthetic dyes, herbicides, pesticides, sugars, detergents, soaps, radionuclides, cysts, viruses
UF	30-50	≥ 0.01	Organic macromolecules, colloids, protein, gelatin, viruses
MF	30-50	≥ 0.1	Turbidity, clay, asbestos, algae, bacteria

Energy requirement in the form of thermal as well as electrical energy can make up between 50-70% of the total operating cost and it is thus not surprising that many of the large-scale thermal desalination plants are co-located with power stations or industries with thermal process energy waste. The globally installed desalting capacity by process in 2002 is shown in Fig. 11.

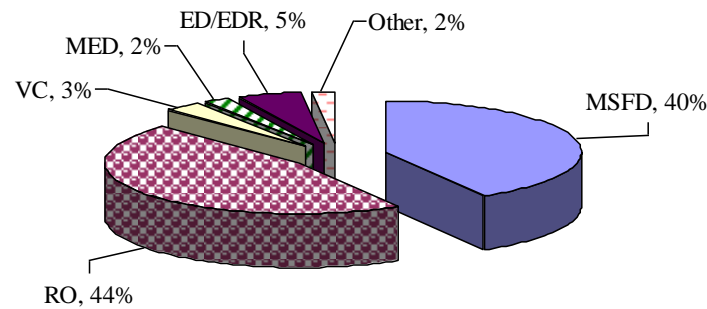


Fig. 11. Global installed desalting capacity by process [10].

The relative power requirements for the various types of desalination processes in the year 2000 are listed in Table 4. It is clear from the data presented in the table that thermal desalination processes require more total energy than RO processes per unit volume of water treated.

Table 4. Relative power requirements of desalination processes [66]

Process	Gain output ratio*	Electrical energy consumption, kWh/m ³	Thermal energy consumption, kWh/m ³	Total energy consumption (kWh/m ³)
MSF	8-12	3.25-3.75	6.75-9.75	10.5-13
MED	8-12	2.5-2.9	4.5-6.5	7.4-9
MED-TVC	8-14	2.0-2.5	6.5-12	9-14
MVC	N/A	9.5-17	N/A	9.5-17
BWRO**	N/A	1.0-2.5	N/A	1.0-2.5
SWRO***	N/A	4.5-8.5	N/A	4.5-8.5

* GOR: Gain Output Ratio – the ratio of fresh water output (distillate) to steam

** BWRO: Brackish water RO

*** SWRO: Seawater RO

3.2. Solar still

Processes driven by solar energy generally fall into two categories, those that capture and utilize the thermal energy of the sun, and those that use photovoltaic (PV) devices to generate electricity. Solar stills are used to produce the hydrological cycle on a much smaller scale by directly utilizing sunshine. Construction and operation principle of solar stills are simple. The basic design of a solar still, which is similar to a greenhouse, is shown in Fig. 12. Solar energy enters the device through a sloping clear glass or plastic panel and heats a basin of salt water. The basin is generally black to absorb energy more efficiently. The heated water evaporates and then condenses on the cooler glass panels. The condensed droplets run down the panels and are collected for use.

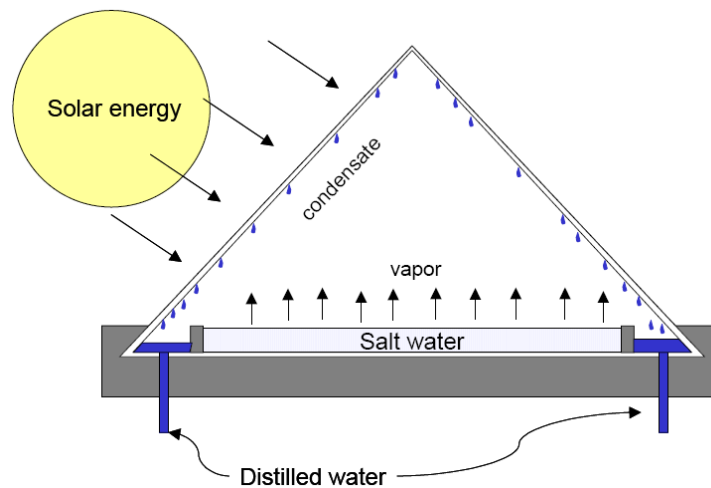


Fig. 12. The basic design of a solar distillation unit [111].

Solar stills typically are less than 50% efficient, e.g. they utilize less than 50% of the incident radiation [67]. A general rule of thumb is that about 1 m² of ground will produce only 4 liters per day of freshwater [68]. Because of this, it is important to use very inexpensive materials of construction to minimize capital costs. Even so, the installation costs of solar stills tend to be considerably higher than other methods [67]. In addition the stills are vulnerable to weather damage and they require large areas of land for installation and have low output. Modifications to the stills to increase efficiency, such as trackers to follow the sun, have generally proven to be too expensive to be practical. However, stationary stills tilted towards the sun do experience an incident energy increase of about 16%. The major energy loss from solar stills is low energy radiation from brine to the cover. Heat losses to the ground are small [67]. Research activities nowadays aim to strengthen the position of solar stills and to increase its water productivity, increase reliability and reduced initial cost. Such actions involve new designs of solar distillation systems that increase output through the increase of water temperature in the still. This can be achieved by heat recovery in multi-effect solar still or by coupling solar still with a heat storage tank, heated by any source nearby.

Therefore, solar stills represent the best technical solution to supply remote villages or settlements with fresh water without depending on high technology and expertise. A capillary film distiller called DIFICAP (distiller with a film in capillary motion) in which a very thin layer of tissue with fine mesh, saturated with water, is maintained in close contact with a metal plate due to the surface tension, which is much greater than the gravitational forces was devised by [69-73]. The different classifications of developments for single effect solar stills are presented in Fig. 13.

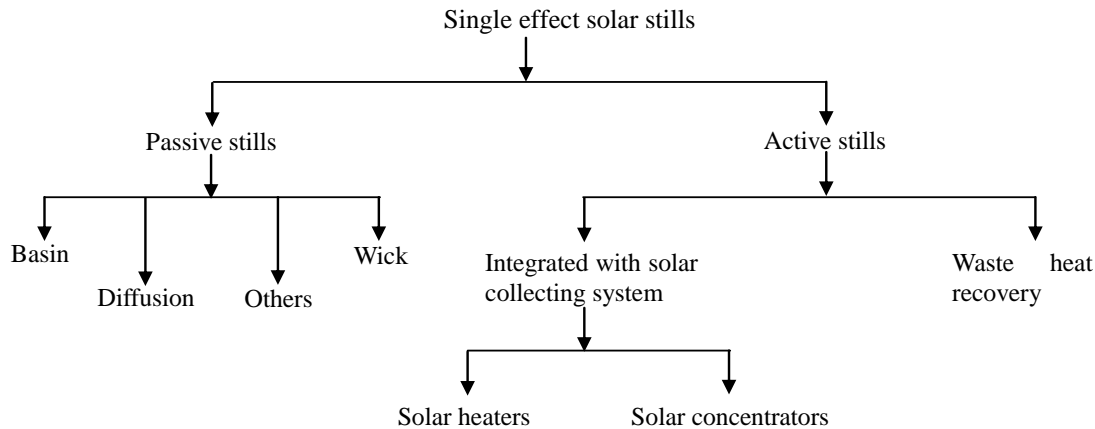


Fig. 13. Classifications of developments for single effect solar stills [adapted from 74].

3.3. PV-driven RO and ED processes

There are mainly two PV driven membrane processes, reverse osmosis (RO) and electro dialysis (ED). Both techniques are described above, and from a technical point of view, PV as well as RO and ED are mature and commercially available technologies at present time. The feasibility of PV-powered RO or ED systems, as valid options for desalination at remote sites, has also been proven [75]. Indeed, there are commercially available standalone, PV powered desalination systems [76]. The main problem of these technologies is the high cost and, for the time being, the availability of PV cells. Many of the early PV-RO demonstration systems were essentially a standard RO system, which might have been designed for diesel or mains power, but powered from batteries that were charged by PV. This approach tends to require a rather large PV array for a given flow of product, due to poor efficiencies both in the standard RO systems and in the batteries. Large PV arrays and regular replacement of batteries would tend to make the cost of water from such systems rather high. Table 5 shows a selection of some brackish –water PV powered RO system. Figure 14 shows diagram of photovoltaic-powered reverse-osmosis (PV-RO) system to desalinate seawater without batteries. The system is operated from seawater and requires no batteries, since the rate of production of freshwater varies throughout the day according to the available solar power. Initial testing of the system, with the modest solar resource available in the UK, provided freshwater at approximately 1.5 m³/day. Nearer to the equator and with a PV array of only 2.4 kW_P, a software model of the system predicts production of over 3 m³/day throughout the year [85].

Table 5. A selection of some brackish-water PV-RO systems.

Location	References	Feed water, ppm	Capacity, m ³ /d	PV, kWp	Batteries, kWh
Sadous, Riyadh, Saudi Arabia	[77] [78]	5800	15	10	264
Haifa, Israel	[79]	5000	3	3.5 plus 0.6 wind	36
Elhamrawien, Egypt	[80]	3500	53	18	200
Heelat ar Rakah, Oman	[81]	1000	5	3.25	9.6
White Cliffs, Australia	[82]	3500	0.5	0.34	NONE
Solarflow, Australia	[83] [84]	5000	0.4	0.12	NONE

3.4. Concentrating solar thermal driven desalination

The concentrating solar technologies are used to convert the sun's energy into high-temperature heat. The heat energy is then used to generate electricity in a steam generator or any other purposes. Concentrating solar power's relatively low cost and ability to deliver power during periods of peak demand i.e., it can be a major contributor to the nation's future needs for distributed sources of energy.

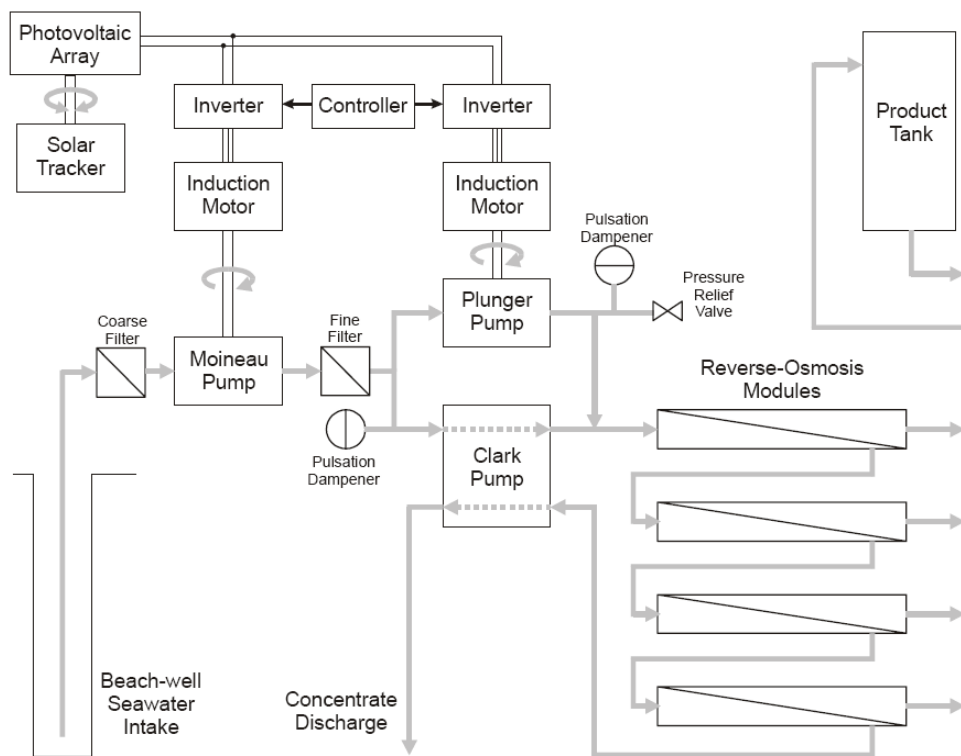


Fig. 14. PV-RO system to desalinate seawater without batteries [85].

The main challenge of solar thermal power engineering and development is to concentrate solar energy which has a relatively low density. Therefore, mirrors with up to 95% reflectivity that continuously track the sun are required for this purpose. The concentrating solar technologies can be trough systems, dish/engine systems and power towers. A parabolic trough solar collector is designed to concentrate the sun's rays via parabolic curved solar reflectors onto a heat absorber element – a “receiver” – located in the optical focal line of the collector. The solar collectors track the sun continuously. The key components of a parabolic trough power plant are mirrors, receivers and turbine.

In solar dish/engine systems, parabolic dishes capture the solar radiation and transfer it to a Stirling engine – an engine which uses external heat sources to expand and contract a fluid – placed in the focus of the parabolic dish. This approach is particularly suited for decentralized electricity generation. Solar heat can be stored during the day in concrete, ceramics or phase change media. At night, it can be extracted from the storage to run the power block. Fossil and renewable fuels like oil, gas and organic waste can be used for co-firing the plant, providing power by demand, as base or peak load (Fig. 15) [86].

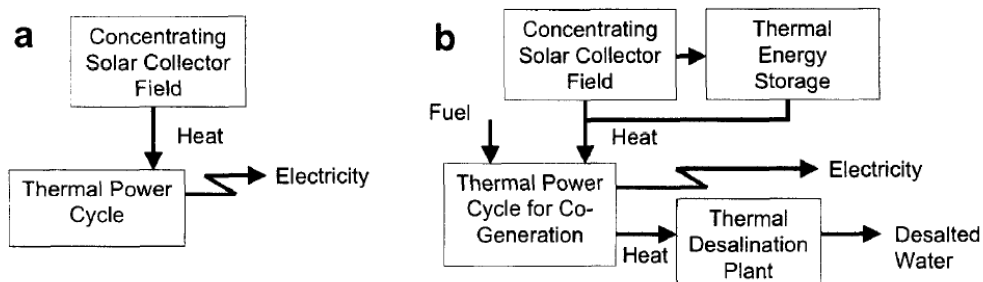


Fig. 15. Solar thermal power plant configuration for (a) electricity generation, and for (b) the combined generation of power and water with backup and energy storage.

The output per collector area is not a definitive guide to the best technology, as it does not take into account reliability and maintenance needs and relative capital costs. Neither has any detailed consideration been given to how the desalination plant could be run at a steady operating point; for example if the desalination is electrically driven how to the solar plant generating capacity would be sized so as to optimize the overall economics. The choice of the RO desalination plant capacity depends on the daily and seasonal variations in solar radiation levels, on the buying and selling prices for electricity, and on the weight given to fossil fuel displacement. A conceptual layout for a solar dish based system with power generation and RO desalination is shown in Fig. 16 [87].

The low temperature waste heat is shown as an input to the feed water as a reduction in RO energy consumption is achieved if the feed water temperature is raised (but only

up to a limit which is determined by the membrane characteristics and other operating parameters). A modification of this arrangement is described in [88]: steam is used primarily to power a steam turbine and generate electricity, but is also extracted from the turbine (at reduced pressure and temperature) and used to drive a booster pump, which provides part of the RO high pressure pumping demand.

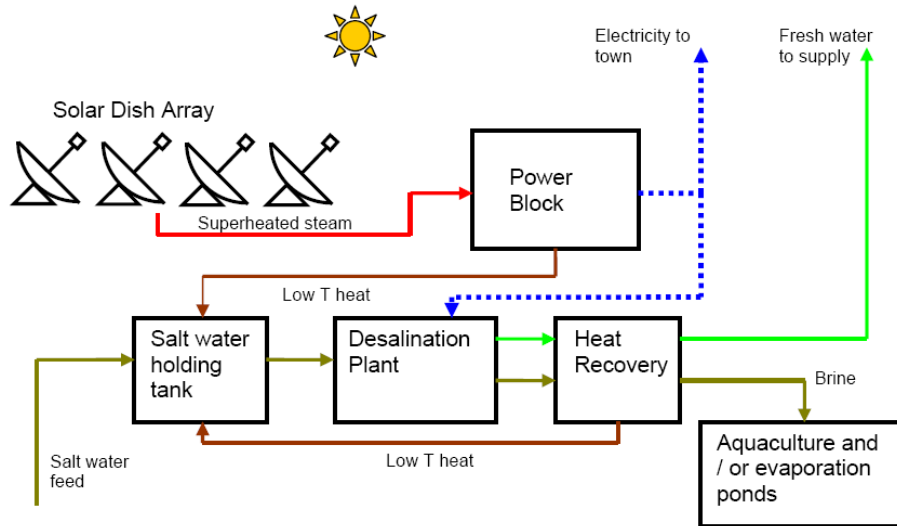


Fig. 15 Combined dish based solar thermal power generation and RO desalination.

3.5. Wind driven water desalination

Remote areas with potential wind energy resources such as islands can employ wind energy systems to power seawater desalination for fresh water production. The advantage of such systems is a reduced water production cost compared to the costs of transporting the water to the islands or to using conventional fuels as power source. Different approaches for wind desalination systems are possible. First, both the wind turbines as well as the desalination system are connected to a grid system. In this case, the optimal sizes of the wind turbine system and the desalination system as well as avoided fuel costs are of interest. The second option is based on a more or less direct coupling of the wind turbine(s) and the desalination system. In this case, the desalination system is affected by power variations and interruptions caused by the power source (wind). These power variations, however, have an adverse effect on the performance and component life of certain desalination equipment. Hence, back-up systems, such as batteries, diesel generators, or flywheels might be integrated into the system. Main research in this area is related to the analysis of the wind plant and the overall system performance as well as to developing appropriate control algorithms for the wind turbine(s) as well as for the overall system. Regarding desalinations, there are different technologies options, e.g. electro-dialysis or vapour compression. However, reverse osmosis is the preferred technology due to the low specific energy consumption [89]. Fig. 16 shows diagram of RO desalination plant wind/ energy recovery.

The European Community, e.g. with the Joule III project, funded different research programs and demonstration projects of wind desalination systems on Greek and Spanish islands. For general information on wind desalination research, see [90-92]. For information on large stand-alone wind desalination systems, see [93, 94]; for small systems, see [95]; and for an overview of the research activities in North America, see [96].

Other wind-driven RO systems are as follows: A RO system driven by a wind power plant, in Island of the County Split and Dalmatia, reported by [97]. A RO plant in the Middle East, which installation starts in 1986. It is a 25 m³/day-plant connected to a hybrid wind–diesel system [98]. Besides that, in Drepanon, Achaia, near Patras (Greece), in 1995 starts the operation of other wind powered RO system [99]. Finally, European Commission (1998) presents other facilities at:

- Island of Suderoog (North Sea), with 6–9 m³/day;
- Ile du Planier, France Pacific Islands, with 0.5 m³/h;
- Island of Helgoland, Germany (2.480 m³/h);
- Island of St. Nicolas, West France (hybrid wind-diesel) and
- Island of Drenec, France (10 kW wind energy converter).

Interesting experimental research about the direct coupling of a wind energy system and a RO unit by means of shaft power has been carried out at the Canary Islands Technological Institute—projects AERODESA I and AERODESA II [100]. In addition, in Coconut Island off the northern coast of Oahu, Hawaii, a brackish water desalination wind-powered RO plant was analyzed. The system coupling directly the shaft power production of a windmill with the high pressure pump; 13 l/min can be maintained for wind speed of 5 m/s [101].

The ED process is interesting for brackish water desalination since it is able to adapt to changes of available wind power and it is most suitable for remote areas than RO. Modeling and experimental tests results of one of such system installed at the ITC, Gran Canaria, Spain is presented by [102]. The capacity range of this plant is 192–72 m³/day.

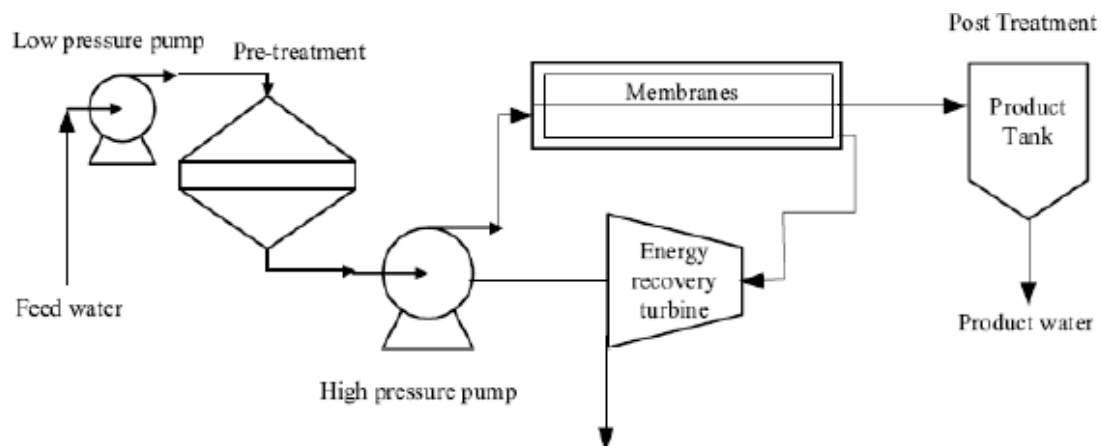


Fig. 16. Diagram of RO desalination plant wind/ energy recovery [60].

3.6. Desalination powered by biomass and geothermal energy

The use of biomass in desalination is not in general a promising alternative since organic residues are not normally available in arid regions and growing of biomass requires more fresh water than it could generate in a desalination plant.

Also, even though geothermal energy is not as common in use as solar (PV or solar thermal collectors) or wind energy, it presents a mature technology which can be used to provide energy for desalination at a competitive cost. Furthermore, and comparatively to other RE technologies, the main advantage of geothermal energy is that the thermal storage is unnecessary, since it is both continuous and predictable [103].

The direct use of geothermal fluid of sufficiently high temperature in connection to thermal desalination technologies is the most interesting option [104]. The main advantage of geothermal energy comparing with other RES is that, the thermal storage is unnecessary, since it is both continuous and predictable [103]. A high-pressure geothermal source allows the direct use of shaft power on mechanically driven desalination, while high temperature geothermal fluids can be used to power electricity-driven RO or ED plants. The availability and/or suitability of geothermal energy, and other RE resources, for desalination, are given by [105].

4. ADVANTAGES AND DISADVANTAGES OF TECHNOLOGIES

A comparative summary of the relative pros and cons identified for the desalination technologies as applied to seawater desalination is provided in Table 6. There are advantages and disadvantages when comparing membrane with thermal technologies and many factors need to be considered depending on the purpose and objectives for considering a particular desalination process. Advantages of membrane processes over thermal processes include [56]:

- Lower capital cost and energy requirements;
- Lower footprint and higher space/production ratio;
- Higher recovery ratios;
- Modularity allows for up- or downgrade and minimal interruption to operation when maintenance or membrane replacement is required;
- Less vulnerable to corrosion and scaling due to ambient temperature operation; and
- Membranes reject microbial contamination.

Advantages of thermal processes over membrane processes include:

- Very proven and established technology;
- Higher quality product water produced;
- Less rigid monitoring than for membrane process required;
- Less impacted by quality changes in feed water; and
- No membrane replacement costs.

5. THE ECONOMICS OF DESALINATION

Several factors affect desalination cost. In general, cost factors associated with implementing a desalination plant are site specific and depend on several variables. The cost estimation procedures are described in [106]. The major cost variables are: i) Quality of feedwater, where, the low TDS concentration in feedwater (e.g. brackish water) requires less energy for treatment compared to high TDS feedwater (seawater). ii) Plant capacity where it affects the size of treatment units, pumping, water storage tank, and water distribution system. Large capacity plants require high initial capital investment compared to low capacity plants. But due to the economy of scale, the unit production cost for large capacity plants can be lower [107, 108]. iii) Site characteristics where it can affect water production cost such as availability of land and land condition, the proximity of plant location to water source and concentrate discharge point is another factor. Pumping cost and costs of pipe installation will be substantially reduced if the plant is located near the water source and if the plants concentrate is discharged to a nearby water body. iv) Costs associated with water intake, pretreatment, and concentrate disposal can be substantially reduced if the plant is an expansion of an existing water treatment plant as compared to constructing a new plant. v) Regulatory requirements which associated with meeting local/state permits and regulatory requirements [109]. It is difficult to compare the costs of desalination installations at an aggregated level because the actual costs depend on a range of variables specific to each site [110].

Desalination plant implementation costs can be categorized as construction costs (starting costs) and operation and maintenance (O & M) costs. Construction costs include direct and indirect capital costs. The direct cost includes land, production wells, surface water intake structure, process equipment, auxiliary equipment, buildings and concentrate disposal (type of desalination technology, plant capacity, discharge location, and environmental regulations). The indirect capital cost is usually estimated as percentages of the total direct capital cost. Indirect costs may include freight and insurance, construction overhead, owner's costs, and contingency costs.

The operating and maintenance (O & M) costs consist of fixed costs and variable costs. Fixed costs include insurance and amortization costs. Usually, insurance cost is estimated as 0.5 % of the total capital cost. Typically, an amortization rate in the range of 5-10 % is used. Major variable costs include the cost of labor, energy, chemicals, and maintenance. For low TDS brackish water, the replacement rate is about 5% per year. For high TDS seawater, the replacement could be as high as 20%. The cost for maintenance and spare parts is typically less than 2% of the total capital cost on an annual basis [109].

It can be observed from these data, that:

- 1) The fixed costs are a major factor for both, brackish water and seawater,
- 2) The major difference in cost between desalination of brackish water and seawater is energy consumption, while the remaining factors are decreased

- proportionally, but remain about the same; and
- 3) Costs associated with membrane replacement, maintenance & parts and consumables are relatively small. These costs depend on the status of technology and may be further reduced as technology evolves, but will not have significant impact on the overall cost of desalination.

Ghoneyem and Ileri [112] estimate that a production-size, solar still can produce water for \$20/ m³ (1994 dollars), while Madani and Zaki [113] estimated solar distilled water production costs as low as \$2.4/ m³. According to Bouchekima et al. [114], recent improvements in solar distillation technology make it the ideal technology for remote isolated areas with a water demand less than 50 m³/d. All other technologies are more expensive at this small scale. Fath [115] believes solar stills are the technology of choice for water production needs up to 200 m³/d. The dominant competing process is RO that has an energy requirement of between 22x10⁶ and 36x10⁶ J/m³ (6 and 10 kWh/m³) of water treated and investment costs of between US\$600 and \$2000/ m³ of production capacity [116]. The most commonly used solar distillation technology is a single effect, single-basin still characterized by a relatively large thermal mass, i.e., the water basin [117].

Table 4: Pros and cons of desalination processes [56].

Process	Recovery and Total dissolved solids	Pros	Cons
RO	30-60% recovery possible for single pass (higher recoveries are possible for multiple pass or waters with lower salinity) < 500 mg/L TDS for seawater possible and < less 200 mg/L TDS for brackish water	<ul style="list-style-type: none"> • Lower energy consumption • Relatively lower investment cost • No cooling water flow • Simple operation and fast start-up • High space/production capacity • Removal of contaminants other than salts achieved • Modular design • Maintenance does not require entire plant to shutdown 	<ul style="list-style-type: none"> • Higher costs for chemical and membrane replacement • Vulnerable to feed water quality changes • Adequate pre-treatment a necessity • Membranes susceptible to biofouling • Mechanical failures due to high pressure operation possible • Appropriately trained and qualified personnel recommended • Minimum membrane life expectancy around five to seven years
ED/EDR	85-94% recovery possible 140 - 600 mg/L TDS	<ul style="list-style-type: none"> • Energy usage proportional to salts removed not volume treated • Higher membrane life of 7-10 years • Operational at low to moderate pressures 	<ul style="list-style-type: none"> • Only suitable for feed water up to 12,000 mg/L TDS • Periodic cleaning of membranes required • Leaks may occur in membrane stacks • Bacterial contaminants not removed by system and post treatment required for potable water use
MSF	25-50% recovery in high temperature recyclable MSF plant < 50 mg/L TDS	<ul style="list-style-type: none"> • Lends itself to large capacity designs • Proven, reliable technology with long operating life • Flashing rather than boiling reduces incidence of scaling • Minimal pre-treatment of feed water required • High quality product water • Plant process and cost independent of salinity level • Heat energy can be 	<ul style="list-style-type: none"> • Large capital investment required • Energy intensive process • Larger footprint required (land and material) • Corrosion problems if materials of lesser quality used • Slow start-up rates • Maintenance requires entire plant to shut-down • High level of technical knowledge required • Recovery ratio low

		sourced by combining with power generation	
MED	0-65% recovery possible < 10 mg/L TDS	<ul style="list-style-type: none"> • Large economies of scale • Minimal pre-treatment of feed water required • Very reliable process with minimal requirements for operational staff • Tolerates normal levels of suspended and biological matter • Heat energy can be sourced by combining with power generation • Very high quality product water 	<ul style="list-style-type: none"> • High energy consumption • High capital and operational cost • High quality materials required as process is susceptible to corrosion • Product water requires cooling and blending prior to being used for potable water needs
VCD	~ 50% recovery possible < 10 mg/L TDS	<ul style="list-style-type: none"> • Developed process with low consumption of chemicals • Economic with high salinity (> 50,000 mg/L) • Smaller economies of scale (up to 10,000 m³/d) • Relatively low energy demand • Lower temperature requirements reduce potential of scale and corrosion • Lower capital and operating costs • Portable designs allow flexibility 	<ul style="list-style-type: none"> • Start-up require auxiliary heating source to generate vapour • Limited to smaller sized plants • Compressor needs higher levels of maintenance

Table 7 shows the percent cost of various factors for desalination of brackish water and seawater in RO plants. These data are reported in the Sandia National Laboratories report compiling data from other sources (Miller 2003).

Table 7. Percent distribution of cost factors [111].

	Brackish water (%)	Seawater (%)
Fixed costs	54	37
Electric power	11	44
Labor	9	4
Membrane- replacement	7	5
Maintenance and parts	9	7
Consumables (chemicals)	10	3

According to Loupasis [118], the RO technologies with energy recovery systems require the least amount of energy to process seawater (at 4-6 kWh/m³) compared to all other technologies. If brackish water is included as a potential input, then the energy requirements for RO drop significantly and are basically equivalent to using ED treatment for brackish water (0.5-2.5 kWh/m³).

Comparison of typical costs for seawater desalination by RO and typical thermal processes have shown that for RO the largest cost reduction potential lies in capital costs and energy (Fig. 17). For a typical large-scale thermal desalination plant, energy use represents 59% of the typical water costs with the other major expense being capital cost (Fig. 18). It would seem that the most effective cost reduction for thermal desalination can be achieved by utilizing alternative sources of heat or energy, such as dual purpose plants. In addition, the development of less costly and corrosion-resistant heat transfer surfaces could reduce both capital and energy costs [110].

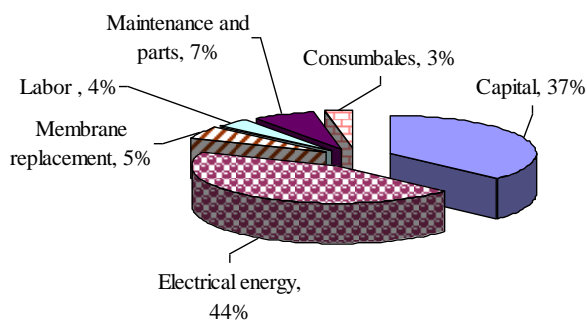


Fig. 17 Typical cost structure for RO desalination of seawater [110]

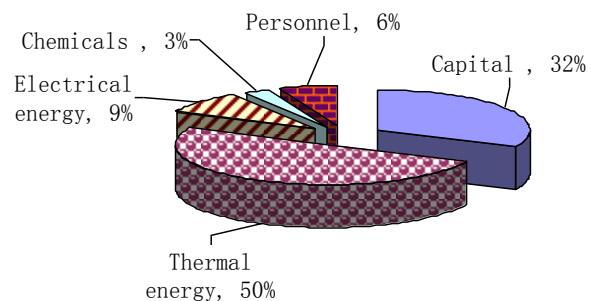


Fig. 18 Typical cost structure for large thermal desalination of seawater [110]

There is more detailed cost comparisons between the different desalination technologies are given in Table 8. Also Table 9 presents the comparison of renewable energy with fossil fuels and nuclear power. The data show that the costs of RO systems ranging from approximately 0.90 cents per gallon (US\$2.37/m³) for a plant with capacity of .03 million gallons per day to 0.21 cents/gallon (US\$0.55/m³) for a 30 m gallons /d capacity system. RO remains the cheaper option at both low and high production capacities in comparison to the other technologies. However, it is important to restate that desalination cost data is extremely site specific, so the comparison of costs across the different technologies is not as straightforward as it may appear in the presented data.

Solar thermal power plants may acquire a considerable share on clean electricity generation in the 21st century. They are one of the best-suited technologies to achieve the global goals of CO₂ emission reduction. The energy payback time of a solar thermal power plant is in the order of 0.5 year, while the economic lifetime is at least 25 years [121].

Life cycle emissions of greenhouse gases amount to 0.010- 0.015 kg/kWh, which is very low in comparison to those of gas fired combined cycles (0.500 kg/kWh) or steam/coal power plants (0.900 kg/kWh).

Table 8. Unit product costs for conventional and novel desalination processes by capacity, plants operating in 2001 [119].

Type of System: Capacity, in millions of gallons per day	Unit Product Cost, \$ Cent/gallon
Novel Processes	
MEE-VS, 30effects, Aluminum alloy, Fluted tubes: 90.53	0.182
MEE-ABS, Absorption heat pump and gas turbine: 2.5	0.133
Mechanical Vapor Compression (MVC)	
0.03	1.894
0.13	1.220
1.06	0.939
1.20	0.920
5.28	0.174
Reverse Osmosis	
5.28 (single stage)	0.242
5.28 (two stage)	0.288
0.03	0.898
1.06	0.750
1.20	0.489
9.99	0.413
10.56	0.314
12.00	0.258
30.00	0.208
Multistage Flash Desalination (MSF)	
7.13 (Dual-purpose)	0.292
7.13 (Single-purpose)	0.621
8.45 (Gas turbine, waste-heat boiler)	0.545
7.13	0.595
9.99	0.473
Multiple-Effect Evaporation (MEE)	
6 (Dual-purpose)	0.330
6 (Single-purpose)	0.739
6	0.529
6	0.470
9.99	0.409
9.99 (Gas turbine, waste-heat boiler)	0.496
MEE-TVC	
5.85 (Single-purpose)	0.886
5.85 (Dual-purpose)	0.496
5.85	0.587

Table 9 Cost of renewable energy compared with fossil fuels and nuclear power [120].

Technology	Current cost (US cents/kWh)	Projected future costs beyond 2020 as the technology matures (US cents/kWh)
Biomass energy <ul style="list-style-type: none"> • Electricity • Heat 	5-15 1-5	4-10 1-5
Wind electricity <ul style="list-style-type: none"> • Onshore • Offshore 	3-5 6-10	2-3 2-5
Solar thermal electricity (Insolation of 2500 kWh/m ² per year)	12-18	4-10
Hydro-electricity <ul style="list-style-type: none"> • Large scale • Small scale 	2-8 4-10	2-8 3-10
Geothermal energy Electricity Heat	2-10 0.5-5.0	1-8 0.5-5.0
Marine energy <ul style="list-style-type: none"> • Tidal barrage (e.g. the proposed severn barrage) • Tidal stream • Wave 	12 8-15 8-20	12 8-15 5-7
Grid connected photovoltaics, according to incident solar energy (Insolation) <ul style="list-style-type: none"> • 1000 kWh/m² per year (e.g. UK) • 1500 kWh/m² per year (e.g. Southern Europe) • 2500 kWh/m² per year (most developing countries) • Stand alone systems (incl. batteries), 2500 kWh/m² per year 	50-80 30-50 20-40 40-60	~8 ~5 ~4 ~10
Nuclear power	4-6	3-5
Electricity grid supplies fossil fuels (incl. T&D) <ul style="list-style-type: none"> • Off-peak • Peak • Average • Rural electrification 	2-3 15-25 8-10 25-80	Capital costs will come down with technical progress, but many technologies already mature and may be offset by rising fuel costs
Costs of central grid supplies, excl. transmission and distribution <ul style="list-style-type: none"> • Natural gas • Coal 	2-4 3-5	Capital costs will come down with technical progress, but many technologies already mature and may be offset by rising fuel costs

6. CONCLUSIONS AND OUTLOOK

The use of renewable energies for desalination appears nowadays as a reasonable and technically mature option towards the emerging and stressing energy and water problems. In spite of intensive research world-wide, the actual penetration of RES-powered desalination installations is still low. Recently there are intense attempt to develop and install effective large-scale desalination plants, mainly powered by RES. Practically, considerable skills and experience has been gained, even if this option appears to have entered a phase of relative stagnation. For low-density population areas world-wide there are lack of fresh water as well as electrical power grid connections. Therefore, the cheap fresh water may be produced from brackish, sea and oceans water by using wind turbines, solar panels and other emerging renewable energy technologies. The successful development of these technologies will be especially important for developing countries that are currently experiencing water scarcity and do not have access (geographically or economically) to sufficient conventional energy resources to implement desalination systems.

The connection of photovoltaic cells to membrane processes in desalination is an interesting alternative for stand-alone desalination systems in remote areas. Nevertheless, if wind power is available, it exhibit lower energy cost than solar PV energy. For brackish water desalination, both of them, RO and ED powered by wind turbines are usually the best selection. Nevertheless, solar distillation may be advantageous for seawater desalination, although other renewable energy resources have to be taken into account. Geothermal energy is suitable for different desalination process at reasonable cost wherever a proper geothermal source is available because there is no energy storage is required.

Moreover, other systems require further analysis for evaluating their potentials of development, applications and performance. The most mature technologies of renewable energy application in desalination are wind and PV-driven membrane processes and direct and indirect solar distillation. Nevertheless, the coupling of renewable energy and desalination systems has to be optimized. Also, the new pretreatments may improve the performance by permitting a considerable increase of the operating temperature in distillation plants. Environmental issues are associated with brine concentrate disposal, energy consumption and associated greenhouse gas production. On the other hand, social issues may include the public acceptance of using recycled water for domestic dual-pipe systems, industrial and agricultural purposes.

ACKNOWLEDGEMENTS

The investigation presented in this paper have been done in the frame of the development of the research project in the Department of Electrical Engineering, Tsinghua University, Beijing for postdoctoral program, which has been funded by the Tsinghua University.

REFERENCES

- [1] G. Fiorenza, V.K. Sharma, G. Braccio, Techno-economic evaluation of a solar powered water desalination plant, *Energy Conversion and Management*, 44 (2003) 2217-2240.
- [2] <http://www.sustainability.ca/index.cfm?body=chunkout.cfm&k1=403>
- [3] Food and Agriculture Organization of the United Nations. The FAOSTAT Database, Population: annual time series, June 2000, Rome.
- [4] UNEP (United Nations Environment Programme) (2003) Key Facts about Water. www.unep.org/wed/2003/keyfacts (accessed January 15, 2006)
- [5] World Health Organization. Guidelines for drinking water quality, Geneva, 1984, Vol. I. Recommendations.
- [6] I. Alatiqi, H.Ettouney, and H.El-Dessouky, Process control in water desalination industry: an overview. *Desalination* 126 (1999) 15-32.
- [7] M.H.I. Dore, Forecasting the economic costs of desalination technology. *Desalination* 172 (2005) 207-214.
- [8] U. Ebersperger and P. Isley, Review of the current state of desalination. *Water Policy Working Paper 2005-008*. Georgia State University. Environmental Policy Program; Water Policy Centre (2005).
- [9] M. Schiffler, Perspectives and challenges for desalination in the 21st century. *Desalination* 165 (2004) 1-9.
- [10] IDA, IDA Worldwide Desalting Inventory 2002, International Desalination Association (2002).
- [11] S. Edward, The potential for wind- powered desalination in water- scarce countries, Master of Arts in Law and Diplomacy Thesis, 7 February 2006, <http://fletcher.tufts.edu>
- [12] E.E. Delyannis, Status of solar assisted desalination: a review. *Desalination* 67 (1987) 3-19.
- [13] L.Garcia-Rodriguez, C.Gomez-Camacho, Perspectives of solar desalination. *Desalination* 136 (2001) 213-218.
- [14] V. Belessiotis, E.E. Delyannis, The story of renewable energies for water desalination. *Desalination* 128 (2000) 147-159.
- [15] E.E. Delyannis, V. Belessiotis, A historical overview of renewable energies. In: *Mediterranean Conference on Renewable Energy Sources for Water Production*. European Commission, EURORED Network, CRES, EDS, Santorini, Greece, (1996) 13-17.
- [16] E. Mathioulakis, V. Belessiotis, E. Delyannis, Desalination by using alternative energy: Review and state-of-the-art, *Desalination* 203 (2007) 346-365.
- [17] L. Garcia-Rodriguez, Renewable energy applications in desalination: state of the art, *Solar Energy* 75 (2003) 381-393.
- [18] P. Baltas, K. Perrakis, E. Tzen, European network to integrate renewable energy into water production. In: *Proceedings of Mediterranean Conference on Renewable Energy Sources for Water Production*. European Commission, EURORED Network, CRES, EDS, Santorini, Greece, 10-12 June (1996) 31-35.

- [19] V. Belessiotis, E.E. Delyannis, Water shortage and renewable energies (RE) desalination—possible technological applications. *Desalination* 139 (2001) 133-138.
- [20] L. Garcia-Rodriguez, Seawater desalination driven by renewable energies: a review. *Desalination* 143 (2002) 103-113.
- [21] Rodriguez -Girones, M. Rodriguez, J. Perez, J. Veza, A systematic approach to desalination powered by solar, wind and geothermal energy sources. In: *Proceedings of the Mediterranean Conference on Renewable Energy Sources for Water Production*. European Commission, EURORED Network, CRES, EDS, Santorini, Greece, 10-12 June (1996) 20-25.
- [22] D. Voivontas, K. Misirlis, E. Manoli, G. Arampatzis, D. Assimacopoulos, A. Zervos, A tool for the design of desalination plants powered by renewable energies. *Desalination* 133 (2001) 175-198.
- [23] A.M. El-Nashar, Optimizing the operating parameters of solar desalination plants. *Solar Energy* 48 (1992) 207-213.
- [24] S. Kalogirou, Use of parabolic trough solar energy collectors for sea-water desalination, *Applied Energy*, 60 (1998) 65-88.
- [25] L. Garcia-Rodriguez, C. Gomez-Camacho, Solar thermal technologies comparison for applications to seawater desalination. *Desalination* 142 (2) (2002)135-142.
- [26] M. Al-Shammiri, M. Safar, Multi-effect distillation plants: state of the art. *Desalination* 126 (1999) 45-59.
- [27] M.F.A. Goosen, S.S. Sablani, W.H. Shayya, C. Paton, H. Al-Hinai, Thermodynamic and economic considerations in solar desalination. *Desalination* 129 (2000) 63-89.
- [28] M.R. Kamal, J. Simandl, J. Ayoub, Cost comparison of water produced from solar powered distillation and solar stills. *International Desalination and Water Reuse* 9/2 (1999) 74-75.
- [29] M.S. Mohsen, O.R. Al-Jayyousi, Brackish water desalination: an alternative for water supply enhancement in Jordan. *Desalination* 124 (1999) 163-174.
- [30] M. Rognoni, A. Trezzi, Dissemination of small desalination plants limiting factors. In: *Proceedings of the International Workshop on Desalination Technologies for Small and Medium Size Plants with Low Environmental Impact*. Accademia Nazionale delle (1998). *Renewable Energy* 14 (1-4) (1999) 275-280.
- [31] H.P. Garg, H.S. Mann, Effect of climatic, operational and design parameters on the year round performance of single-sloped and double-sloped solar still under Indian arid zone conditions. *Solar Energy*, 18(1976) 159-63.
- [32] A.K. Rajvanshi, Effect of various dyes on solar distillation. *Solar Energy*, 27 (1981) 51-65.
- [33] G.N. Tiwari, A. Minocha, P. Sharma, M. Khan, Simulation of convective mass transfer in a solar distillation process. *Energy Conversion and Management*, 38 (1997) 761-70.
- [34] G.N. Tiwari, K. Mukherjee, K.R. Ashok, Y.P. Yadav, Comparison of various designs of solar stills. *Desalination*, 60 (1986) 191-202.
- [35] G.M. Zaki, A.M. Radhwan, A.O. Balbeid, Analysis of assisted coupled solar

- still. *Solar Energy*, 51(1993) 277-88.
- [36] H. Al-Hussaini, I.K. Smith, Enhancing of solar still productivity using vacuum technology. *Energy Conversion and Management*, 36 (1995) 1047-51.
- [37] A.K. Singh, G.N. Tiwari, P.B. Sharma, E..Khan, Optimization of orientation for higher yield of solar still for given location. *Energy Conversion and Management*, 36 (1995) 175-86.
- [38] F. BenJemaa, I. Houcine, M.H.Chahbani, Desalination in Tunisia. Past experience and future prospects, *Desalination*, 116 (1998) 123-34.
- [39] Rodriguez-Girones, M. Rodriguez, J. Perez, J. Veza, A systematic approach to desalination powered by solar, wind and geothermal energy sources. *Proceedings Mediterranean conference on renewable energy sources for water production, Santorini, Greece, June 10-12, (1996) 20-25.*
- [40] E. Tzen, Successful Desalination RES Plants Worldwide (Hammamet, Tunisia: Centre for Renewable Energy Sources) (2005) <
www.adu-res.org/pdf/CRES.pdf>
- [41] D. Voivontas, K. Yannopoulos, K. Rados, A. Zervos and D. Assimacopoulos, Market potential of renewable energy powered desalination systems in Greece, *Desalination*, 121 (1999) 159-172.
- [42] G.F. Leitner, Breaking the cost barrier for seawater desalting, *Int. Desalination and Water Reuse Quart.*, 8(1) (1998) 15–20.
- [43] MEDRC R&D Report, Matching Renewable Energy with Desalination Plants, IT Power Ltd, 2001.
- [44] Joule-Thermie Programme, Desalination guide using renewable energies, European Commission, 1998.
- [45] A. Hanafi, Desalination using renewable energy sources, *Desalination*, 97(1-3) (1994) 339-352.
- [46] J. Rheinlander, F. Lippke, M. Schmitz-Goeb and G.F. Tusel, Electricity and potable water from a solar tower power plant, *Renewable Energy*, 14(1-4) (1998) 23-28.
- [47] G. Caruso and A. Naviglio, A desalination plant using solar heat as a heat supply, not affecting the environment with chemicals, *Desalination*, 122 (1999) 225-234.
- [48] REDES, Decision support system for the integration of renewable energies into water desalination systems, Final Report, EEC, DG XII, APAS RENA CT94-0058, 1996.
- [49] PRODESAL, Towards the large scale development of decentralized water desalination, Final Report, EEC, DG XII, APAS RENA CT94-0005, 1996.
- [50] MEDCODESAL, Mediterranean cooperation for water desalination policies in the perspective of sustainable development, Task 2, Interim Report, EEC, DG XII, INCO, 1999.
- [51] F. Ben Jemaa, I. Houcine and M.H. Chahbani, Potential of renewable energy development for water desalination in Tunisia, *Renewable Energy*, 18 (1999) 331-347.
- [52] R. Vujcic and M. Kmeta, Wind-driven seawater desalination plant for agricultural development on the islands of the County of Split and Dalmatia, *Renewable Energy*, 19 (2000) 173-183.

- [53] H.T. El-Dessouky, H.M. Ettouney and F. Mandani, International Workshop for small and medium size plants with limited environmental impact, Rome, 1998, *Accademia Nazionale delle Scienze detta Dei XL*, (1999) 281-312.
- [54] R. Oldach, Matching Renewable Energy with Desalination Plants (Muscat, Sultanate of Oman: The Middle East Desalination Research Center, MEDRC), MEDRC Series of R&D Reports, MEDRC Project: 97-AS-006a, September (2001).
- [55] E. Delyannis and V. Belessiotis, A historical overview of renewable energies, Proc. Mediterranean Conference on Renewable Energy Sources for Water Production, Santorini, Greece, 10-12 June 1996, EUORED network, CRES, EDS, (1996) 13-17.
- [56] ASIRC (Australian Sustainable Industry Research Centre Ltd.), Overview of Treatment Processes for the Production of Fit for Purpose Water: Desalination and Membrane Technologies Report No.: R05-2207, 25 July (2005).
- [57] H.M. Ettouney, H.T. El-Dessouky, I. Alatiqi, *Chemical Engineering Progress*, September (1999) 43.
- [58] Lindsey R. Evans and James E. Miller, Sweeping gas membrane desalination using commercial hydrophobic hollow fiber membranes, SAND report, SAND 2002-0138, Unlimited Release, Printed January (2002).
- [59] A.M.El-Nashar, The economic feasibility of small solar MED seawater desalination plants for remote arid areas. *Desalination* 134 (2001) 173-186.
- [60] R. Semiat, Desalination: Present and future (*International Water Resources Association, Water International*, Volume 25, Number 1, pp. 54-65, March (2000).
- [61] IAEA. International Atomic Energy Agency. Introduction of nuclear desalination; A guidebook. Technical report series No. 400. Vienna Austria (2000).
- [62] GWIP, Desalination Markets 2005-2015: A Global Assessment and Forecast. Global Water Intelligence Publication (2004).
- [63] O.K. Buros, The ABCs of Desalting (Topsfield, MA: International Desalination Association) (2000), www.idadesal.org/ABCs1.pdf (accessed November 29, 2005).
- [64] WHO, Water Treatment and Pathogen Control: Process Efficiency in Achieving Safe Drinking Water. World Health Organisation (LeChevallier, M.W. and Au, K.-K) (2004).
- [65] S.J. Duranceau and L.R. Henthorne, Membrane pre-treatment for seawater reverse osmosis desalination. *Florida Water Resources Journal*, November, (2004) 33-37.
- [66] Water Corporation, A Strategic Review of Desalination Possibilities for Western Australia, September (2000).
- [67] K.S. Spiegler and Y.M. El-Sayed, A Desalination Primer, Balaban Desalination Publications, Santa Maria Imbaro, Italy (1994).
- [68] O.K. Buros, "The ABCs of Desalting, Second ed." International Desalination Association, Topsfield, Mass, (2000).
- [69] S. Kumar and G.N. Tiwari, Performance evaluation of an active solar distillation system, *Energy*, 21 (1996) 805-808.

- [70] S.A. Lawrence and G.N. Tiwari, Theoretical evaluation of solar distillation under natural circulation with heat exchanger, *Energy Conv. Mgmt.*, 30 (1990) 205-213.
- [71] Y.P. Yadav and L.K. Jha, A double-basin solar still coupled to collector and operating in the thermosiphon mode, *Solar Energy*, 14 (1989) 653-659.
- [72] H.S. Soliman, Solar still coupled with solar heater, Mosul University, Mosul, Iraq, 1976, p. 43.
- [73] G.M. Zaki, A. M. Radhwan and A. O. Balbeid, Analysis of assisted coupled solar stills. *Solar Energy*, 51 (4) (1993) 277.
- [74] Hassan E.S. Fath, Solar distillation: a promising alternative for water provision with free energy, simple technology and a clean environment, *Desalination* 116 (1998) 45-56.
- [75] MEDRC R&D Report, VARI-RO Solar Powered Desalting Study. SAIC, USA, 2000.
- [76] T. Espino, B. Peñate, G. Piernavieja, D. Herold and A. Neskakis, Optimised desalination of seawater by a PV powered reverse osmosis plant for a decentra-lised coastal water supply, *Desalination*, 156 (2003) 349-350.
- [77] Alawaji, Saleh, Mohammed Salah Smiai, Shah Rafique and Byron Stafford (1995). PV Powered Water Pumping and Desalination Plant for Remote Areas in Saudi Arabia. *Applied Energy* 52(2-3) 283-289.
- [78] Syed M. Hasnain and A. Alajlan Saleh, Coupling of PV-powered RO brackish water desalination plant with solar stills. *Desalination* 116(1) (1998) 57-64
- [79] Weiner, Dan, David Fisher, Eduard J. Moses, Baruch Katz and Giora Meron, Operation experience of a solar- and wind-powered desalination demonstration plant, *Desalination* 137(1-3) (2001) 7-13
- [80] www.nrea.gov.eg/pv.htm (accessed: Sept. 2007)
- [81] Al Suleimani, Zaher and V. Rajendran Nair (2000). Desalination by solar-powered reverse osmosis in a remote area of the Sultanate of Oman. *Applied Energy* 65(1-4): 367-380
- [82] Bryce S. Richards and Andrea I. Schafer, Photovoltaic-powered desalination system for remote Australian communities. *Renewable Energy* 28(13) (2003) 2013-2022
- [83] Mathew, Kuruvilla, Stewart Dallas, Goen Ho and Martin Anda, Innovative Solar-Powered Village Potable Water Supply. Women Leaders on the Uptake of Renewable Energy Seminar. Perth, Australia, June (2001) Also available at: <http://acre.murdoch.edu.au/unep/papers/Mathew.pdf> (accessed: Sept. 2007)
- [84] Maslin, Anthony, David Annandale and Marc Saupin, Decentralised water solutions Island infrastructure project. Proceedings of Renewable Energy Sources for Islands, Tourism and Water Desalination Conference. Crete, Greece, May 2003, EREC (European Renewable Energy Council) (2003) 287-294
- [85] A.M. Thomson, Reverse-osmosis desalination of seawater powered by photovoltaics without batteries, PhD Thesis, Loughborough University, 30th June 2003.
- [86] Franz Trieb, Joachim Nitsch, Stefan Kronshage, Christoph Schillings, Lars-Arvid Brischke, Gerhard Kniesb, G. Czisch, Combined solar power and

- desalination plants for the Mediterranean region - sustainable energy supply using large-scale solar thermal power plants, *Desalination* 153 (2002) 39-46.
- [87] G. Burgess and K. Lovegrove, Solar thermal powered desalination: membrane versus distillation technologies, Centre for Sustainable Energy Systems, Department of Engineering, Australian National University, Canberra ACT 0200, Australia.
- [88] Rostek Associates, Inc. & US Dept of the Interior Bureau of Reclamation, *Desalting Handbook for Planners*, 3rd Ed, July 2003.
- [89] Thomas Ackermann, Lennart Soder, An overview of wind energy-status 2002, *Renewable and Sustainable Energy Reviews* 6 (2002) 67-128.
- [90] Rodriquez-Girones PJ et al. Experience on desalination with renewable energy sources—EURORED project. University De Las Palmas De Gran Canaria, 1996.
- [91] Desalination guide using renewable energies. Maxibrochure under THERMIEDG XVII published by C.R.E.S. Centre for Renewable Energy Sources, Pikermi-Attiki, Greece, 1998.
- [92] Feron P. Use of windpower in autonomous reverse osmosis seawater desalination. *Wind Engineering* 9(3) (1985) 180-99.
- [93] Rahal Z, Infield DG. Wind powered stand alone desalination. In: *Proceedings of the European Wind Energy Conference*, Dublin, Ireland, October 1997; also available at: <http://info.lboro.ac.uk/departments/el/research/crest/publicitn.html>
- [94] Rahal Z, Infield DG. Computer modelling of a large scale stand alone wind-powered desalination plant. In: *Proceedings of the British Wind Energy Conference*, Stirling, UK, August 1997, also available at: <http://info.lboro.ac.uk/departments/el/research/crest/publicitn.html>
- [95] Infield D. Performance analysis of a small wind powered reverse osmosis plant. *Solar Energy* 61(6) (1997) 415-21.
- [96] Manwell JF, McGowan JG. Recent renewable energy driven desalination system research and development in North America. *Desalination* 94(3) (1994) 229-41.
- [97] R. Vujcic, M. Krneta, Wind-driven seawater desalination plant for agricultural development on the islands of the County of Split and Dalmatia. *Renewable Energy* 19 (2000) 173-183.
- [98] M. Stahl, Small wind powered RO seawater desalination plant design, erection and operation experience. Seminar on New Technologies for the Use of Renewable Energies in Water Desalination. Athens, 26-28 September (1991). Commission of the European Communities, DG XVII for Energy, CRES (Centre for Renewable Energy Sources).
- [99] C. Kostopoulos, *Proceedings of the Mediterranean Conference on Renewable Energy Sources for Water Production*. European Commission, EURORED Network, CRES, EDS, Santorini, Greece, 10-12 June (1996) 20-25.
- [100] ITC (Canary Islands Technological Institute), *Memoria de gestion* (in Spanish) 2001.
- [101] C.C.K. Lui, J.-W. Park, R. Migita, G. Qin, Experiments of a prototype wind-driven reverse osmosis desalination system with feedback control. *Desalination* 150 (2002) 277-287.

- [102] J. Veza, B. Penate, F. Castellano, Electrodialysis desalination designed for wind energy (on-grid test). *Desalination* 141 (2001) 53-61.
- [103] E. Barbier, Geothermal energy technology and current status: an overview, *Renewable Sustain. Energy Rev.*, 6 (2002) 3-65.
- [104] MEDRC R&D Report, Matching Renewable Energy with Desalination Plants, IT Power Ltd, 2001.
- [105] V. Belessiotis and E. Delyannis, Renewable energy resources, in *Encyclopedia of Life Support Systems (EOLSS)*, Desalination: Desalination with Renewable Energies, available on line:
<http://www.desware.net/DeswareLogin/LoginForm.aspx>.
- [106] Cost Estimating Procedures. In: *Desalting Handbook for Planners* (Chapter 9). United States Department of Interior, Bureau of Reclamation, Technical Service Center, Desalination and Water Purification Research and Development Program Report No. 72 (3rd Edition). P. (2003) 187-231.
- [107] LBG-Guyton Associates. *Brackish Groundwater Manual for Texas Regional Water Planning Groups*. Prepared for Texas Water Development Board. (2003) 31 pp.
- [108] T. Younos, The Feasibility of Using Desalination to Supplement Drinking Water Supplies in Eastern Virginia. VWRRC Special Report SR25-2004. Virginia Water Resources Research Center, Virginia Tech, Blacksburg, VA. (2004) 114 pp.
- [109] Tamim Younos, The Economics of Desalination, *Universities Council on Water Resources Journal of Contemporary Water Research & Education*, Issue 132, pp. 39-45, December 2005.
- [110] NRC Review of the Desalination and Water Purification Technology Roadmap. National Research Council; The National Academies Press, Washington DC.
- [111] Miller J. E. 2003. Review of Water Resources and Desalination Technologies. Sandia National Laboratories, Albuquerque, NM. (2004) 49 pp.
http://www.sandia.gov/water/docs/MillerSAND2003_0800.pdf
- [112] A. Ghoneyem, A. Ileri, Software to analyze stills and an experimental study on the effects of the cover. *Desalination* 114 (1997) 37-44.
- [113] A.A.Madani, G.M.Zaki, Yield of stills with porous basins. *Applied Energy* 52, (1995) 273-281.
- [114] B. Boucekima, B. Gros, R. Oahes, M.Diboun, Performance study of the capillary film solar distiller. *Desalination* 116 (1998) 185-192.
- [115] H.E.S. Fath, High performance of a simple design, two effects, solar distillation unit. *Energy Conversion and Management* 38 (1997) 1895-1905.
- [116] E. Komgold, E. Korin, I. Ladizhensky, Water desalination by pervaporation with hollow fiber membranes, *Desalination* 107 (1996) 121-129.
- [117] M. M. Aboabboud, L. Horvath, G. Mink, M. Yasin, and A. I. Kudish, An energy saving atmospheric evaporator utilizing low grade thermal or waste energy, *Energy* 21 (12) (1996) 1107-1117.
- [118] S. Loupasis, Technical Analysis of Existing RES Desalination Schemes (Commission of the European Communities Directorate-General for Energy and Transport, Altener Programme, Renewable Energy Driven Desalination Systems – REDDES, Contract number 4.1030/Z/01-081/2001) (2002).

- [119] U. Ebensperger, and P. Isley, Review of the Current State of Desalination: Water Policy Working Paper 2005-008 (Georgia Water Planning and Policy Center, (2005). <http://www.h2opolicycenter.org/wp2005.shtml> (accessed Sept. 15, 2007)
- [120] REN21 Renewable Energy Policy Network Renewables 2005 Global Status Report (Washington, DC: Worldwatch Institute) (2005).
- [121] Franz Trieb, Joachim Nitsch, Stefan Kronshage, Christoph Schillings, Lars-Arvid Brischke, Gerhard Kniesb, G. Czisch, Combined solar power and desalination plants for the Mediterranean region - sustainable energy supply using large-scale solar thermal power plants, *Desalination* 153 (2002) 39-46.