

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

186,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Application of Renewable Energies for Water Desalination

Mattheus Goosen¹, Hacene Mahmoudi²,
Noredine Ghaffour³ and Shyam S. Sablani⁴

¹*Office of Research and Graduate Studies,
Alfaisal University, Riyadh,*

²*Renewable Energy Development Centre (CDER), Bouzareah, Algiers,
Hassiba Ben Bouali University, Chlef,*

³*Water Desalination & Reuse Centre,
King Abdullah University of Science and Technology (KAUST),*

⁴*Dept. of Biological Systems Engineering,
Washington State University, Pullman, Washington,*

^{1,3}*Saudi Arabia*

²*Algeria*

⁴*USA*

1. Introduction

Renewable energy technologies such as wind, solar, and geothermal and even alternatives such as nuclear show great promise for water desalination (Serpen et al., 2010; Goosen et al., 2010; Stock Trading, 2010; Khamis, 2009; Misra, 2010). These energy driven desalination systems fall into two categories. The first includes distillation processes driven by heat produced directly by the renewable energy system (RES), while the second includes membrane and distillation processes driven by electricity or mechanical energy produced by RES. With the world's fresh water demands increasing, much research has been directed at addressing the challenges in using renewable (and environmentally friendly) energy to meet the power needs for desalination plants. Lack of water, for instance, has caused great distress among the population in large parts of the MENA countries (Middle East and North Africa). The economic and industrial potentials of renewable energies, such as geothermal, solar and wind, as well as the environmental advantages have been pointed out in several recent studies (Serpen et al., 2010; Mahmoudi et al., 2010; Huang, 2010; Lund, 2007; and Cataldi, et al., 1999). Lund (2007) noted that recorded accounts show uses of, for example, geothermal water by Romans, Japanese, Turks, Icelanders, Central Europeans and the Maori of New Zealand for bathing, cooking and space heating. The first use of geothermal energy for electric power production occurred in Italy a century ago with the commissioning of a commercial power plant (250 kWe). Small decentralised water treatment plants can also be connected to a wind energy convertor system (WECs). The wind turbines as well as the desalination system can be connected to a grid system (Eltawil et al., 2009). The Kwinana Desalination Plant, for example, located south of Perth in Western Australia, produces

nearly 140 megalitres of drinking water per day, supplying the Perth metropolitan area (BlurbWire 2010). Electricity for the plant is generated by the 80 MW Emu Downs Wind Farm located in the state's Midwest region.

Solar energy can also be converted to thermal or electrical (i.e. photovoltaic) energy and then used in water desalination directly or indirectly, respectively (Mahmoudi et al., 2008, 2010; Goosen and Shayya, 1999). Thermal energy, for instance, can be employed in solar stills, collectors, or solar ponds. Electrical energy can be produced from solar energy directly by PV conversion or via solar thermal power plant. The coupling of renewable energies such as wind, solar and geothermal with desalination systems holds great promise for water scarce regions (Mahmoudi et al., 2008, 2010; Goosen and Shayya, 1999; Tester et. al., 2007). We can argue that an effective integration of these technologies will allow countries to address water shortage problems with a domestic energy source that does not produce air pollution or contribute to the global problem of climate change. Furthermore this approach will help to bypass the problems of rising fuel prices and decreasing fossil fuel supplies. Desalination plants, for example, may be run with geothermal of energy being employed directly to heat the saline or brackish water in multiple effect distillation units and/ or it could be used indirectly to generate electricity for operating reverse osmosis units (Kalogirou, 2005). In addition, alternative energy sources such as nuclear also need to be considered (Khamis, 2009; Misra, 2010). The Shevchenko BN350 nuclear fast reactor and desalination plant, for instance, situated on the shore of the Caspian Sea, in Kazakhstan, during its lifetime of some 27 years could generate 135 MWe of electric power and provide steam for an associated desalination plant which produced 80,000 m³/ day of potable water (Kadyrzhanov et al., 2007). About 60% of the plants power was used for heat and desalination.

Bourouni et al. (1999a, 1999b, 2001) reported on installations using humidification dehumidification processes in the form of evaporators and condensers made of polypropylene and operated at a temperature between 60 and 90 °C. Bouchekima (2003) reported on the use of brackish underground geothermal water to feed a solar still installed in the South of Algeria. Furthermore, with the recent progress in membrane distillation technology, the utilization of direct geothermal brine with temperature up to 60 °C has shown promise (Houcine, et al., 1999). Iceland is widely considered as the most successful state in the geothermal community. The country of just over 300,000 people is fully (i.e. 100%) powered by renewable forms of energy, ranking the highest in the 15 top countries that generate electricity from geothermal resources. Wright (1998) has estimated that given that the worldwide energy utilization is equal to about 100 million barrels of oil per day, the Earth's thermal energy to a depth of 10 kilometers could theoretically supply all of mankind's power needs for several million years.

The aim of this chapter is to provide a critical review of recent trends in water desalination using renewable as well as alternative energy resources. After providing an overview of desalination using renewable energies, specific case studies will be presented as well as an assessment of environmental risks and sustainability. The chapter will conclude with a section on market potential and risk management.

2. Water desalination using renewable and alternative energies

The combination of renewable energy with desalination systems holds immense promise for improving potable water supplies in arid regions (Mahmoudi et al., 2008, 2009a, 2009b, 2010). We can argue that an efficient amalgamation of these technologies will allow nations

to deal with water shortage problems with a domestic energy source that does not produce air pollution or contribute to the global crisis of climate change. Furthermore, while fuel prices are rising and fossil fuel supplies are decreasing, the fiscal outlay for desalination and renewable energy systems are steadily decreasing. The latter is due in part to a variety of possible arrangements that can be envisaged between renewable power supplies and desalination technologies (Rodríguez et al, 1996).

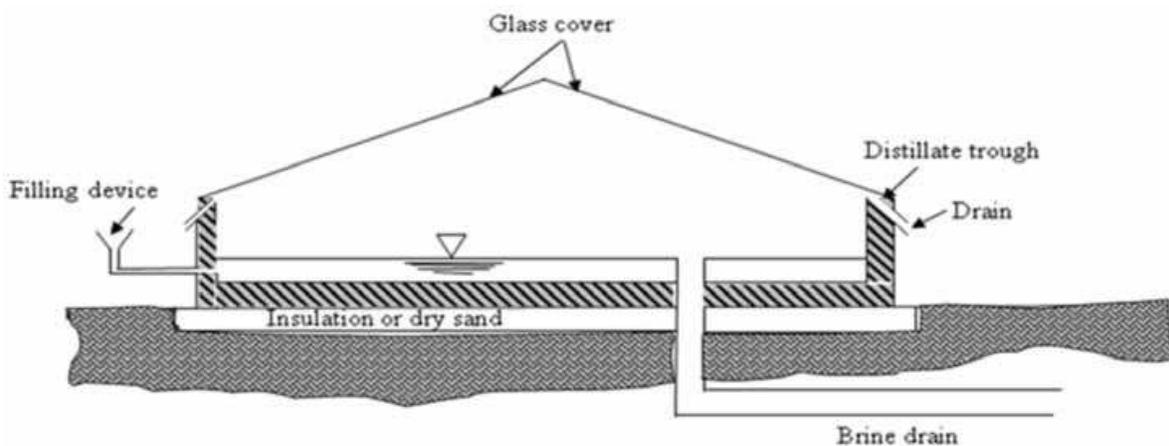
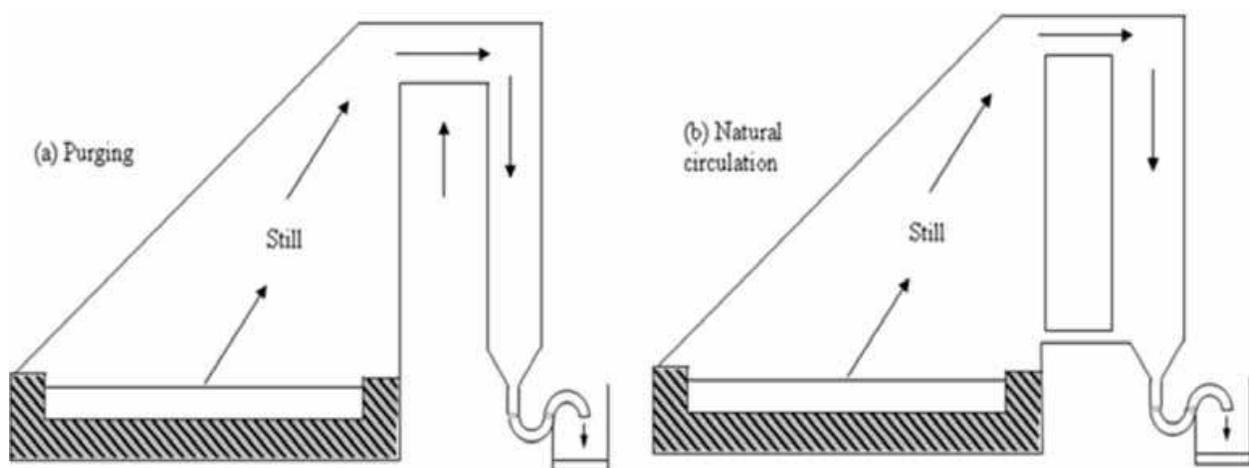
2.1 Applications of solar energy for water desalination

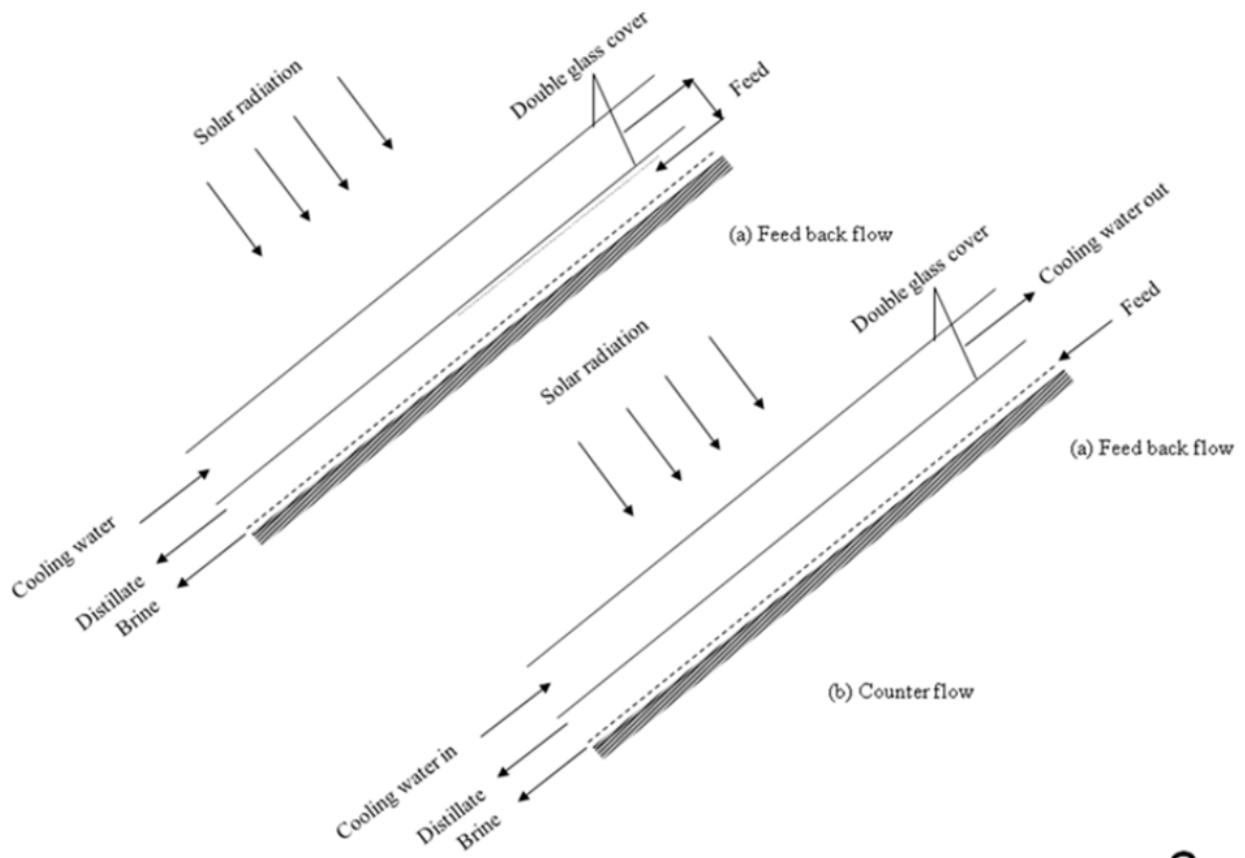
Desalination by means of solar energy is a suitable alternative to conventional methods (e.g. fossil powered thermal distillation) to providing fresh water, especially for remote and rural areas where small quantities of water for human consumption are needed (Al-Hallaj et al., 1998). Attention has been directed towards improving the efficiencies of the solar energy conversions, desalination technologies and their optimal coupling to make them economically viable for small and medium scale applications. Solar energy can be used directly as thermal or it can be converted to electrical energy to drive reverse osmosis units. The thermal energy can be achieved in solar stills, collectors, or solar ponds. Electrical energy can be produced from solar energy directly by photo-voltaic (PV) conversion or via a solar thermal power plant.

Solar stills, for example, which have been in use for several decades, come in a variety of options (Figure 1) (Goosen et al., 2000). The simple solar still (Figure 1A) is a small production system yielding on average 2 – 5 L/ day. It can be used wherever fresh water demand is low and land is inexpensive. Many modifications to improve the performance of the solar stills have been made. These include linking the desalination process with the solar energy collectors (Figure 1E), incorporating a number of effects to recover the latent heat of condensation (Figures 1D & 1F), improving the configurations and flow patterns to increase the heat transfer rates (Figures 1B, 1C, 1E, and 1F), and using low-cost materials in construction to reduce the cost. Nevertheless these systems are not economically viable for large-scale applications. One of the more successful solar desalination devices is the multiple-effect still (Figure 1F) (Al-Hallaj et al., 1998). Latent heat of condensation is recovered, in two or more stages (generally referred to as multi-effects), so as to increase production of distillate water and improve system efficiency. A key feature in improving overall thermal efficiency is the need to gain a better understanding of the thermodynamics behind the multiple use of the latent heat of condensation within a multi-effect humidification-dehumidification solar still (Al-Hallaj et al., 1998). In addition, while a system may be technically very efficient it may not be economic (i.e., the cost of water production may be too high) (Fath, 1998). Therefore, both efficiency and economics need to be considered when choosing a desalination system. We can further argue that desalination units powered by renewable energy systems are uniquely suited to provide water and electricity in remote areas where water and electricity infrastructures are currently lacking.

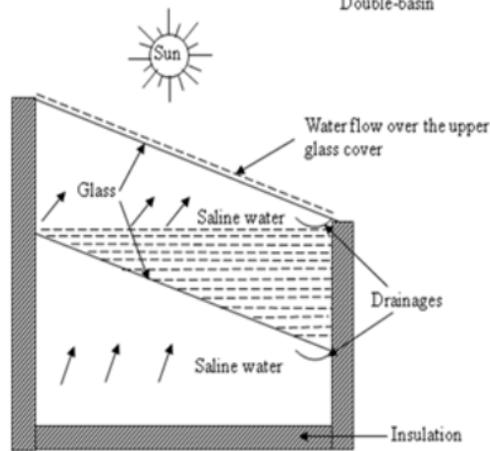
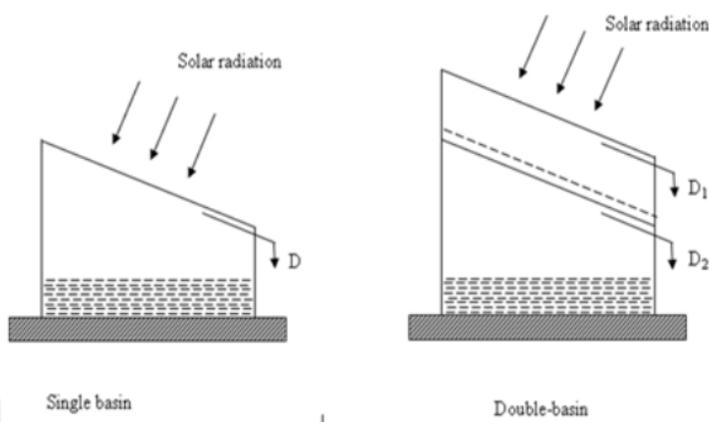
Solar collectors are usually classified according to the temperature level reached by the thermal fluid in the collectors (Table 1) (Kalogirou, 2005). Low temperature collectors provide low-grade heat, only a few degrees above ambient air temperature and use unglazed flat plate collectors. This low-grade heat is not useful to serve as a heat source for conventional desalination distillation processes (Fahrenbruch and Bube, 1983; Kalogirou, 2005). Medium temperature collectors provide heat of more than 430C and include glazed

flat plate collectors as well as vacuum tube collectors using air or liquid as the heat transfer medium. They can be used to provide heat for thermal desalination processes by indirect heating with a heat exchanger. High temperature collectors include parabolic troughs or dishes or central receiver systems. They typically concentrate the incoming solar radiation onto a focal point, from which a receiver collects the energy using a heat transfer fluid. The high temperature energy can be used as a thermal energy source in thermal desalination processes or can be used to generate electricity using a steam turbine. As the position of the sun varies over the course of the day and the year, sun tracking is required to ensure that the collector is always kept in the focus of the reflector for improving the efficiency. For large-scale desalination applications, these systems need large collector areas.

**A****B**



C



D

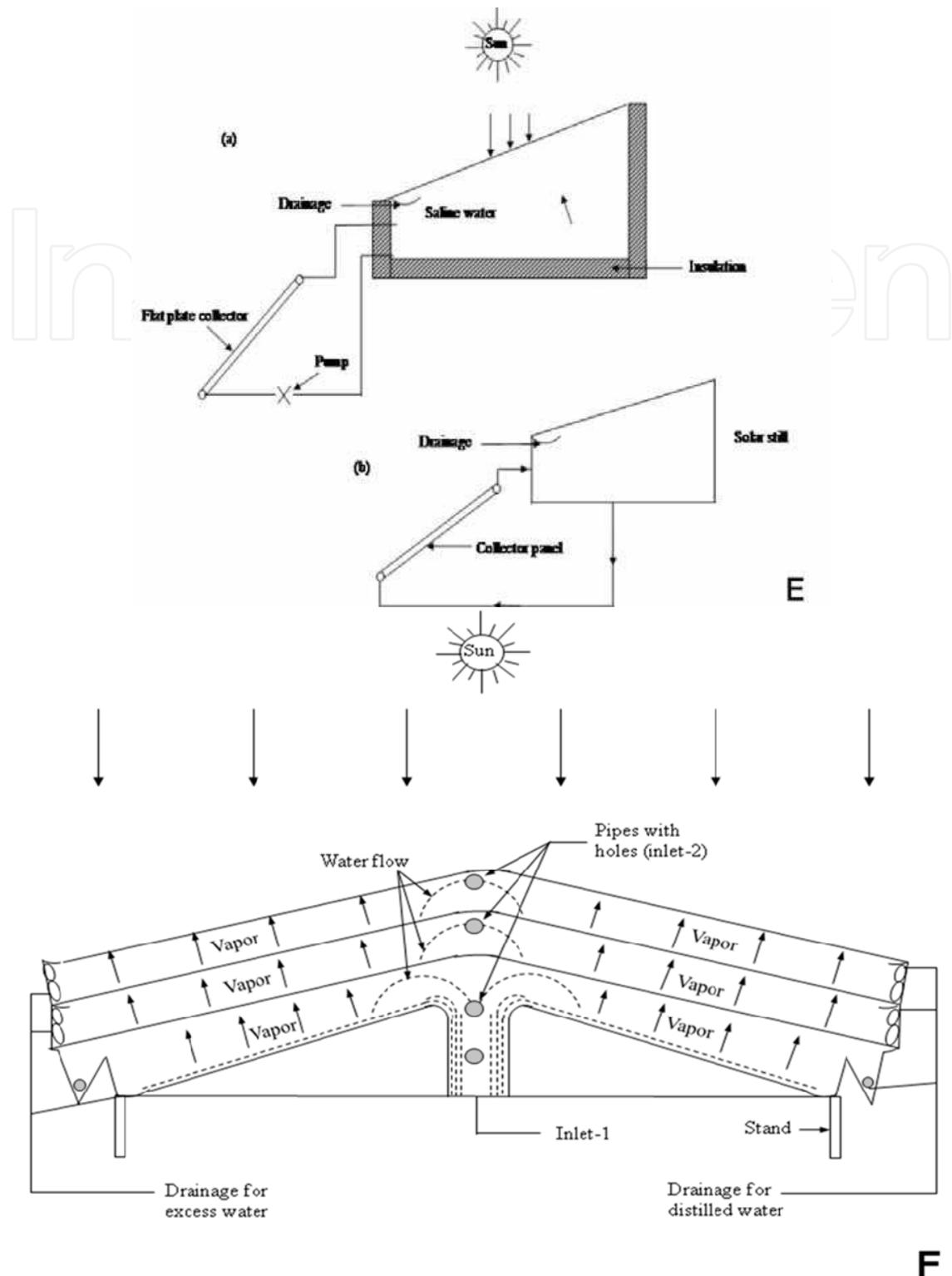


Fig. 1. Solar desalination systems (Goosen et al., 2000; adapted from Fath, 1998). A. Single-effect basin still. B. Single-sloped still with passive condenser. C. Cooling of glass cover by (a) feedback flow, and (b) counter flow. D. Double-basin solar stills: (a) schematic of single and double-basin stills and (b) stationary double-basin still with flowing water over upper basin. E. Directly heated still coupled with flat plate collector: (a) forced circulation and (b) natural circulation. F. Typical multi-effect multi-wick solar still.

| Indicative temperature range (8C) | Concentration ratio | Absorber type | Collector type | Motion |
|-----------------------------------|---------------------|---------------|------------------------------------|----------------------|
| 30–80 | 1 | Flat | Flat plate collector (FPC) | Stationary |
| 50–200 | 1 | Flat | Evacuated tube collector (ETC) | |
| 60–240 | 1–5 | Tubular | Compound parabolic collector (CPC) | |
| 60–300 | 5–15 | Tubular | Compound parabolic collector (CPC) | Single-axis tracking |
| 60–250 | 10–40 | Tubular | Linear Fresnel reflector (LFR) | |
| 60–300 | 15–45 | Tubular | Parabolic trough collector (PTC) | |
| 60–300 | 10–50 | Tubular | Cylindrical trough collector (CTC) | |
| 100–500 | 100–1000 | Point | Parabolic dish reflector (PDR) | Two-axes tracking |
| 150–2000 | 100–1500 | Point | Heliostat field collector (HFC) | |

Table 1. Solar Energy Collectors (Kalogirou, 2005) Note: Concentration ratio is defined as the aperture area divided by the receiver/ absorber area of the collector.



Fig. 2a. (Left) Solar pond for heating purpose demonstration in Australia (http://www.aph.gov.au/library/pubs/bn/sci/RenewableEnergy_4.jpg). 2b. (Right) Solar Ponds Schematic The salt content of the pond increases from top to bottom. Water in the storage zone is extremely salty. As solar radiation is absorbed the water in the gradient zone cannot rise, because the surface-zone water above it contains less salt and therefore is less dense. Similarly, cooler water cannot sink, because the water below it has a higher salt content and is denser. Hot water in the storage zone is piped to, for example, a boiler where it is heated further to produce steam, which drives a turbine. (Wright, 1982; and www.energyeducation.tx.gov/.../index.html)

Solar ponds (Figure 2) combine solar energy collection with long-term storage. 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. A salt concentration gradient in the pond helps in storing the energy. Whereas the top temperature is close to ambient, a temperature of 90 °C can be reached at the bottom of the pond where the salt concentration is highest (Figure 2b). The temperature difference between the top and bottom layer of the pond is large enough to run a desalination unit, or to drive the vapour generator of an organic Rankine cycle engine (Wright, 1982). The Rankine cycle converts heat into work. The heat is supplied externally to a closed loop, which usually uses water. This cycle generates about 80% of all electric power used throughout the world including virtually all solar thermal, biomass, coal and nuclear power plants (Wright, 1982). An organic Rankine cycle (ORC) uses an organic fluid such as n-pentane or toluene in place of water and steam. This allows use of lower-temperature heat sources, such as solar ponds, which typically operate at around 70–90 °C. The efficiency of the cycle is much lower as a result of the lower temperature range, but this can be worthwhile because of the lower cost involved in gathering heat at this lower temperature.

Solar ponds have a rather large storage capacity. This allows seasonal as well as diurnal thermal energy storage. The annual collection efficiency for useful heat for desalination is in the order of 10 to 15% with sizes suitable for villages and small towns. The large storage capacity of solar ponds can be useful for continuous operation of desalination plants. It has been reported that, compared with other solar desalination technologies, solar ponds provide the most convenient and least expensive option for heat storage for daily and seasonal cycles (Kalogirou, 2005). This is very important, both from operational and economic aspects, if steady and constant water production is required. The heat storage allows solar ponds to power desalination during cloudy days and night-time. Another advantage of desalination by solar ponds is that they can utilize what is often considered a waste product, namely reject brine, as a basis to build the solar pond. This is an important advantage for inland desalination. If high temperature collectors or solar ponds are used for electricity generation, a desalination unit, such as a multistage flash system (MSF), can be attached to utilize the reject heat from the electricity production process. Since, the standard MSF process is not able to operate with a variable heat source, a company ATLANTIS developed an adapted MSF system that is called 'Autoflash' which can be connected to a solar pond (Szacsavay, et al., 1999). With regard to pilot desalination plants coupled to salinity gradient solar ponds the seawater or brine absorbs the thermal energy delivered by the heat storage zone of the solar pond. Examples of different plants coupling a solar pond to an MSF process include: Margarita de Savoya, Italy: Plant capacity 50–60 m³/ day; Islands of Cape Verde: Atlantis 'Autoflash', plant capacity 300 m³/ day; Tunisia: a small prototype at the laboratoire of thermique Industrielle; a solar pond of 1500 m² drives an MSF system with capacity of 0.2 m³/ day; and El Paso, Texas: plant capacity 19 m³/ day (Lu et al., 2000).

Solar photo-voltaic (PV) systems directly convert the sunlight into electricity by solar cells (Kalogirou, 2005). Solar cells are made from semiconductor materials such as silicon. Other semiconductors may also be used. A number of solar cells are usually interconnected and encapsulated together to form a PV module. Any number of PV modules can be combined to form an array, which will supply the power required by the load. In addition to the PV module, power conditioning equipment (e.g. charge controller, inverters) and energy storage equipment (e.g. batteries) may be required to supply energy to a desalination plant. Charge controllers are used for the protection of the battery from overcharging. Inverters are used to convert the direct current from the photovoltaic modules system to alternating current to the loads. PV is a mature technology with life expectancy of 20 to 30 years. The

main types of PV systems are the following: - Stand-alone systems (not connected to the utility grid): They provide either DC power or AC power by using an inverter. - Grid-connected systems: These consist of PV arrays that are connected to the electricity grid via an inverter. In small and medium-sized systems the grid is used as a back-up source of energy, (any excess power from the PV system is fed into the grid). In the case of large centralized plants, the entire output is fed directly into the grid.- Hybrid systems: These are autonomous systems consisting of PV arrays in combination with other energy sources, for example in combination with a diesel generator or another renewable energy source (e.g. wind). There are mainly two PV driven membrane processes, reverse osmosis (RO) and electrodialysis (ED). 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 (Childs et al., 1999). 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.

Burgess and Lovegrove (2005) compared the application of solar thermal power desalination coupled to membrane versus distillation technology. They reported that a number of experimental and prototype solar desalination systems have been constructed, where the desalination technology has been designed specifically for use in conjunction with solar thermal collectors, either static or tracking. To date such systems are either of very low capacity, and intended for applications such as small communities in remote regions, or else remain unproven on a larger scale. Several systems which are of some interest were discussed. Schwarzer et al (2001) described a simple system which has flat plate collectors (using oil as a heat transfer fluid) coupled to desalination "towers" in which water evaporates in successive stages at different heights (similar to the multi effect still shown in Figure 1F). The condensation of vapour in one stage occurs at the underside of the next stage, transferring heat and increasing the gain output ratio. A very similar system (not mentioned by Schwarzer), called a "stacked plate still", is described by Fernandez (1990). Furthermore, the Vari-Power Company, based in California, has developed an RO based desalination system which is specifically tailored to solar thermal input (Childs et al, 1999). A patented direct drive engine (DDE) converts heat to the hydraulic power required by RO. Desalinated water production using the DDE is projected to be more than 3 times greater (for an identical dish collector) than that which would be obtained by RO driven by a dish-Stirling electricity generation system or PV power. Burgess and Lovegrove (2005) noted that the project remains at the pilot stage with the DDE not commercially available: it has perhaps become less attractive due to the advances in conventional RO. 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 Figure 3.

2.2 Wind power and desalination

Kalogirou (2005) in a rigorous review on renewable energy sources for desalination argued that purely on a theoretical basis, and disregarding the mismatch between supply and demand, the world's wind energy could supply an amount of electrical energy equal to the

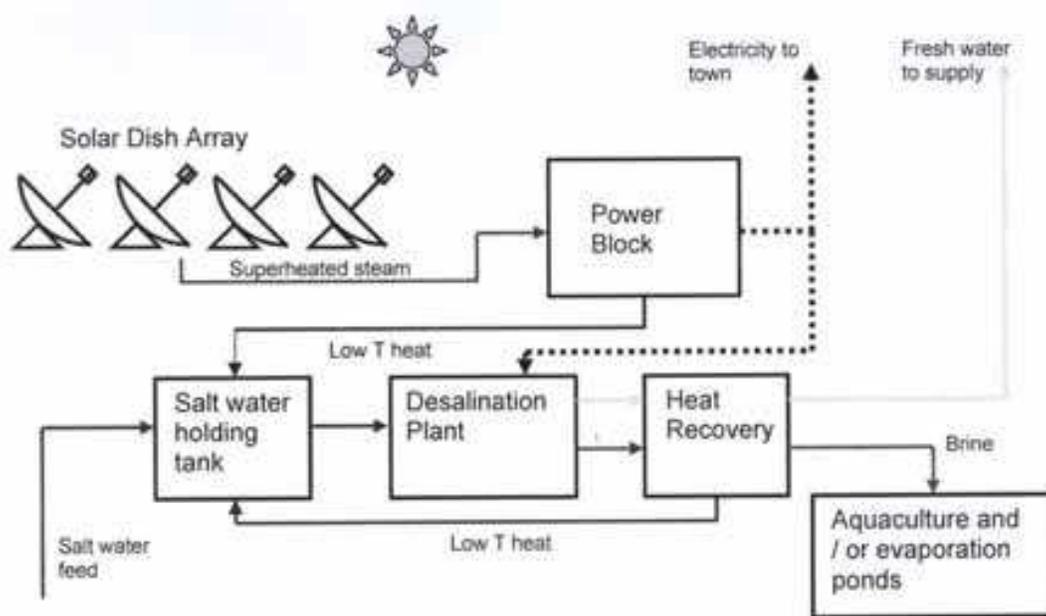


Fig. 3. Combined dish based solar thermal power generation and RO desalination (Burgess and Lovegrove, 2005)

present world electricity demand. 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 (Soerensen, 1979). This power generates a kinetic energy reservoir of 750 EJ with a turnover time of 7.4 days. 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, which is more than sufficient to supply the world's current electricity requirements. Small decentralised water treatment plants combined with an autonomous wind energy convertor system (WECs) (Figure 4a) show great potential for transforming sea water or brackish water into pure drinking water (Koschikowski and Heijman, 2008) Also, 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.

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. The only electrical energy required is for pumping the water



Fig. 4a (Upper Left) Wind Farm (Kalogirous, 2005); 4b (Right) Wind turbines and PV cells of Sureste SWRO plant (Sadhvani, 2008; IDA Conference, 2008); 4c (Lower Left) Wave Energy. The Aquabuoy 2.0 is a large 3 meter wide buoy tied to a 70-foot-long shaft. By bobbing up and down, the water is rushed into an acceleration tube, which in turn causes a piston to move. This moving of the piston causes a steel reinforced rubber hose to stretch, making it act as a pump. The water is then pumped into a turbine which in turn powers a generator. The electricity generated is brought to shore via a standard submarine cable. The system is modular, which means that it can be expanded as necessary (Chapa, 2007).

to a relatively high operating pressure. The use of special turbines may reclaim part of the energy. Operating pressures vary between 10 and 25 bars for brackish water and 50–80 bars for seawater (Eltawil et al., 2009). The Kwinana Desalination Plant, located south of Perth in Western Australia, is one example where wind power and reverse osmosis desalination have been successfully combined. The plant produces nearly 140 megalitres of drinking water per day (BlurbWire 2010). Electricity for the plant is generated by the 80 MW Emu Downs Wind Farm located in the state's Midwest region. The reverse osmosis plant was the first of its kind in Australia and covers several acres in an industrial park.

Recently, many medium and large scale water treatment and desalination plants are partially powered with renewable energy mainly wind turbines, PV cells or both. The energy demand of Sureste seawater reverse osmosis (SWRO) plant located in Gran Canaria, Canary Islands, of a capacity of 25,000 m³/d is provided by a combination of PV cells (rooftop) with minor share of RO energy demand and the rest from the grid which consist of energy mix including wind energy (Figure 4b) (Sadhvani, 2008; IDA Conference, 2008).

2.3 Wave power desalination

Wave-powered desalination offers an environmentally sensitive solution for areas where there is a shortage of water and sufficiently energetic waves. Energy that can be harvested from oceans includes waves, tides and underwater oceanic currents (Figure 4c). Most of the work on wave energy conversion has focused on electricity production (Davies, 2005); any such converter could, in principle, be coupled to electrically-driven desalination plant, either with or without connection to the local electricity grid. Worldwide exploitable wave energy resource is estimated to be 2 TW, so it is a promising option for electricity generation. Thus, there is a potential option of coupling wave power with seawater reverse osmosis. A study by Davies (2005) focused on the potential of linking ocean-wave energy to desalination. They found that along arid, sunny coastlines, an efficient wave-powered desalination plant could provide water to irrigate a strip of land 0.8 km wide if the waves are 1 m high, increasing to 5 km with waves 2 m high. Wave energy availabilities were compared to water shortages for a number of arid nations for which statistics were available. The maximum potential to correct these shortages varied from 16% for Morocco to 100% for Somalia. However, the author noted that wave energy is mainly out-of-phase with evapotranspiration demand leading to capacity ratios of 3–9, representing the ratios of land areas that could be irrigated with and without seasonal storage. In a related study, Magagna and Muller (2009) described the development of a stand-alone, off-grid reverse osmosis desalination system powered by wave energy. The system consisted of two main parts; a high pressure pump (Wave Catcher) that allows generation of a high pressure head from low head differences, and a wave driven pump to supply the necessary head to the Wave Catcher. The high pressure pump could produce 6 MPa of pressure which is necessary to drive a RO membrane for desalination of water. We can argue that wave energy technology is still at prototype stage, there is no standard technology. Wave energy has also an intermittent and variable behaviour similar to wind energy.

2.4 Geothermal desalination

Geothermal energy is widely distributed along the world (White, 2002). This energy can be used for heat and electricity generation. Thus, there is a potential use for thermal (MED, MSF, MD, VC) and membrane (RO, EDR) desalination processes. Geothermal reservoirs can produce steam and hot water. Superheated dry steam resources are mostly easily converted into useful energy, generally producing electricity, which can be cheaper than that from conventional sources. Geothermal production of energy is 3rd highest among renewable energies. It is behind hydro and biomass, but before solar and wind. In the case of Iceland, 86% of space heating and 16% of electricity are supplied by geothermal energy.

Lack of water causes great distress among the population in large parts of the MENA countries (Middle East and North Africa). Small decentralised water treatment plants with an autonomous energy convertor system (WECs) can help solve this problem by transforming sea water or brackish water into pure drinking water (Koschikowski and Heijman, <http://www.sciencedirect.com/elsevier.com/science/journal/09582118> 2008).

Considering that the energy requirements for desalination continues to be a highly influential factor in system costs, the integration of renewable energy systems with desalination seems to be a natural and strategic coupling of technologies (Tzen et al., 2004). As an example of the potential, the southern part of the country of Algeria consists almost

entirely (i.e. 90%) of the great expanse of the Sahara Desert. This district has fresh water shortages but also has plenty of solar energy (Bouchekima, 2003), wind energy (Mahmoudi et al., 2009a, 2009b) and important geothermal reservoirs (Fekraoui and Kedaid, 2005; Mahmoudi et al., 2010). The amalgamation of renewable resources with desalination and water purification is thus very attractive for this district (Table 2). We will discuss this example in more detail in the Case Study section.

When using geothermal energy to power systems such as desalination plants we avoid the need for thermal storage. In addition, the energy output of this supply is generally stable compared to other renewable resources such as solar and wind power (Bourouni and Chaibi, 2005). Kalogirou (2005) has shown that the ground temperature below a certain depth remains relatively constant throughout the year. Popiel et al (2001) reported that one can distinguish three ground zones; surface, shallow and deep, with geothermal energy sources being classified in terms of their measured temperatures as low (<100 C), medium (100–150 C) and high temperature (>150 C), respectively.

Geothermal wells deeper than 100 m can reasonably be used to power desalination plants (Kalogirou, 2005). We can also envisage the utilization of geothermal power directly as a stream power in thermal desalination plants. Furthermore, with the recent progress on membranes distillation technology, the utilization of direct geothermal brine with temperature up to 60 °C has become a promising solution (Houcine, et al., 1999). Fridleifsson et al. (2008) has reported that electricity is produced by geothermal means in 24 countries, five of which obtained up to 22% of their needs from this source. Furthermore, direct application of geothermal energy for heating and bathing has been reported by 72 countries. By the end of 2004, the worldwide use of geothermal energy was 57 TWh/ yr of electricity and 76 TWh/ yr for direct use. Six developing countries are among the top fifteen states reporting direct use with China on the top of the list. Fridleifsson et al. (2008) goes on to argue that it is considered possible to increase the installed world geothermal electricity capacity from the current 10 GW to 70 GW with present technology, and to 140 GW with enhanced technology.

| Desalting technologies | | | | | | |
|-------------------------------|-----------------------------|-----------------------------|--------------------------------|--------------------------------------|----------------------------|--|
| Compression (MVC) | Electrodialysis (ED) | Reverse osmosis (RO) | Multi-stage flash (MSF) | Multiple effect boiling (MEB) | Feed water salinity | Renewable energy sources technology |
| | | | ✓ | ✓ | Seawater | Solar thermal |
| | | ✓ | | | Seawater | Photovoltaic |
| | ✓ | ✓ | | | Brackish water | |
| ✓ | | ✓ | | | Seawater | Wind |
| | | ✓ | | | Brackish water | |
| | | | | ✓ | Seawater | Geothermal |

Table 2. Renewable energy sources (RES) desalination combinations (Mahmoudi et al., 2010)

2.5 Desalination using hydrostatic pressure

The potential exploitation of the hydrostatic pressure of seawater at a sufficient operative depth was considered by several investigators in the 1960s in view of increasing the energy efficiency of the then developing RO industrial desalination technology (Drude, 1967; Glueckstern, 1982). More recently, several configurations were proposed for fresh water production from seawater using RO and hydrostatic pressure: submarine, underground and ground-based (Reali et al., (1997). In conventional surface-based industrial desalination plants applying RO technology, the freshwater flow at the membrane outlet is approximately 20–25% of the inlet seawater flow, depending on membrane type and characteristics. The resulting brine is disposed off in the sea. While RO installations generate the required pressure with high-pressure pumps, the submarine approach uses seawater hydrostatic pressure. The desalinated water, produced at about atmospheric pressure and collected in a submarine tank at the same working depth, is pumped to the sea surface. It was shown that this approach saves about 50% of the electricity consumption with respect to an efficient conventional RO plant (about 2–2.5 kWh/ m³) since only the outlet desalinated water is pumped instead of the inlet seawater, thus reducing the pumping flow rate by 55–80% (Pacanti et al., 1999). The advantage of this configuration is also to avoid the pre-treatment of the inlet seawater, therefore saving costs for chemicals and equipment (Charcosset, 2009).

3. Case studies

3.1 Capacity building strategies and policies for desalination using renewable energies in Algeria

Among the major challenges facing the region are limited water and energy resources as well as risk management of the environment (Mahmoudi et al., 2009b; Laboy et al., 2009). Mahmoudi et al. (2010) has noted that due to the world economic crisis and the decreasing oil and gas reserves, decision makers in arid countries such as Algeria, need to review their policies regarding the promotion of renewable energies. Algeria is an oil and gas producer; hence decision makers believed that encouraging using renewable energies can affect the country's oil exports (Mahmoudi et al., 2009b). The country is also Africa's second-largest nation and the eleventh in the world in terms of land area, being bordered in the north by 1200 km of Mediterranean coastline.

In 1988, an ambitious program was established with the aim to expand the utilization of geothermal heated greenhouses in regions affected by frost; sites in eastern and southern region of the state. Unfortunately, this program has been hampered by security concerns (Fekraoui and Kedaid, 2005). In the last few decades, much effort has also been expended to exploit the numerous thermal springs of the North and the hot water wells of the Saharian reservoir (Figure 5b). More than 900 MWt is expected to be produced in the future (Fekraoui and Kedaid, 2005). Geothermal energy represents one of the most significant sources of renewable energies in the case study area. This can be divided into two major structural units by the South Atlas Fault (Figure 5a); with Alpine Algeria in the north and the Saharan Platform in the south. The northern region formed by the Tellian Atlas, the High Plains and the Saharian Atlas. This part is characterized by an irregular distribution of its geothermal reservoirs (Figure 5b).

The Tellian nappes, constitute the main geothermal reservoirs. Hot ground water is generally at neutral pH, total dissolved salts (TDS) are up to 10 g/ l and can reach a temperature in the



Fig. 5. a. Geological units of Northern Algeria (Mahmoudi et al., 2010; Kedaid, 2007)

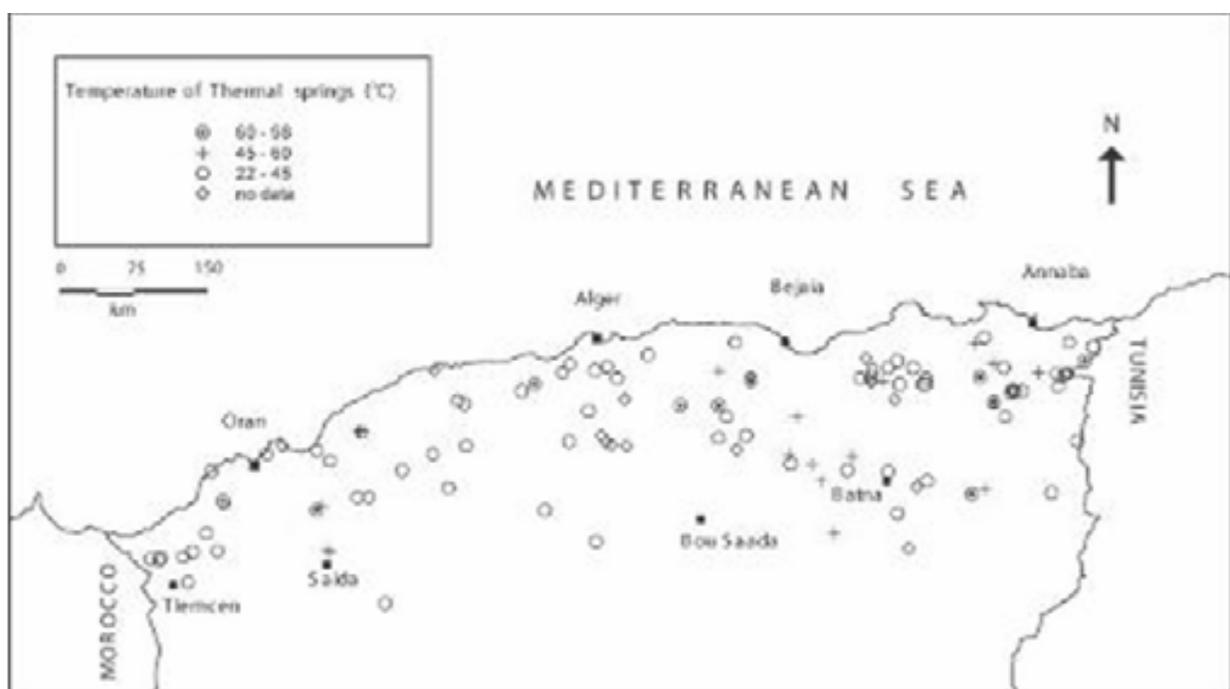


Fig. 5. b. Main thermal springs in northern Algeria (Mahmoudi et al, 2010; Kedaid, 2007)

range of 22°C to 98°C (Fekraoui and Kedaid, 2005). The southern region formed by the Algeria northern Sahara is characterized by a geothermal aquifer which is commonly named 'Albian reservoir'. The basin extends to Libya and Tunisia in the East and covers a total surface of 1 million km². This part of Algeria is estimated at 700 000 km² and contains approximately 40 thousand billion m³ of brackish groundwater water. The depth of the reservoir varies between 200 m in the west to more than 1000 m in the east. Deeper wells can provide water at 50 to 60 °C temperature, 100 to 400 L/ s flow rate and average TDS (total dissolved solids) of 2g/ L.

Mahmoudi et al., (2010) in a recent report proposed the application of geothermal sources to power a brackish water greenhouse desalination system for the development of arid and relatively cold regions, using Algeria as a case study (Figure 6a). He noted that countries which have abundant sea/ brackish water resources and good geothermal conditions are ideal candidates for producing fresh water from sea/ brackish water. The establishment of human habitats in these arid areas strongly depends on availability of fresh water. Geothermal resources can both be used to heat the greenhouses and to provide fresh water needed for irrigation of the crops cultivated inside the greenhouses.

University of Queensland's Geothermal Energy Center's director Hal Gurgenci was quoted as saying that geothermal-powered desalination systems could be a boon for small towns facing water shortage (Wash Technology, 2009). He went on to state that this is a clever combination where desalination is coupled with an agricultural function which is both cost-efficient and environmentally-friendly. Gurgenci said that while some of the geothermal resources may not be hot enough for power generation, they would be a perfect fit for thermal desalination of underground brackish aquifers. Studies indicate that for plants in the range of one to 100 megalitres (megalitre is one million liters) per day, thermal desalination technologies are more suitable than reverse osmosis especially if there is a cheap and abundant supply of heat. Geothermal heat can be used to heat and to humidify a greenhouse and produce fresh water at the same time.

The innovative idea of a seawater greenhouse was originally developed by Seawater Greenhouse Ltd in 1991 (Paton and Davies, 1996; Sablani et al., 2003). The first pilot was built and tested in the Canary Island of Tenerife in 1992, once known as the 'Garden of the Gods', but now arid and gravely damaged by excessive abstraction of ground water (Paton and Davies, 1996). The early results showed were promising and demonstrated the possibility to develop the technology in other arid regions. A modified and improved novel seawater greenhouse was constructed on Al-Aryam Island, Abu Dhabi, United Arab Emirates in 2000 (Davies and Paton, 2005). For both pilot studies the production of crops was excellent, and fresh water was successfully produced for the greenhouse irrigation proposes. In 2004 Seawater Greenhouse Ltd in collaboration with Sultan Qaboos University built a new pilot Seawater Greenhouse near Muscat, Oman (Figure. 6b) (Mahmoudi et al, 2008). The aim of the project was to demonstrate the technology to local farmers and organizations in the Arabian Gulf.

The brackish water is pumped and filtered from a well and sent into a ground heat exchanger where it absorbs heat from a geothermal fluid. This heat exchanger can be built of polyethylene to conserve costs. The heated brackish water is then fed in a cascade to the first evaporator then to the second evaporator. The brine can be circulated in the circuit several times until its concentration increases over an acceptable dissolved salt concentration. The concentrated brine is finally collected in a tank, where it is stored for later treatment or processing or reinjection. The evaporator is the entire front wall of the greenhouse structure. It consists of a cardboard honeycomb lattice and faces the prevailing wind. Hot brackish water trickles down over this lattice, heating and humidifying the ambient cooler air passing through into the planting area and contributing to the heating of the greenhouse. Fans draw the air through the greenhouse. Air passes through a second evaporator and is further humidified to saturation point. Air leaving the evaporator is nearly saturated and passes over the passive cooling system with a condenser (IC) immersed in a water basin. The fresh water condensing from the humid air is piped for irrigation or other purposes. This design can be scaled up to provide 10-20 kL/ day while also helping greenhouse plant growing.

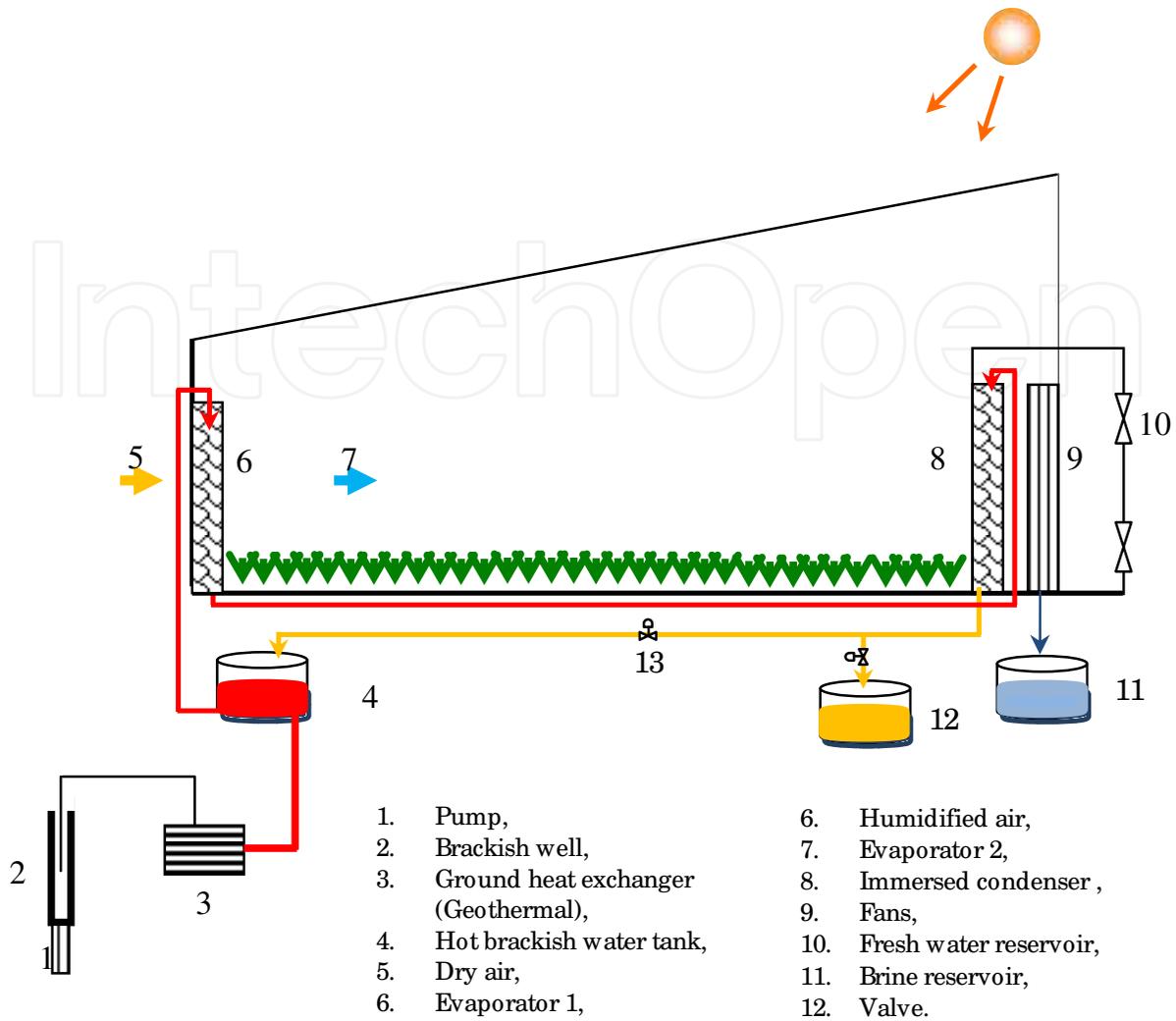


Fig. 6. Top (a): Process schematic for Brackish Water Greenhouse coupled to geothermal system (Mahmoudi et al., 2010). Greenhouse cover is normally plastic sheeting and the feed water to the pump is either brackish groundwater or sea water from a beach well; Bottom (b): The Seawater Greenhouse at Al-Hail, Muscat, Oman (Mahmoudi, 2008).

3.2 Seawater greenhouse development for the Arabian Gulf

A key feature in improving overall efficiency is the need to gain a better understanding of the thermodynamics of the processes and how the designs can be made more efficient. Goosen et al. (2003) determined the influence of greenhouse-related parameters on a desalination process that combines fresh water production with the growth of crops in a greenhouse. A thermodynamic model was used based on heat and mass balances. A software program developed by Light Works Limited, England was used to model thermodynamic analysis of the humidification/ dehumidification Seawater Greenhouse system. The computer program consisted of several modules: Seapipe, Airflow, Evaporator 1, Roof, Planting Area, Evaporator 2, Condenser (air/ water heat exchanger) (Figure 6a.).

Weather data for the year 1995 obtained from the Meteorological Office situated at Muscat, Sultanate of Oman, were used. The software needs a weather data file and a bathymetric (seawater temperature) file. These are specific to a location. The file contained transient data on solar radiation on a horizontal surface, dry bulb temperature and relative humidity of air, wind speed and wind direction. The bathymetric file contained temperature of the seawater at distance along the sea bed from the coast. The software program predicts the inside air conditions and water production for a given configuration/ dimension of the greenhouse, and weather and bathymetric data. The program allows many parameters to be varied. These variables can be grouped into following categories: Greenhouse (i.e. dimension of the greenhouse, and its orientation, roof transparency of each layer, height of front and rear evaporative pads, height of the planting area, condenser); Seawater pipe; Air exchange. Three parameters i.e. dimension of the greenhouse, roof transparency and height of the front evaporator were taken as variables. These parameters were varied as follows: Dimensions of Greenhouse (width x length): Area was kept constant at 10^4 m^2 ; 50 x 200, 80 x 125, 100 x 100, 125 x 80 and 200m x 50m; Roof Transparency 0.63 x 0.63 and 0.77 x 0.77; Height of the Front Evaporator 3 and 4m. The parameters kept constant were: Height of Planting Area = 4m; Height of the Rear Evaporator = 2m; Height of the Condenser = 2m, Orientation of Greenhouse = 40° N ; Seawater pipe diameter = 0.9m, length = 5000m; Volumetric flow = $0.1 \text{ m}^3/\text{s}$; Pit depth = -3m, height = 7.5m, wall thickness = 0.1m; Air change = 0.15 (fraction)/ min; Fin spacing = 0.0025m and depth = 0.1506m.

Three climatic scenarios were considered. In the *temperate version* the temperature in the growing area is cool and the humidity high. This version is suited to lettuces, French beans, carrots, spinach, tomatoes, strawberries and tree saplings, for example. In the *tropical version* the temperature in the growing area is warm and the humidity very high. Examples of suitable crops include aubergines, cucumbers, melons, pineapples, avocados, peppers and pineapple. The design is similar to that of the temperate version, but the airflow is lower. The *oasis version* allows for a diversity of crops. This version is separated into temperate and tropical sections of equal area. The areas covered by these Greenhouses were 1080 m^2 (Temperate and Tropical) and 1530 m^2 (Oasis).

The overall water production rate increased from 65 to $100 \text{ m}^3 \cdot \text{d}^{-1}$ when the width to length ratio increased from 0.25 to 4.00. Similarly the overall energy consumption rate decreased from 4.0 to $1.4 \text{ kW} \cdot \text{h} \cdot \text{m}^{-3}$ when the width to length ratio increased from 0.25 to 4.00. Analyses showed that the dimensions of the greenhouse (i.e. width to length ratio) had the greatest overall effect on water production and energy consumption. The overall effects of roof transparency and evaporator height on water production were not significant. It was possible for a wide shallow greenhouse, 200 m wide by 50 m deep with an evaporator height of 2 m, to give $125 \text{ m}^3 \cdot \text{d}^{-1}$ of fresh water. This was greater than a factor of two

compared to the worst-case scenario with the same overall planting area (50 m wide by 200 m deep) and same evaporator height, which gave $58 \text{ m}^3 \cdot \text{d}^{-1}$. For the same specific cases, low power consumption went hand-in-hand with high efficiency. The wide shallow greenhouse consumed $1.16 \text{ kW} \cdot \text{h} \cdot \text{m}^{-3}$, while the narrow deep structure consumed $5.02 \text{ kW} \cdot \text{h} \cdot \text{m}^{-3}$.

While the Tropical version produced water most efficiently (i.e. lowest power consumption), it also produced the smallest surplus of water over that transpired by the crop inside. In this case the fan and pumps are run at their lowest rate to maintain high temperatures and humidity while still producing water in all conditions. Total fresh water production for the three climate scenarios was also calculated. One year's detailed meteorological data from Seeb Airport, Muscat was entered into the model to test the performance sensitivity for the various designs. The model results predicted that the Seawater Greenhouse would perform efficiently throughout the year, but with measurable variations in performance between the alternative versions. For example, the water production rate and energy efficiency results from the simulations using optimized and constant values for fan and pump speeds showed that the *temperate scenario* had almost double the water production rate per hectare compared to the *tropical scenario* (i.e. $20,370 \text{ m}^3 / \text{hectare}$ compared to $11,574 \text{ m}^3 / \text{hectare}$) while the power consumption for the former was only slightly higher (i.e. 1.9 and $1.6 \text{ kWh} / \text{m}^3$, respectively).

3.3 Water desalination with renewable energies in Baja Peninsula Mexico

In Mexico, specifically in the arid region of Baja California, there is not only an abundance of traditional renewable resources like sun and wind but also hot springs, tidal currents and tidal amplitudes of over six meters in the upper part of the Gulf of California (Alcocer et al., 2008). The National University of Mexico (UNAM) assessed the extent of these renewable resources and looked at ways to use them for desalinating sea water. It was established that at only 50 m depth, very high temperatures could be obtained, sufficient for use in binary geothermal power plants to generate electricity for desalination. It was also found that the amount of electrical power that could be generated with tidal storage and from deep sea hydrothermal vents was of the order of several thousands of MW. Many locations with hot sea water were discovered (Figure 7), the best being at Los Cabos. As soon as the water table was reached, a temperature of 85°C was found at 50 meters from the sea shore. Alcocer et al., (2008) went on to claim that to have sea water at 90°C is a real advantage for thermal desalination; because this suggests temperatures around 150°C as one drills deeper.

Using satellite imagery, hundreds of anomalous "hot spots", where large amounts of hot water reach the surface through geological fractures, were identified. The information was corroborated by measuring the water temperature directly in the field, and obtaining samples of the water to determine its isotopic composition and to better understand its origin. Although some of these hot springs and wells were on-shore, many were under-sea, close to the coast and at very shallow depths. The most important of these shallow, hot sea-water vents were near Puertecitos, Bahia Conception and Ensenada. In those cases field measurements and sampling required some diving. Each hot spring was different; some had high amounts of dissolved gases; others had lower salinity than the surrounding sea water; others had high sulfur content. This information was very valuable for the group in charge of designing the thermal desalinating equipment where the availability and the quality of the hot sea water were very important.

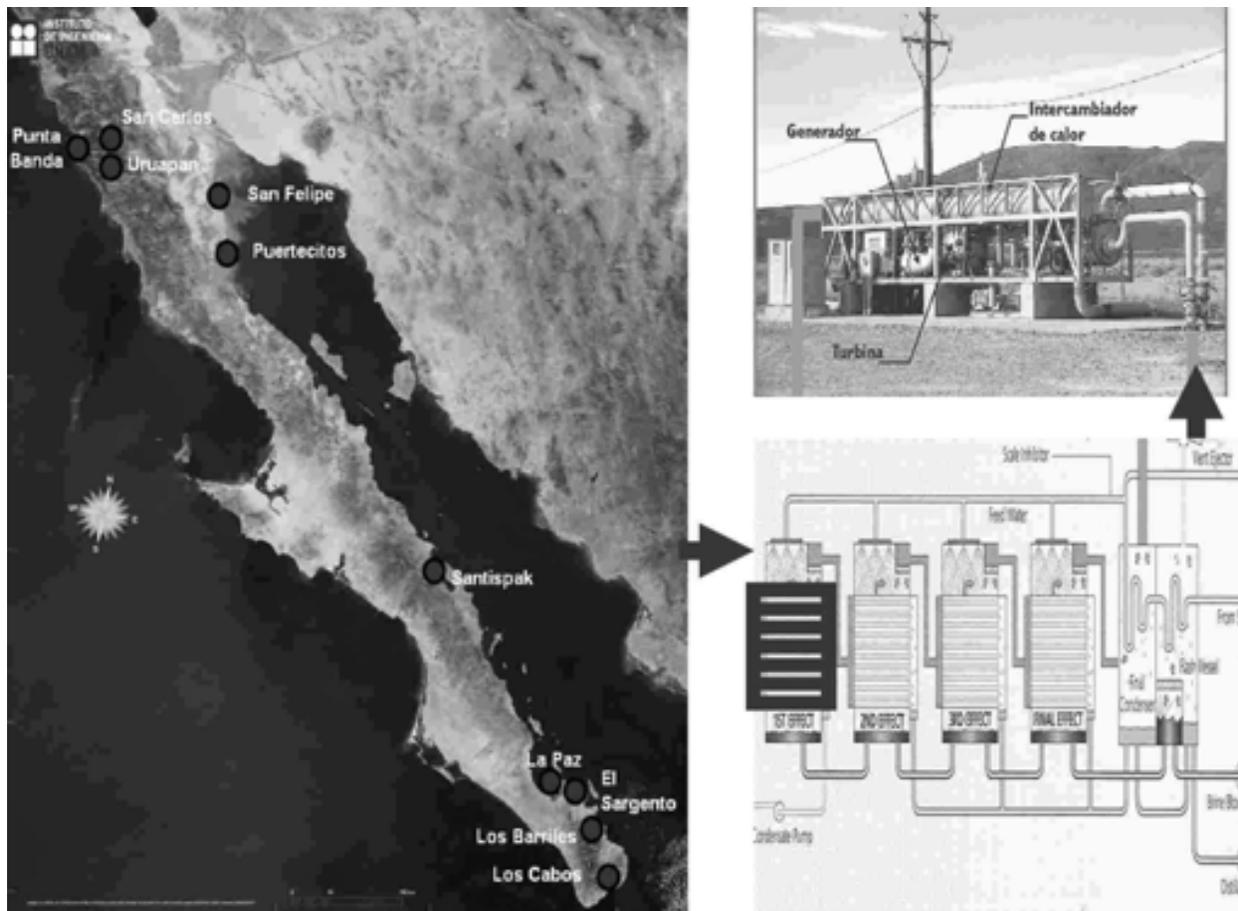


Fig. 7. *Left*: Locations with hot sea water at 50 m depths in the Baja Peninsula in Mexico (dots on map) with the Pacific Ocean on western side and the Gulf of California on the eastern side (Alcocer and Hiriart, 2008). *Lower right*: Schematic of multiple effects boiling/ distillation (MEB) (or flashing) thermal desalination system with first effect highlighted in red. *Upper right*: Actual boiling or flashing effect (highlighted in black in previous schematic). (See also Table 2 for further information about MEB)

Hot water was used in a heat exchanger to heat clean seawater and then to decrease the pressure to produce instantaneous evaporation in a multistage set of chambers (Figure 7). The innovation introduced in the design was the use of hot sea-water to heat all the chambers, not just the first one as in a conventional Multi-Stage Flash (MSF) plant. The innovation can be considered as a combination of Multi-Effect Distillation/ Boiling (MED or MEB) and Multi-Stage Flash (MSF), called “Multi-Flash with Heaters” (MFWH). Preliminary results indicated that for an initial temperature of 150°C, 4m³ of sea water were required to produce 1m³ of desalinated water. At an initial temperature of 80°C, 14 m³ were required. For additional information on this topic see Rodriguez et al. (1996).

3.4 The Kwinana desalinationp and wind farm in Perth, Western Australia

A larger scale seawater reverse osmosis (SWRO) plant located in Perth at Kwinana, with a capacity of 140,000 m³/ d, is the largest plant worldwide using renewable energy (BlurbWire 2010; Pankratz, 2008). The energy demand of the plant is 3.5 KWh/ m³ (185 GWh/ a) which is met by wind energy. The plant’s total energy consumption is offset by energy production from an 82 MW wind farm (Figure 8) with an expected power output of 272 GWh/ a. The

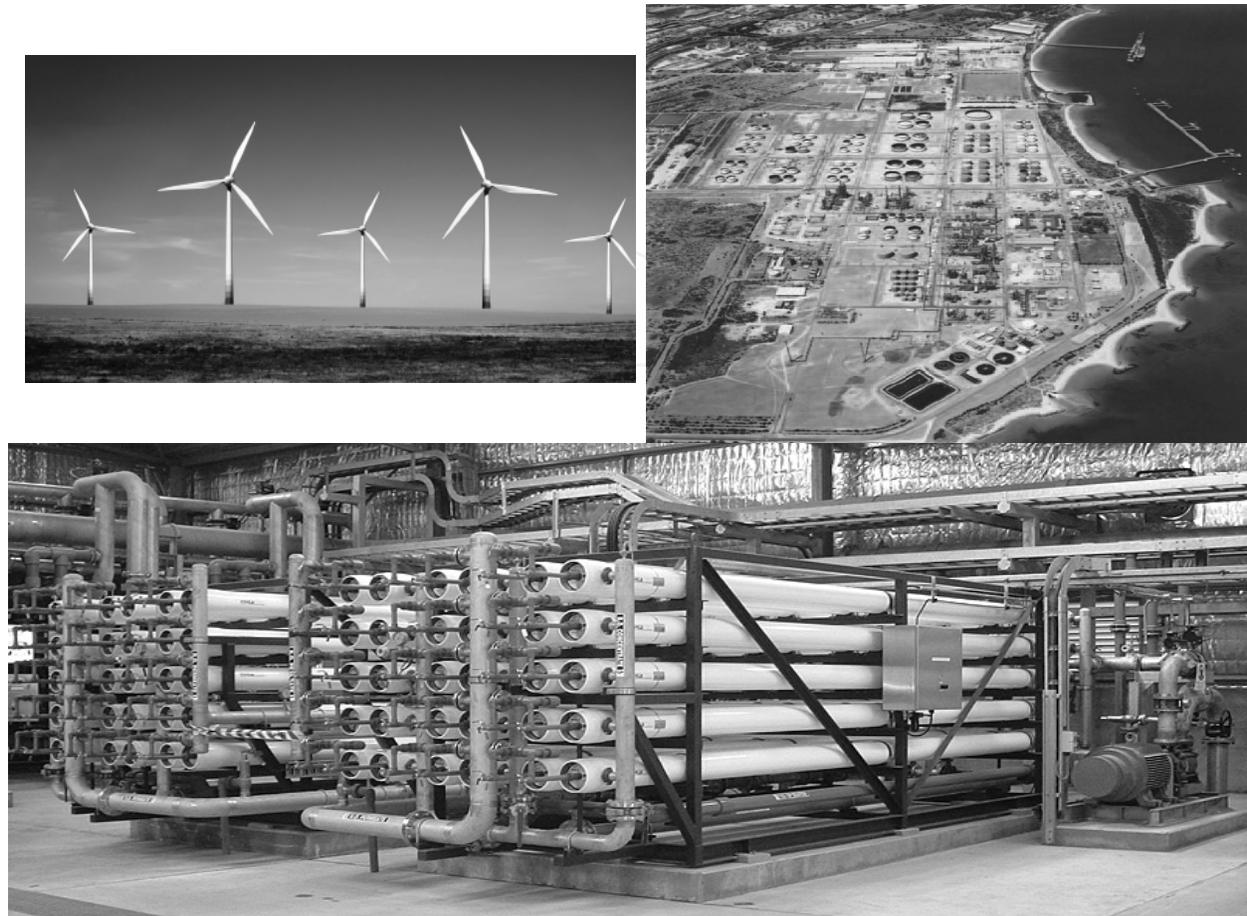


Fig. 8. The Kwinana Seawater Reverse Osmosis Desalination (SWRO) Plant and Wind Farm in Perth, Western Australia . 8a (*Upper Left*) The SWRO Plant seaside location in Perth; 8b (*Upper Right*) The Emu Downs Wind Farm consisting of 48 Vestas wind turbines each with 1.65 MW generating capacity; 8c (*Lower*) The desalination plant, with 12 SWRO trains with a capacity of 160 megalitres per day and six BWRO trains delivering a final product of 144 megalitres per day. (Pankratz, 2008).

plant will be run continuously generating a constant base load electricity demand (Water Corporation, 2002). The reverse osmosis plant was the first of its kind in Australia and covers several acres in an industrial park near the suburb of Kwinana. The Wind Farm is a joint development between Stanwell Corporation and Griffin Energy. Construction of the project commenced in November 2005, and the project was commissioned in October 2006. Emu Downs Wind Farm consists of 48 Vestas wind turbines each with 1.65 MW generating capacity, a substation, interconnection to the main 132 kV electricity grid, administration and stores buildings, and a network of access roads. The wind farm is close to the coast, with a good quality wind resource that has increased wind speeds and reliability aligning with periods for peak power demand. Emu Downs Wind Farm is accredited under the Australian Government's Renewable Energy Electricity Act 2000 and as a Green Power Generator by the Sustainable Energy Development Authority. The wind farm contributes 270 GWh/ year into the general power grid, offsetting the 180 GWh/ year requirement from the desalination plant. The desalination plant, with 12 SWRO trains with a capacity of 160 megalitres per day and six BWRO trains delivering a final product of 144 megalitres per

day, will have one of the world's lowest specific energy consumptions, due in part to the use of pressure exchanger energy recovery devices. The devices are isobaric chamber types which recover energy in the brine stream and deliver it to water going to the membrane feed at a net transfer efficiency at up to 98%. As a condition of its continued operation the Perth plant has a comprehensive environmental monitoring program, measuring the seawater intake and brine outfall. Excess water from the plant is stored in the hills dams.

3.5 Desalination using nuclear energy in Kazakhstan, India and Japan

The feasibility of integrated nuclear desalination plants has been proven with over 150 reactor-years of experience, chiefly in Kazakhstan, India and Japan (Stock Trading, 2010; Khamis, 2009; Misra, 2010). Large-scale deployment of nuclear desalination on a commercial basis will depend primarily on economic factors. Indicative costs are US\$ 70-90 cents per cubic metre, much the same as fossil-fuelled plants in the same areas. One obvious strategy is to use power reactors which run at full capacity, but with all the electricity applied to meeting grid load when that is high and part of it to drive pumps for RO desalination when the grid demand is low. The BN-350 fast reactor at Aktau, in Kazakhstan, successfully supplied up to 135 MWe of electric power while producing 80,000 m³/ day of potable water over some 27 years, about 60% of its power being used for heat and desalination (Kadyrzhanov et al., 2007). In Japan, some ten desalination facilities linked to pressurised water reactors operating for electricity production have yielded 1000-3000 m³/ day each of potable water, and over 100 reactor-years of experience have accrued. MSF was initially employed, but MED and RO have been found more efficient there. The water is used for the reactors' own cooling systems. India has been engaged in desalination research since the 1970s. In 2002 a demonstration plant coupled to twin 170 MWe nuclear power reactors (PHWR) was set up at the Madras Atomic Power Station, Kalpakkam, in southeast India. This hybrid Nuclear Desalination Demonstration Project comprises a reverse osmosis (RO) unit with 1800 m³/ day capacity and a multi-stage flash (MSF) plant unit of 4500 m³/ day costing about 25% more, plus a recently-added barge-mounted RO unit. They incur a 4 MWe loss in power from the plant. In 2009 a 10,200 m³/ day MVC plant was set up at Kudankulam to supply fresh water for the new plant. It has four stages in each of four streams. An RO plant there supplies the plant's township. China Guangdong Nuclear Power has commissioned a 10,080 m³/ day desalination plant at its new Hongyanhe project at Dalian in the northeast. Much relevant experience comes from nuclear plants in Russia, Eastern Europe and Canada where district heating is a by-product. Large-scale deployment of nuclear desalination on a commercial basis will depend primarily on economic factors. The UN's International Atomic Energy Agency (IAEA) is fostering research and collaboration on the issue.

4. Environmental considerations and sustainability

Desalination of sea and brackish water requires large quantities of energy which normally results in a significant environmental impact if fossil fuels are used (e.g. CO₂ and SO₂ emissions, thermal pollution of seawater). The operating cost of different desalination techniques is also very closely linked to the price of energy. This makes the use of renewable energies associated with the growth of desalination technologies very attractive. Let us take a closer look at the environmental impacts that must be considered during utilization of geothermal resources as outlined by Rybach (2007), Lund (2007); Kagel, et al., (2005) and

Fridleifsson, et al. (2008). These include emission of harmful gases, noise pollution, water use and quality, land use, and impact on natural phenomena, as well as on wildlife and vegetation. The environmental advantages of renewable energy can be seen when comparing, for instance, a coal-fired power plant to a geothermal power plant; the former produces about 25 times as much carbon dioxide (CO₂) and sulfur dioxide (SO₂) emissions per MWh (i.e. 994kg vs. up to 40kg for CO₂, 4.71kg vs. up to 0.16kg for SO₂, respectively) (Lund, 2007; Fridleifsson, et al., 2008). However, in a geothermal power plant hydrogen sulfide (H₂S) also needs to be routinely treated and converted to elemental sulfur since about 0.08kg H₂S may be produced per MWh electricity generated. We can argue that this is still much better than oil-fired power plants and natural gas fired plants which produce 814 kg and 550 kg of H₂S per MWh, respectively.

Binary power plants and direct-use projects normally do not produce any pollutants, as the water is injected back into the ground after use without exposing it to the atmosphere. We can argue that the ready availability of inexpensive oil and natural gas reserves in such areas of the world as the Arabian Gulf may reduce the need for using renewable energy for desalination. However, looking at this more closely we see that this is non-sustainable since fossil fuels are non-renewable, and with a continually growing population there is an ever increasing demand on the use of fossil fuels for desalination. Take Saudi Arabia as a specific example; in 2008 total petroleum (i.e. oil and gas) production was 10.8 million bbl/ d with internal oil consumption at 2.4 million bbl/ d (i.e. about 25% of the total production) (U. S. Energy Information Administration, 2010). Most of the internal consumption was used for electricity generation and water desalination. The population is expected to increase from 30 million in 2010 to approximately 100 million by 2050 (U.S. Census Bureau, 2004). It has been estimated that by then 50% of the fossil fuel production will be used internally in the country for seawater desalination in order to provide fresh water for the people. This will reduce the state's income, increase pollution and is clearly non-sustainable. There are also concerns about the resulting political instability which could arise due to these effects (Cristo and Kovaleik, 2008). A possible solution to the environmental and sustainability problems is the increased use of renewable, including nuclear, energy sources for desalination (Lund, 2006, 2007; Fridleifsson, et al., 2008; Stock Trading, 2010)

5. Market potential, process selection and risk management

Kalogirou (2005) in a thorough study reviewed 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 renewable energy 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 seemed to be more promising in terms of economic and technological feasibility than others. However, their applicability strongly depended on the local availability of renewable energy resources and the quality of water to be desalinated. Kalogirou (2005) argued that the most popular combination of technologies is multiple effect boiling (MEB) with thermal collectors (Figure 9a) and reverse osmosis with photo voltaics (PV). PV is particularly good for small applications in sunny areas (Figure 9b). For large units, wind energy was reported to be more attractive as it requires less space than solar collectors. With distillation processes, large sizes were more

attractive due to the relatively high heat losses elements in determining water costs when water is produced from desalination plants.

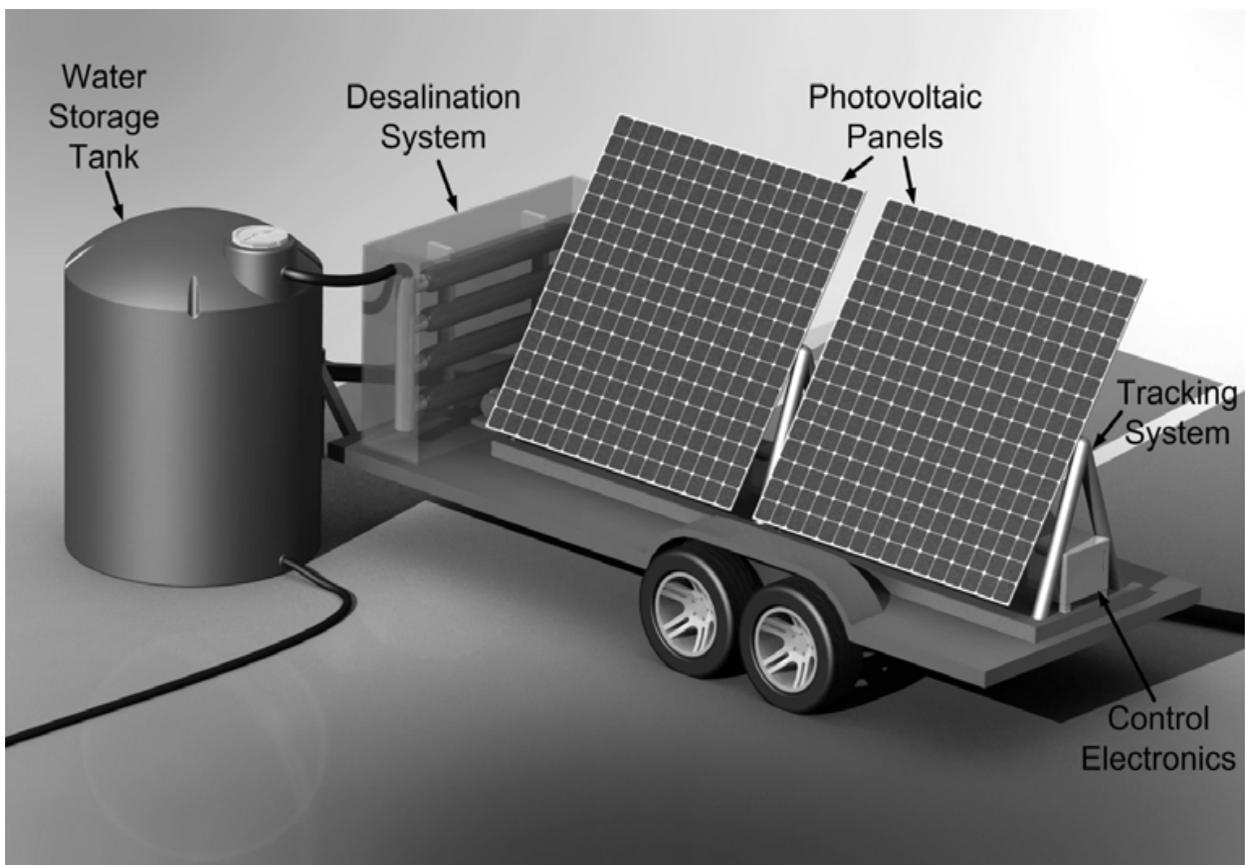
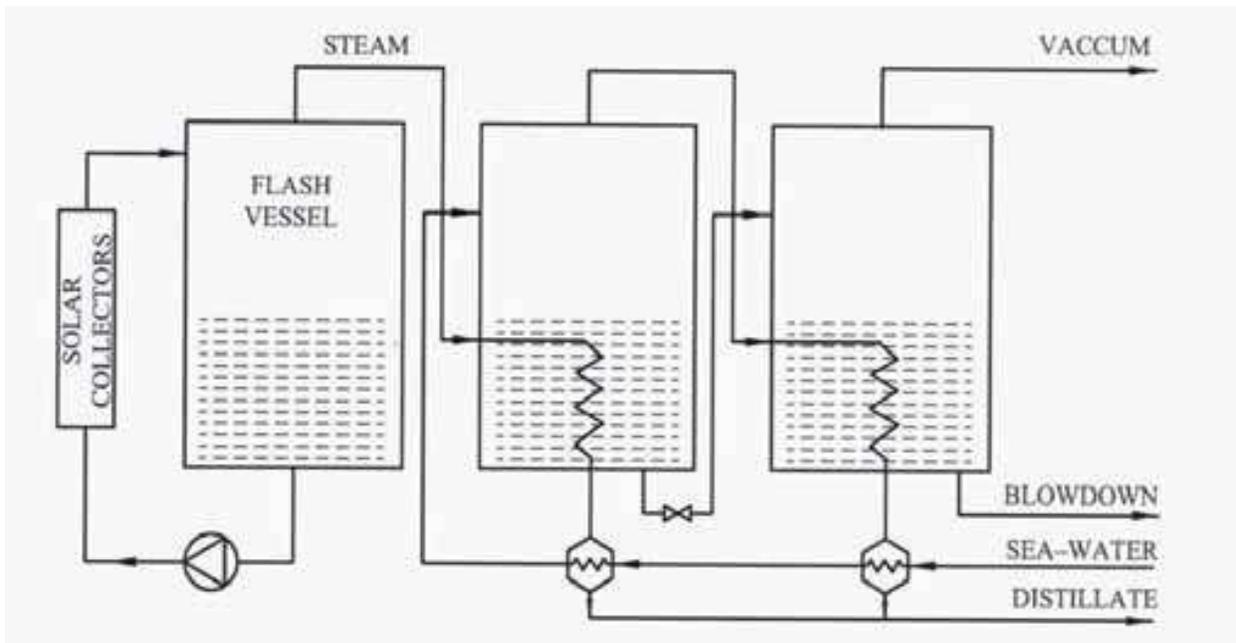


Fig. 9. a. (Top) Schematic of a multiple effect boiler (MEB) (Kalogirou (2005). 9b. (Bottom) A simple mobile solar powered reverse osmosis system (Dubowsky, 2010).

Many factors enter into the capital and operating costs for desalination: capacity and type of plants, plant location, feed water, labor, energy, financing, concentrate disposal, and plant reliability (USBR, 2003). For example, the price of desalted seawater is about 3 to 5 times the cost of desalting brackish water from the same size plant, due primarily to the higher salt content of the former. In any state or district, the economics of using desalination is not just the number of dollars per cubic meter of fresh water produced, but the cost of desalted water versus the other alternatives (e.g. superior water management by reducing consumption and improving water transportation). In many arid areas, the cost of alternative sources of water (i.e. groundwater, lakes and rivers) is already very high and often above the cost of desalting. Any economic evaluation of the total cost of water delivered to a customer must include all the costs involved. This includes the costs for environmental protection (such as brine or concentrate disposal), and losses in the storage and distribution system. The capital and operating costs for desalination plants have tended to decrease over the years due primary to improvements in technical efficiency (Reif, 2008). At the same time that desalting costs have been decreasing, the price of obtaining and treating water from conventional sources has tended to increase because of the increased levels of treatment being required to meet more stringent water quality standards. This rise in cost for conventionally treated water also is the result of an increased demand for water, leading to the need to develop more expensive conventional supplies, since the readily accessible water sources have already been used up.

Reif (2008) performed a profitability analysis and risk management of geothermal projects being implemented in Bavaria Germany. Reif's study concluded that the sensitive response of the project's rate of return to changes in the parameters of their computer simulations made it clear that geothermal projects are financially risky. For instance, every project faced the usual business risks, such as budget over-runs, increases in interest rates, and delays. Project management was used to limit these risks. It was recommended that the initiators of a plan must run profitability simulations in order to analyze varying scenarios before implementing the project. The results needed to be updated as the project progressed. Reif (2008) argued that reserves must always be planned for in the financing. In addition, business risks could also be limited by suitable structuring of the contracts with the partners in the project (e.g. drilling companies, power-plant supplier, and civil-engineering companies).

6. Concluding remarks

Water scarcity is an increasing problem around the world and there is a consensus that seawater desalination can help to alleviate this situation. Among the energy sources suitable to drive desalination processes, solar, wind, wave and geothermal energy, in addition to nuclear energy, are the most promising options, due to the ability to couple the availability of energy with water demand supply requirements in many world locations.

The cost for conventional desalination can be significant because of its intensive use of energy. However, the selection of a specific process should depend on a careful study of site conditions and the application at hand. Local circumstances will always play a significant role in determining the most appropriate process for an area. The best desalination system should be more than economically reasonable in the study stage. It should work when it is installed and continue to work and deliver suitable amounts of fresh water at the expected quantity, quality, and cost for the life of a project. Seawater desalination in itself is an

expensive process, but the inclusion of renewable energy sources and the adaptation of desalination technologies to renewable energy supplies can in some cases be a particularly less expensive and economic way of providing water. The utilization of conventional energy sources and desalination technologies, notably in conjunction with cogeneration plants, is still more cost effective than solutions based on only renewable energies and, thus, is generally the first choice.

In closing, the world's water demands are rising considerably. Much research has been directed at addressing the challenges in using renewable energy to meet the power needs for desalination plants. Renewable energy technologies are rapidly emerging with the promise of economic and environmental viability for desalination. There is a need to accelerate the development of novel water production systems from renewable energies. These technologies will help to minimize environmental concerns. Our investigation has shown that there is great potential for the use of renewable energy in many parts of the world. Solar, wind, wave, geothermal and even nuclear sources could provide a viable source of energy to power both seawater and the brackish water desalination plants. Finally, it must be noted that part of the solution to the world's water shortage is not only to produce more water, but also to do it in an environmentally sustainable way and to use less of it. This is a challenge that we should well be able to meet.

7. References

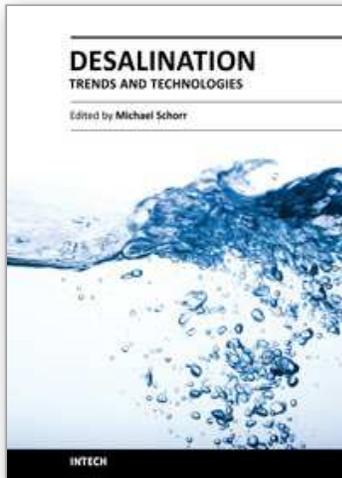
- Alcocer, S. M. and Hiriart G. (2008). An applied research program on water desalination with renewable energies. *Am. J Environ. Sci.*, 4, 3, 204-211
- Al-Hallaj, S.; Farid, M. M. and Tamimi, A. R. (1998). Solar desalination with a humidification-dehumidification cycle: performance of the unit. *Desalination*, 120, 273-280
- BlurbWire (2010). Kiwana desalination plant (http://www.blurbwire.com/topics/Kwinana_Desalination_Plant) (accessed 8 August 2010)
- Bouhekima B. (2003). A small solar desalination plant for the production of drinking water in remote arid areas of southern Algeria. *Desalination*, 159, 197-204
- Bourouni K.; Martin R. and Tadrist, L. (1999a). The International Workshop on Desalination Technologies for Small and Medium Size Plants With Limited Environmental Impact, Rome, Italy (03/ 12/ 1998), vol. 122, no 2-3, pp. 301-313
- Bourouni K.; Martin R.; Tadrist L. and Chaibi M.T. (1999b). Heat transfer and evaporation in geothermal desalination units, *Applied Energy*, 64, 1, 129-147
- Bourouni, K. and Chaibi M. T. (2005). Application of geothermal energy for brackish water desalination in the south of Tunisia. *Proceedings World Geothermal Congress*, Antalya, Turkey, 24-29 April
- Bourouni K.; Chaibi M. T. And Tadrist, L. (2001). Water desalination by humidification and dehumidification of air: state of the art. *Desalination*, 137, 167-176
- Burgess, G. and Lovegrove, K. (2005). Solar thermal powered desalination: membrane versus distillation technologies (online: solar-thermal.anu.edu.au/wp-content/uploads/DesalANZSES05.pdf) (accessed 14 August 2010)
- Cataldi, R., S. Hodgson and J. Lund (editors), 1999. *Stories from a Heated Earth – Our Geothermal Heritage*, Geothermal Resources Council, Davis, CA, 569 p.

- Chapa, J (2007) Wave energy: Aquabuoy 2.0 (<http://www.inhabitat.com/2007/10/08/wave-energy-aquabuoy-20-wave-power-generator/>) (accessed 16 August 2010)
- Charcosset, C. (2009). A review of membrane processes and renewable energies for desalination. *Desalination*, 245, 214–231
- Childs, W. D.; Dabiri, A. E.; Al-Hinai, H. A. and Abdullah, H. A. (1999) VARI-RO solar powered desalting study. *Desalination*, 125, 155-166
- Cristo, M. W. and Kovalcik, M. P. (2008). Population pressure and the future of Saudi state stability. Master of Science Thesis, Naval Postgraduate School, Monterey CA, December, 77pp.
- Davies P.A. and Paton C. (2005). The seawater greenhouse in the United Arab Emirates: Thermal modelling and evaluation of design options. *Desalination*, 173,103-111
- Davies, P.A. (2005) Wave-powered desalination: resource assessment and review of technology, *Desalination*, 186, 97–109
- Drude, B. C. (1967). Submarine units for reverse osmosis, *Desalination*, 2, 325–328
- Dubowsky, S.; Wiesman, R.; Bilton, A.; Kelley, L. and Heller, R. (2010). Smart power and water for challenging environments. MIT current projects (<http://robots.mit.edu/projects/KFUPM/index.html>) (accessed 20 August 2010)
- Eltawil, M. A.; Zhengminga, Z. and Yuana, L. (2009). A review of renewable energy technologies integrated with desalination systems. *Renewable and Sustainable Energy Reviews*. 13, 9, 2245-2262
- Fahrenbruch, A. and Bube, R. H. (1983). *Fundamentals of solar Cells*. Academic Press, Orlando FL, USA. 559pg
- Fath, M. E. S. (1998). Solar desalination: A promising alternative for water provision with free energy, simple technology and a clean environment. *Desalination*, 116, 45-56
- Fekraoui A. and Kedaid F. (2005). Geothermal resources and uses in Algeria: A country update report. *Proceedings World Geothermal Congress 2005*, Antalya, Turkey, 24-29 April.
- Fernández J. L. and Norberto Chargoy N. (1990). Multistage, indirectly heated solar still. *Solar Energy*, 44, 4, 215-223
- Fridleifsson, I. B.; Bertani, R.; Huenges, E.; Lund, J. W.; Ragnarsson, A. and Rybach, L. (2008). The possible role and contribution of geothermal energy to the mitigation of climate change. In: *IPCC Scoping Meeting on Renewable Energy Sources, Proceedings*, O. Hohmeyer and T. Trittin (Eds.) Luebeck, Germany, 20-25 January, 59-80
- Glueckstern, P. (1982). Preliminary considerations of combining a large reverse osmosis plant with the Mediterranean–Dead Sea project, *Desalination*, 40, 143–156
- Goosen M. F. A. and Shayya W. (1999). Water management, purification and conservation in arid climates. In: *Water Management, Purification and Conservation in Arid Climates: Volume I Water Management*. M. F. A. Goosen and W. H. Shayya (EDS.), Technomic Publishing Co., Lancaster, Pennsylvania, 1-6
- Goosen, M. F. A.; Sablani, S.; Shayya, W. H.; Paton, C. and Al-Hinai, H. (2000). Thermodynamic and economic considerations in solar desalination”, *Desalination*, 129, 63-89
- Goosen, M. F. A.; Sablani, S.; Paton, C.; Perret, J.; Al-Nuaimi, A.; Haffar, J.; Al-Hinai, H. and Shayya, W. (2003). Solar energy desalination for arid coastal regions: development of a humidification-dehumidification seawater greenhouse, *Solar Energy*, 75, 413-419

- Goosen, M. F. A.; Mahmoudi, H. and Ghaffour, N. (2010). Water desalination using geothermal Energy. *Energies*, 3, 1423-1442
- Houcine, I.; Benjemaa, F.; Chahbani, M. H. and Maalej, M. (1999) Renewable energy sources for water desalting in Tunisia. *Desalination*, 125, 1-3, 123-32
- Huang, S. and Liu, J. (2010). Geothermal energy stuck between a rock and a hot place, *Nature*, 463, 293
- International Desalination Association (IDA) Conference (2008). 360 Environmental Presentation, Gran Canaria, 2007 & Environmental Management Consultants Newsletter, Perth, 2008 (<http://www.360environmental.com.au/>).
- Kadyrzhanov, K. K.; Lukashenko, S. N. and Lushchenko, V. N. (2007). Assessment of environmental impact of reactor facilities in Khazakstan. In: *Safety Related Issues of Spent Nuclear Fuel Storage*, J. D. B. Lambert and K. K. Kadyrzhanov (Eds), Springer. (<http://www.springerlink.com/content/64270j0u525166u5/>) (accessed 10 August 2010)
- Kagel, A.; Bates, D. and Gawell, K. (2005). *A guide to geothermal energy and the environment*, Geothermal Energy Association, Washington, D. C., 75 p.
- Kalogirou S. (2005). Seawater desalination using renewable energy sources. *Progress in Energy and Combustion Science*; 31, 242-281
- Kedaid, F. Z. (2007). Database on the geothermal resources of Algeria. *Geothermics*, 36, 3, 265-275
- Khamis, I. (2009). A global overview on nuclear desalination. *Int. J of Nuclear Desalination*, 3, 4, 311-328
- Koschikowski, J. and Heijman, B. (2008). Renewable energy drives desalination processes in remote or arid regions. *Membrane Technology*, 8, August, 8-9
- Laboy, E.; Schaffner, F.; Abdelhadi, A. And Goosen, M.F.A. (Eds), (2009). *Environmental Management, Sustainable Development & Human Health*, Taylor & Frances (Balkema NDL) London. 35 Chapt, 594 pp ISBN: 978-0-415-46963-0
- Lu, H.; Walton, J. C. and Swift, A. H. P. (2000). Zero discharge desalination. *Int Desalination Water Reuse Q*, 10, 3, 35-43
- Lund, J. W. (2006). Chena Hot Springs, *Geo-Heat Center Quarterly Bulletin*, 27, 3 (September), Klamath Falls, OR, 2-4
- Lund, J. W. (2007). Characteristics, development and utilization of geothermal resources, *GHC Bulletin*, June, 1-9
- Magagna, D. and Muller, G. (2009). A wave energy driven RO stand-alone desalination system: initial design and testing. *Desalination and Water Treatment*, 7, 47-52
- Mahmoudi, H.; Spahis, N.; Goosen, M.F.A.; Ghaffour, N.; Drouiche N. and Ouagued, A. (2010). Application of geothermal energy for heating and fresh water production in a brackish water greenhouse desalination unit: A case study from Algeria, *J Renew Sustain Energy Rev*, 14, 1, 512-517
- Mahmoudi, H.; Spahis, N.; Goosen, M.F.A.; Sablani, S.; Abdul-Wahab, S.; Ghaffour, N. and Drouiche, N. (2009a). Assessment of wind energy to power solar brackish water greenhouse desalination units: A case study from Algeria. *J Renew Sustain Energy Rev*, doi:10.1016/j.rser.2009.03.001
- Mahmoudi, H.; Ouagued, A. and Ghaffour, N. (2009b). Capacity building strategies and policy for desalination using renewable energies in Algeria, *J Renew Sustain Energy Rev*; 13, 921-926

- Mahmoudi, H. ; Abdul-Wahab, S. A.; Goosen, M. F. A. ; Sablani, S. S. ; Perret, J and Ouagued, A. (2008). Weather data and analysis of hybrid photovoltaic–wind power generation systems adapted to a seawater greenhouse desalination unit designed for arid coastal countries, *Desalination*, 222, 119–27
- Misra, B. M. (2010). Sustainable desalination technologies for the future. *Int. J of Nuclear Desalination*, 4, 1, 37-48
- Ophir, A. (1982). Desalination plant using low grade geothermal heat, *Desalination*, 40, 125–32
- Pacienti, P.; de Gerloni, M.; Reali, M.; Chiaramonti, D.; Gärtner, G. O.; Helm, P. and Stöhr, M. (1999). Submarine seawater reverse osmosis desalination system, *Desalination*, 126, 213–218
- Pankratz, T. (2008). Water desalination report (WDR), *MEDRC Workshop*, Muscat (www.waterdesalreport.com)
- Paton, C. and Davies, A. (1996). The seawater greenhouse for arid lands. *Proc. Mediterranean Conference on Renewable Energy Sources for Water Production*, Santorini, Greece, 10–12 June
- Popiel, C.; Wojtkowiak, J and Biernacka, B. (2001). Measurements of temperature distribution in ground. *Exp Thermal Fluid Sci*, 25, 301–9
- Reali, M.; de Gerloni, M. and Sampaolo, A. (1997). Submarine and underground reverse osmosis schemes for energy-efficient seawater desalination, *Desalination*, 109, 269–275
- Reif, T. 2008 Profitability analysis and risk management of geothermal projects, *GHC Bulletin*, January, 1-4
- Rodriguez, G.; Rodriguez, M., Perez, J and Veza, J (1996). 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, 20–5
- Rybach, L. (2007). Geothermal sustainability, *Proceedings European Geothermal Congress*, Unterhaching, Germany, 5 p.
- Sablani, S.; Goosen, M. F. A.; Paton, C.; Shayya, W. H. and Al-Hinai, H. (2003). Simulation of fresh water production using a humidification–dehumidification Seawater Greenhouse. *Desalination*, 159, 283–288
- Sadhwani, J. J. and Veza, J. M. (2008). Desalination and energy consumption in Canary Islands, *Desalination* 221, 143–150
- Schwarzer K., Vieira M.E., Faber C. and Müller C. (2001) *Solar thermal desalination system with heat recovery*. *Desalination*, 137 (1-3), 23-29.
- Serpen, U.; Aksoy, N. and Öngür, T. 2010. 2010 present status of geothermal energy in Turkey, *Proceedings of Thirty-Fifth Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, 1-3 February SGP-TR-188
- Soerensen, B. (1979). *Renewable Energy*. London: Academic Press.
- Stefansson, V. (2005). World geothermal assessment. *Proceedings of the World Geothermal Congress*, Antalya, Turkey, 24-29 April (<http://iga.igg.cnr.it>)
- Stock Trading (2010). How quickly will Saudi Arabia turn to nuclear vitality? (July 3rd, 2010 by admin) (<http://www.profitablenicheinnovation.com/trading/day->

- trading/ stock-trading-how-quickly-will-saudi-arabia-turn-to-nuclear-vitality)
(accessed on 27 July 2010)
- Szacsvay, T.; Hofer-Noser, P. and Posnansky, M. (1999). Technical and economic aspects of small-scale solar-pond-powered seawater desalination systems. *Desalination*, 122, 185–93
- Tester, J. W.; Anderson, B. J.; Batchelor, A. S.; Blackwell, D. D.; DiPippo, R.; Drake, E. M.; Garnish, J.; Livesay, B.; Moore, M. C.; Nichols, K.; Petty, S.; Toksoz, M. N.; Veatch, R. W.; Baria, R.; Augustine, C.; Murphy, E.; Negraru, P. and Richards, M. (2007). Impact of enhanced geothermal systems on U. S. energy supply in the twenty-first century, *Phil Trans R Soc A*, 365, 1057-1094
(http://www1.eere.energy.gov/geothermal/future_geothermal.html) ISBN: 9780615134383
- Tzen, E.; Theofiloyianakos, D and Karamanis, K. (2004). Design and development of a hybrid autonomous system for seawater desalination. *Desalination*, 166, 267–274
- USBR (U.S. Bureau of Reclamation) (2003). Cost estimating procedures. In *Desalting Handbook for Planners*, 3rd ed.; Desalination and Water Purification Research and Development Program Report No. 72; United States Department of Interior, Bureau of Reclamation, Technical Service Center, US Government Printing Office: Washington DC, USA, Chapter 9, pp. 187–231
- U.S. Census Bureau, (2004). Table A-4 Population by Region and Country 1950-2050, (<http://www.census.gov/prod/2004pubs/wp-02.pdf>)
- U. S. Energy Information Administration/ International/ Country Briefs/ Saudi Arabia (2010). (http://www.eia.doe.gov/cabs/Saudi_Arabia/Profile.html) (Accessed 27 July 2010)
- Wash Technology, (2009). Geothermal desalination: hot rocks key to producing low cost fresh water. 9 December
- Water Corporation (2002) Perth Metropolitan Desalination Proposal, Perth
- White, D. E. and Williams, D. L. (Eds.), (1975). Assessment of geothermal resources of the United States – 1975, U.S. Geological Survey Circular 727, U.S., Government Printing Office, 155 p.
- Wright, J. D. (1982) Selection of a working fluid for an organic Rankine cycle coupled to a salt-gradient solar pond by direct-contact heat exchange, *J Sol. Energy Eng.*, 104, 4, 286–293
- Wright, M. (1998). *Nature of Geothermal Resources*, in *Geothermal Direct-Use Engineering and Design Guidebook*, John W. Lund, (Ed), Geo-Heat Center, Klamath Falls, OR, 27-69



Desalination, Trends and Technologies

Edited by Michael Schorr

ISBN 978-953-307-311-8

Hard cover, 334 pages

Publisher InTech

Published online 28, February, 2011

Published in print edition February, 2011

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

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Mattheus Goosen, Hacene Mahmoudi, Noredine Ghaffour and Shyam S. Sablani (2011). Application of Renewable Energies for Water Desalination, Desalination, Trends and Technologies, Michael Schorr (Ed.), ISBN: 978-953-307-311-8, InTech, Available from: <http://www.intechopen.com/books/desalination-trends-and-technologies/application-of-renewable-energies-for-water-desalination>

INTECH
open science | open minds

InTech Europe

University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia

InTech China

Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元

www.intechopen.com

Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

Phone: +86-21-62489820
Fax: +86-21-62489821

IntechOpen

IntechOpen

© 2011 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the [Creative Commons Attribution-NonCommercial-ShareAlike-3.0 License](#), which permits use, distribution and reproduction for non-commercial purposes, provided the original is properly cited and derivative works building on this content are distributed under the same license.

IntechOpen

IntechOpen