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Renewable energy desalination: performance analysis and operating data of existing RES desalination plants

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ABSTRACT

During the last decades, several small autonomous brackish or seawater desalination units driven by renewable energy sources (RES) have been developed within EU and non-EU projects around the world. A significant number of these units were designed, developed, and operated by research centers/universities, in collaboration with companies working in the field of RES and desalination, in their own premises (laboratories) in order to investigate the reliability and performance of the technologies matching in small-scale and autonomous operations. Some systems were also developed for the supply of fresh water to remote areas, and particularly to cover the needs of small villages or communities. Few renewable energy desalination units were installed by RES/desalination market stakeholders as already commercially available products. The present work aims at analyzing the story and operation of selected RES desalination units, representative of a larger number of systems operating all around the world at present. The advantages and disadvantages of the technologies matching, problems encountered, and their solutions, costs, units' performance as well as the progress of market-available RES desalination packages will also be presented.

Keywords: RES desalination; Performance parameters; Lessons learnt; RES desalination market

1. Introduction

Worldwide, several renewable energy sources (RES) desalination pilot plants have been installed and the majority has been in operation successfully. Virtually, all of them are custom designed for specific locations and utilize solar, wind or geothermal energy to produce fresh water from seawater (SW) or brackish water (BW) resources.

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As it concerns the type of energy adopted, RE desalination technologies mainly fall into two categories. The first category includes evaporative desalination technologies driven by thermal energy provided by solar collectors or geothermal wells, while the second includes mechanically or electrically driven processes, which basically consists of reverse osmosis (RO) and electrodialysis (ED) membrane processes powered either by photovoltaic, wind or other minor RES sources. Evaporative processes with mechanical vapor compression (MVC) couple the concept of evaporative processes with the requirement of mechanical energy for powering the mechanical compression, being suitable for the coupling with PV or wind energy (WT).

Numerous combinations such as photovoltaic units (PV) with RO plants, WT with RO, electrodialysis (ED or EDR), and solar thermal distillation plants have been in operation, most of them within research programmes. Several scientific publications on the matching of the two technologies exist and a lot of work has been done, in particular, from research centers (Fig. 1). Many of these combinations may not be viable under certain circumstances, but they are included in the researcher's assessment [1].

In the last decade, there has been also a significant growth of novel technologies, such as solar membrane distillation (MD) and solar humidification/de-humidification (H/DH). In these processes, the driving force is not a difference in hydrostatic pressure at the two sides of a dense, hydrophilic membrane like in RO, but a difference in vapor pressure at the two sides of a micro-porous, hydrophobic membrane or between two chambers, physically or virtually separated, where the evaporation/condensation processes takes place. Therefore, the process is typically triggered by a temperature difference between a hot and a cold zone of the module, with hot feed temperatures typically ranging from 60 to 90°C, and low temperature heat sources, like solar energy, are suitable for the process. Harvesting solar energy is not free, though, and the high investment required for the power supply constitutes one of the main barriers for the installation of solar MD and H/DH plants [3]. Thanks to the support of EU within FP5 and FP7 programmes, a great research work has been, and is being, done by researchers in order to make these technologies more efficient and economically affordable, focusing, in particular, in the capacity range of 0.1–10 m^3/d.

However, at present and according to the author's available data, the matching of PV RO for seawater and BW desalination is still the most popular technology. Fig. 2 provides the share of the RES desalination matching, regarding the installed small-scale stand-alone applications around the world.

It is worth mentioning that also a small number of RES desalination units were installed from 2010 to 2013 as commercial products to cover the needs of areas characterized by lack of fresh water and electricity grid (Figs. 3–5).

2. Description of the most adopted RE desalination technologies

A renewable energy driven desalination plant can be designed to operate, coupled to the grid and off-grid (stand-alone or autonomous). The matching of the desalination process to a renewable energy source

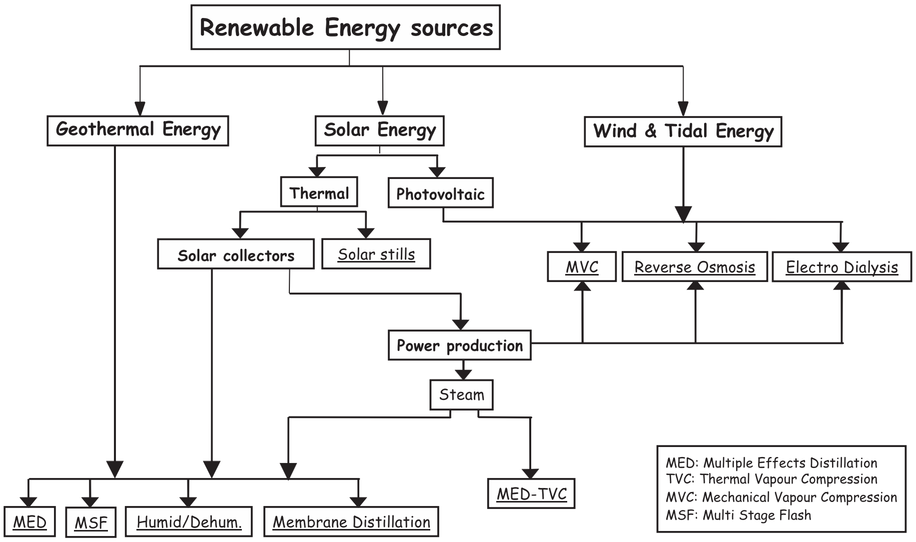

Fig. 1. Possible technology matching between most important RES and desalination processes [2].

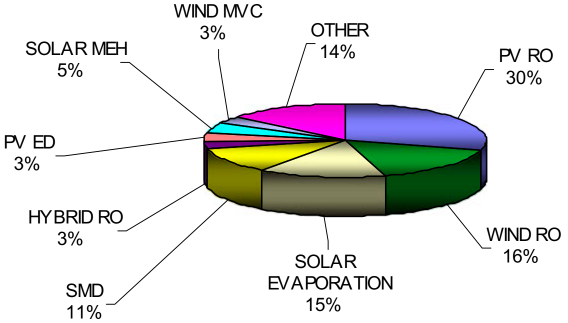

Fig. 2. Share of the stand-alone RES DES installations for seawater and BW desalination (as a percentage of the total installations).
Source: CRES.

Fig. 3. 8 m^3/d SWRO unit in Strogili island, Greece.
Source: PHOTOVOLTAIC, Greece [4].

Fig. 4. 20 kWp PV unit, Strogili island, Greece.
Source: PHOTOVOLTAIC, Greece [4].

Fig. 5. View of the inverters, Strogili island, Greece.
Source: PHOTOVOLTAIC, Greece [4].

is fairly complex, especially regarding autonomous operation, which often involves the adoption of energy storage devices or the implementation of integrated energetic schemes for cogeneration of energy and water from different RES [1,5,6].

In general, desalination systems were traditionally designed to operate with a constant power input; but, unpredictable and non-steady power input forces the desalination plant to operate in sub-optimal conditions. According to CRES data, around 150 stand-alone RES desalination have been installed around the world for brackish and seawater desalination, most of which use energy storage systems to provide stable power to the desalination load. RES desalination systems operating under variable power conditions have not yet proven their performance and economic advantage.

Where the system is grid connected, the desalination plant can operate continuously as a conventional plant and the renewable energy source merely acts as a fuel substitute. Where no electricity grid is available, autonomous systems have to be developed which allow the intermittent nature of the renewable energy source. The latter case poses the problem of renewable energy variability because most energy systems lack an inherent energy storage mechanism.

A short description of the most adopted technologies matching and examples of stand-alone applications are presented below.

2.1. Solar desalination

Indirect use of solar energy by means of solar thermal systems and photovoltaics (PVs) in tandem with desalination seems to be the most applicable technology, opening the room for a large number of different technology couplings, as illustrated in Fig. 6. On the other side, direct use of solar energy for desalination, as in solar stills, is the oldest, simplest, and most widely used method in arid and remote areas when very small quantities of drinking water are needed [7].

2.1.1. Photovoltaic reverse osmosis

RO is a membrane separation process, in which the water from a pressurized saline solution is separated from the solutes (the dissolved salts) by forcing it to flow through a semi-permeable membrane. The amount of desalinated water that can be obtained (recovery ratio) ranges between 30 and 75% of the volume of the feed water, depending on the initial water quality, the quality of the product needed, and the technology and membranes adopted.

No heating or phase change is necessary for this separation. The major energy input for desalting is required for pressurizing the feed water (the saline feed water is pumped into a closed vessel where it is pressurized against the membrane).

Theoretically, the only energy requirement is to pump the feed water at a pressure above the osmotic pressure. In practice, higher pressures must be used, typically 9–17 bar for BW and from 55 to 80 bar for seawater desalination, in order to have a sufficient amount of water passing through the membrane.

Since, the only power requirement is electrical energy, (for feed water pumping, dosing/filter pumps, permeate water pump, high-pressure pump), the RO technology can be easily driven by wind (WT) and/or photovoltaic (PV) systems. A typical stand-alone PV system consists of PV modules, charge controller(s), battery bank, and inverters(s).

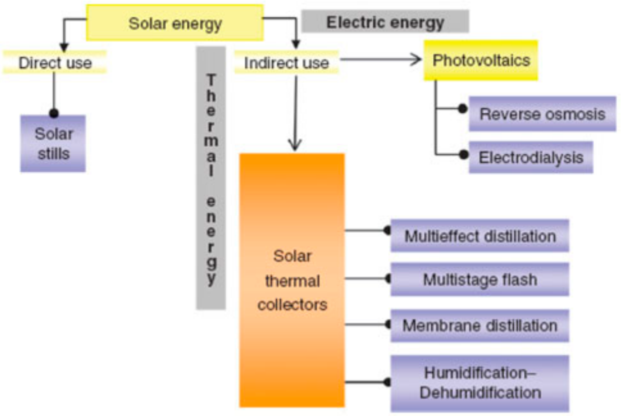

Fig. 6. Solar energy-desalination matching [7].

The main advantages in the coupling of PV with desalination units are the ability to develop reliable and efficient small-scale desalination plants, the limited maintenance cost of PV panels, as well as easy transportation and installation. Moreover, the ability to use energy recovery devices (ERDs) and high efficient pumps for the operation of the RO units reduces significantly the energy requirements even in small scales. Special care should be given to the design of these systems and especially to the selection of high-pressure pumps/ERDs, for sizes in the range of 20–100 m^3/d. The balance between the initial cost and the energy consumption (running costs) during the units' operation is of vital importance. For instance, a unit of 20 m^3/d for seawater desalination without an ERD has an estimated specific energy consumption of around 7 kWh/m^3, while with ERD (reverse running pump) the specific energy consumption will be reduced to about 5 kWh/m^3. With the use of the ERD the initial cost will increase, but the running cost regarding the energy consumption will be less.

Based on the literature information, the unit water cost from already installed PV or PV/Wind (Hybrid) seawater (SW) or BW RO systems of small scale ranges between 2 and 10 €/m^3 (Table 1) [8]. As it is obvious, the cost of PV SWRO is higher, mostly due to the higher energy requirements. In general, the unit water cost from RES desalination units is site-specific and is highly depended on RES potential, system design, availability of energy storage and storage autonomy, availability of ERD, etc. Moreover, it should be mentioned that costs provided in the literature do not commonly include detailed analysis of all cost items, in particular those concerning the O&M (including, most importantly, the replacement cost of modules, batteries, etc. as well as the manpower), so it is not possible to have a rigorous and realistic view of the cost of all the RES desalination installations.

According to the market, photovoltaic panels, energy storage systems and inverters have decreased their prices significantly. However, the energy storage is still a subject under investigation regarding the cost and the environmental aspects mainly for units with a water capacity of more than 10 m^3/d.

During the last decade, the perceived unit water cost for both, BW and SWRO, has obtained a substantial decrease mostly due to the availability of more efficient and less expensive equipment. For instance, according to studies conducted by the Instituto Tecnologico de Canarias (ITC), the cost of small PV SWRO units is estimated between 3 and 5 €/m^3, while for small PV BWRO is estimated at 2–4.5 €/m^3.

According to the available data, the largest and the most known stand-alone PV–RO seawater plant was

Table 1
PV, PV/Wind (Hybrid) RO applications

Installation	RES nominal power, KW	Nominal water capacity, m^3/h	Unit water cost, €/m^3
SWRO PV, Pozo Izquierdo (1998)	4.8 kWp PV	0.4	9
SWRO PV, Lampedusa (1990)	100 kWp PV	5	~6
BWRO Hybrid, Maagan (1997)	3.5 kWp PV, 600 W WG	0.4	~7
SWRO Hybrid CRES, Greece, (2001/2004)	4 kWp PV, 900 W WG	0.13	10
BWRO PV, CREST, UK (2003)	1.54 kWp PV	0.5	2
SWRO PV, Pozo Izquierdo (2004)	5.6 kWp PV (solar tracking)	1.33	3–5

installed in 1990 in Lampedusa Island (Italy). The plant has been characterized by successful operation, providing freshwater at a reasonable cost (around 6 €/m^3). The RO unit consists of two units with a total water production capacity of 5 m^3/h. The power supply system consists of 100 kWp PV arrays, 2 × 2,000 Ah at 220 V(DC)—880 kWh batteries and inverters [9].

During the following years, several stand-alone units were installed around the world for seawater and BW desalination (Figs. 7–10). The size of the installed PV RO units ranges from few liters (50 l/d) to 100 m^3/d (Table 2).

2.1.2. Photovoltaic Electrodialysis

Electrodialysis (ED) is an electrochemical process and a low-cost method for the desalination of BW.

Due to the dependency of the energy consumption on the feed water salt concentration, the ED process is not yet economically attractive for the desalination of sea water. In electrodialysis process, ions are transported through selective cationic and anionic exchange membranes by means of an electrical field applied at the sides of a membrane pile. An ED plant consists of the following basic components (Fig. 11):


Fig. 7. View of a 20 m^3/d RO unit, Jordan Valley. Source: NERC.


Fig. 8. The installed 10.4 kWp PV system, Jordan Valley. Source: NERC.


Fig. 9. View of a 1 m^3/h RO unit installed in Morocco. Source: ITC.

Fig. 10. The installed 4 kWp PV system, Morocco.
Source: ITC.

(1) pre-treatment system
(2) membrane stack
(3) low pressure circulation pump
(4) power supply for direct current (rectifier)
(5) post-treatment

A modification to the basic electrodialysis process is the electrodialysis with polarity reversal (EDR). An EDR unit operates on the same general principle as a standard ED plant, except that both, the product and the brine channels, are identical in construction. In this process, the polarity of the electrodes changes periodically in time, reversing the flow through the membranes. Such procedure allows the minimization of membrane fouling generated by charged colloidal particles, thus allowing a very long life to the membranes and the unit itself. To avoid product contamination, immediately following the reversal of polarity and flow, the product water is dumped until the stack and lines are flushed out and the desired water quality is restored.

Electrodialysis process is mainly used for BW desalination since it is more economically attractive for the treatment of low salinity water. The major energy input is related to the direct current, used to force the passage of ionic species through the membranes within the stack.

In general, the total energy consumption, under ambient temperature conditions and assuming product water of 500 ppm TDS, would be between 1.5 and 4 kWh/m^3 for a feed water of 1,500 –3,500 ppm TDS, respectively. Additional pumping energy requirements as well as costs due to maintenance operations are low.

Electrodialysis units can be driven by a PV system or a Wind Turbine or a hybrid system (PV, Wind). A

Table 2
PV SWRO and BWRO applications [7]

Plant location	Water type	RO capacity	PV installed power	Commissioning year
El Hamrawein, Egypt	BW	10 m^3/h	~20 kWp	1986
Hassi-Khebi, Algeria	BW	0.95 m^3/h	2.6 kWp	1988
Univ. of Almeria, Spain	BW	2.5 m^3/h	23.5 kWp	1988
Lampedusa island, Italy	SW	3 + 2 m^3/h	100 kWp	1990
Lipari island, Italy	SW	2 m^3/h	63 kWp	1991
Sadous Riyadh Region, Saudi Arabia	BW	600 l/h	10.89 kWp	1994
St. Lucie, Florida	SW	0.6 m^3/d	2.7 kWp	1995
Gillen Bore, Australia	BW	1.2m^3/d	4.16 kWp	1996
Maagan Michel, Israel	BW	0.4 m^3/h	3.5 kWp PV, 0.6 kW W/T + 3 kW diesel	1997
Pozo Izquierdo, Gran Canaria island, DESSOL	SW	3–4 m^3/d	4.8 kWp	1998/2000
Sadous Village, Saudi Arabia	BW	600 l/h	10.08 kWp	2001
CREST, UK	SW	3 m^3/d	2.4 kWp	2001/02
CRES, Greece	SW	130 l/h	4 kWp PV, 1 kW W/T	2002
White Cliffs, New South Wales, Australia	BW	500 l/d	150 Wp	2003
Aqaba, Jordan	BW	3.4 m^3/h	16.8 kWp	2004
Ksar Ghilene, Tunisia, ADIRA Project	BW	2.1 m^3/h	10.5 kWp	2006
Benhsaine, Morocco, ADIRA	BW	1 m^3/h	4.8 kWp	2006/07
Msaim, Morocco, ADIRA Project	BW	1 m^3/h	3.9 kWp	2006/07

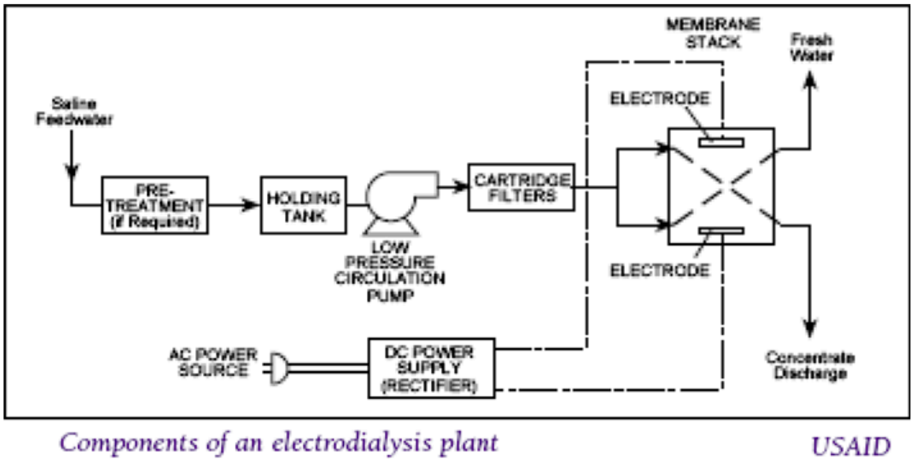

Fig. 11. Schematic diagram of an ED plant.
Source: ITC.

small number of PV EDR systems have been installed, in all cases for BW desalination (Fig. 12).

According to the available data, the water capacities of installed PV ED/EDR until today ranges from 1 m^3/d to about 200 m^3/d. A 98 m^3/d PV-EDR unit was tested at the ITC facilities under variable voltage operation [10].

2.1.3. Solar Thermal Distillation—MED

The MED process takes place in a series of vessels (effects) and uses the principles of condensation and evaporation at reduced ambient pressure in the various effects. This permits the seawater feed to evaporate without the need for supplying additional heat beyond the first effect.

In general, an evaporation effect consists of a vessel, a heat exchanger, and devices for transporting the various fluids between the effects. The feed seawater or brine in the MED process passes through a series of pre-heaters, and after passing through the last of these, it enters the top effect, where the heating steam raises its temperature to the saturation temperature at the effect's pressure. Further, amounts of steam, either from a solar collector system or from a conventional boiler, are used to produce evaporation in this effect. The vapor then goes, in a small part, to heat the incoming feed (in the pre-heaters) and, in a larger part, to provide the heat supply for the second effect, which operates at a lower pressure and receives its feed from the brine of the first effect. This process is repeated, all the way, through (down) the plant (see Fig. 13). Some pictures of the solar MED plant installed and operated at the Plataforma Solar de Almeria (Spain) are reported in Fig. 14.

The thermal energy requirements could be provided by solar collectors. A solar MED diagram is presented at Fig. 15.

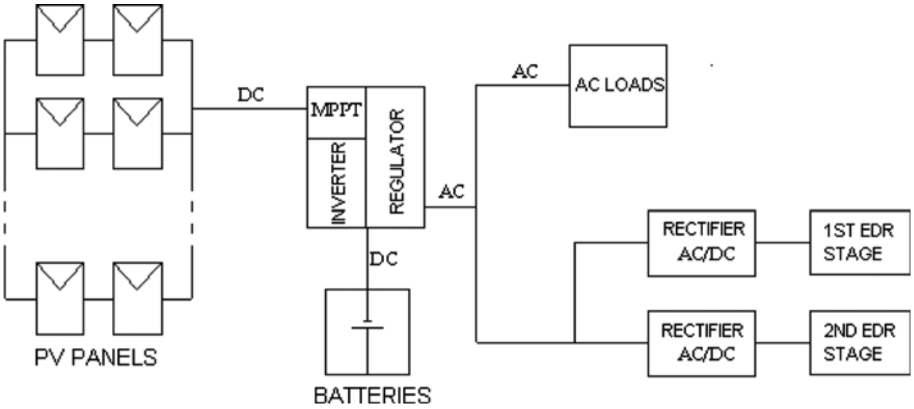

Fig. 12. Electrical scheme of a PV EDR system.
Source: ITC.

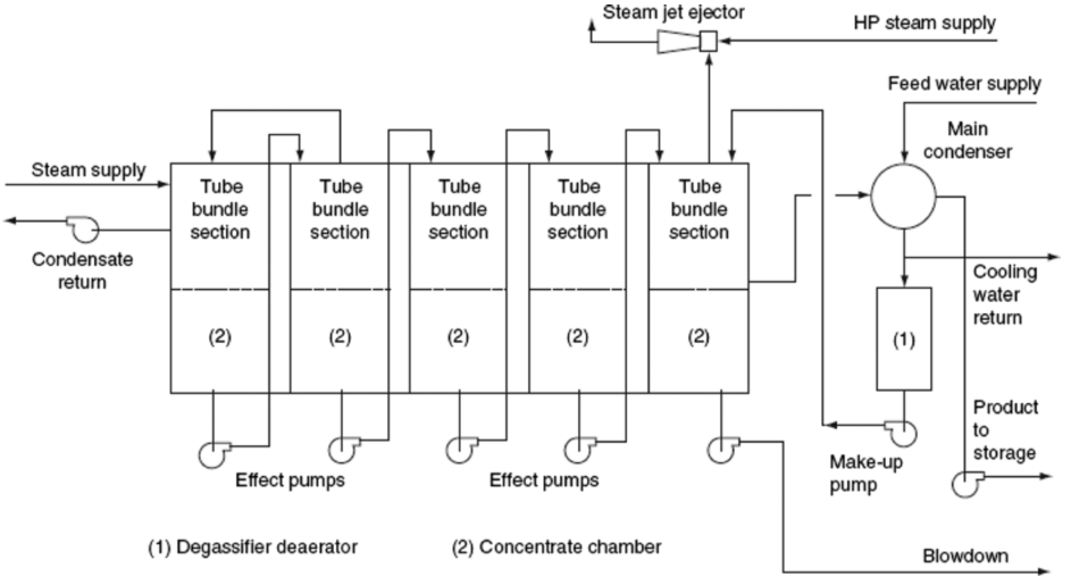

Fig. 13. Schematic representation of the MED process [11].

Fig. 14. View of the solar MED plant at PSA/CIEMAT and thermal storage tanks.

Moreover, for the needs of the circulation pumps, electric energy is required, which can be provided by a PV, Wind or conventional power source.

The temperature of the first (hottest) effect can vary from 70°C up to around 85°C depending on the design of the system. Based on data from existing applications, for small MED units the specific thermal energy consumption is around 60–75 kWh_{th}/m^3, while the specific electricity consumption for pumps operation is of 2–5 kWh/m^3.

According to the literature, several solar (solar thermal collectors, solar ponds) MED and, in general, distillation units have been installed around the world with a large range of water capacities, from few m^3 to 3,000 m^3/d. However, most MED units driven by solar thermal collectors ranged between water capacities of some m^3 to about 100 m^3/d.

The most known solar thermal MED plant is the Abu Dhabi Solar MED plant. The Abu Dhabi Solar MED plant is situated at the Umm Al Nar Power and Desalination Station about 20 miles east of Abu Dhabi city. The plant was commissioned in 1984. The plant was designed as a demonstration unit aimed at evaluating the technical and economic feasibility of using

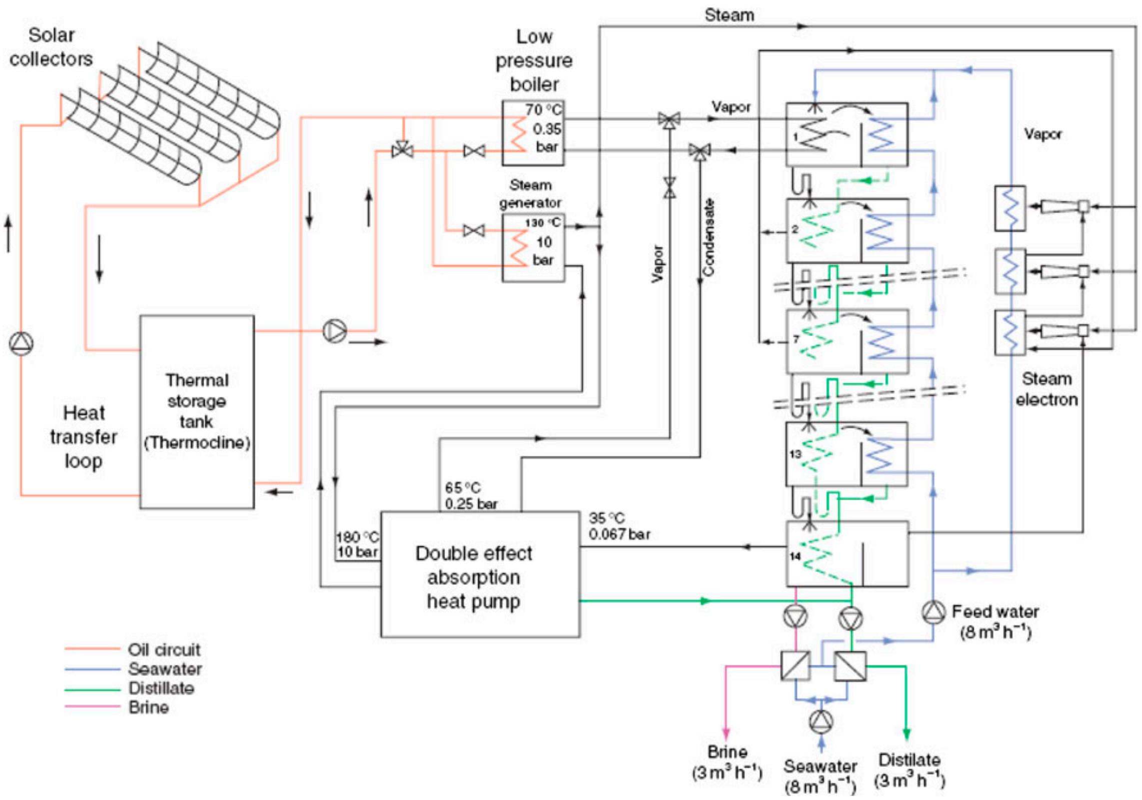

Fig. 15. Schematic diagram of the original solar MED plant at CIEMAT, Spain [7].

this type of technology to provide the remote coastal communities in UAE with freshwater. The seawater has a salinity of 55,000 ppm TDS.

A bank of evacuated-tube and flat-plate collectors with a total absorber area of 1,862 m^2 is used to provide the thermal energy required by a multiple-effect stack-type evaporator having a rated capacity of 80–120 m^3/d. The plant has been in operation for over 16 years. According to the literature after 16 years, the performance of the collector field and evaporator subsystems has not declined to any appreciable degree [7].

Another more advanced solar MED plant is operating at the Plataforma Solar de Almería (Spain) of the Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT). It is a forward-feed vertically stacked plant with 14 effects, manufactured by ENTROPIE in 1987 under the framework of a previous research project in which a parabolic-trough solar field was coupled with conventional MED unit, optimizing the overall heat consumption of the system by the incorporation of a double -effect absorption (LiBr-H2O) heat pump. The project lasted until 1994 [12]. Originally, the first effect was powered by low-pressure saturated steam (300 kg/h at 70℃, 0.31 bar). In 2005, during the AQUASOL project, it was replaced with a new stage able to work directly with hot water coming from a solar field made up of 252 stationary solar collectors, (CPC 1.12x made by Ao Sol), with a total area of approximately 500 m^2 arranged in four rows (35° tilt) of 63 collectors. With this new configuration, the thermal power of the MED unit is 150 kW, and the estimated distillate production capacity is 2.2 m^3/h with a performance ratio of 10 [13].

The MED plant is coupled to a double-effect absorption heat pump (DEAHP) manufactured by ENTROPIE in 2005, which uses a water/lithium bromide solution as working fluid with the two solution circuits connected in series. This DEAHP delivers 150 kW of thermal energy at 65℃ to the MED plant, which devaluates this energy along its 14 effects. The desalination process uses only 70 kW of the 150 kW, while the remaining 80 kW are recovered by the DEAHP at 35℃ and pumped to a usable temperature of 65℃. For this operation, the DEAHP needs only 70 kW of thermal power at 180℃. The MED plant feeds the steam produced in the last cell at 35℃ to the DEAHP evaporator, instead of condensing it with cold seawater in the final condenser of the MED unit, thus avoiding ,wasting this heat in the rejected cooling water.

Thermal energy supplied by the solar field is transferred to a thermal storage tank using water as working fluid. A gas-fired backup system is used to guarantee necessary operating conditions (absorption heat pump requires saturated steam at 180°C) and allow 24-h MED plant operation (necessary to reduce the impact of capital costs in the final water price). Operation and maintenance experience with the AQUASOL desalination system has proven this system to be highly reliable. The coupling of a DEAHP allowed increasing the performance ratio of the overall desalination system to 20.

Based on the available data, the unit water cost from solar MED systems can range from 3 to 7 €/m^3 for unit's capacity larger than 50 m^3/d. The cost of smaller units is much higher.

The capital cost of such systems is still high. According to the literature [7], the total cost (procurement, transportation, installation costs) of the Abu Dhabi Solar MED was around 2.000.0000 $. The cost of the evaporator was estimated to be around 2,500 $/($m^3$/d). Moreover, according to the market (2012 prices), the cost of smaller distillation units in the order 5–10 m^3/d water capacity is much higher and could reach 10.000,0 €/(m^3/d).

2.1.4. Solar MD

MD is a thermally driven process, which uses a hydrophobic and micro-porous membrane for the separation of vapor from aqueous solution. The driving force for the process is the trans-membrane vapor pressure difference, depending also on the temperature difference across the membrane. The vapor formed due to the vapor/liquid equilibrium at the membrane surface permeates through membrane pores, while the aqueous solution flowing parallel to the membrane cannot pass because of the high hydrophobicity of membranes adopted. Several examples of MD units have been so far developed [14,15] aiming at the generation of fresh water for small-scale applications and using heat as a main energy input. MD systems can differ for the vapor condensation strategy, the presence of internal heat integration for thermal energy efficiency increase and geometrical configuration of the module, going from plate and frame [16,17] to spiral wound [18,19], hollow fibers [20] and planar multi-stage arrangements [21]. Production capacity can vary from few 100 l/d up to several tens of m^3/d, although the number of large (above 10 m^3/d) MD installations is still very limited.

Energy requirements in MD systems range from 1 to 2 kWh_{el}/m^3 electrical/mechanical energy (required for feed circulating pumps and auxiliary units) and from 100 to 400 kWh_{th}/m^3 thermal energy (required for generating the partial evaporation of the feed stream), normally supplied in a low temperature range, i.e. 70–90°C. For such reason, MD is particularly suitable for the coupling with solar thermal collectors, geothermal sources or any type of low-temperature waste heat source, e.g. low-T energy discarded from CSP plants. Electric energy requirements can be satisfied either by adding a PV system (the variability of the energy source is, thus, similar for the two energy inputs, and stable operation of the RES unit are guaranteed when solar energy is available) or by grid connection.

Coupling schemes can vary, depending on the plant capacity and installation scenario [15,22]. For small capacities and maximum ease of operation a compact system coupling can be proposed, where solar energy is directly transferred into the feed stream by means of a corrosion-resistant solar collector (Fig. 16(a)). For larger capacities, or plant including an energy storage device, a two-loop system coupling scheme can be applied, where solar energy is collected and stored in a primary loop and then transferred to a secondary loop by a corrosion-resistant heat exchanger where the feed stream is heated before entering the MD module (Fig. 16(b)).

Thermal energy storage is possible for stable and continuous operations by means of thermocline storage tanks allowing the stratification of hot water in the higher part when solar energy surplus is available and using such stored sensible heat, when solar energy is missing.

Solar MD technology presents several advantages for small-scale applications, such as easy modularity, low-maintenance, easy operation and feasible coupling with low temperature heat sources. Different MD design can lead to better energetic performances in terms of lowering specific energy consumptions, but this turns out to increase the required membrane area. Thus, a proper trade-off has to be normally achieved during the system design, based on energy and membrane costs.

Most of the solar MD units are scaled from 0.1 to 10 m^3/d. Specific water cost can range from few euros up to 15 €/m^3, regardless of the feed water salinity (brackish or seawater), with larger costs relevant to smaller units. Fig. 17 reports some pictures of installed MD units.

2.1.5. Solar stills

Solar still desalination is a process in which the energy of the sun is directly used to evaporate freshwater from sea or BW. The process has been used for

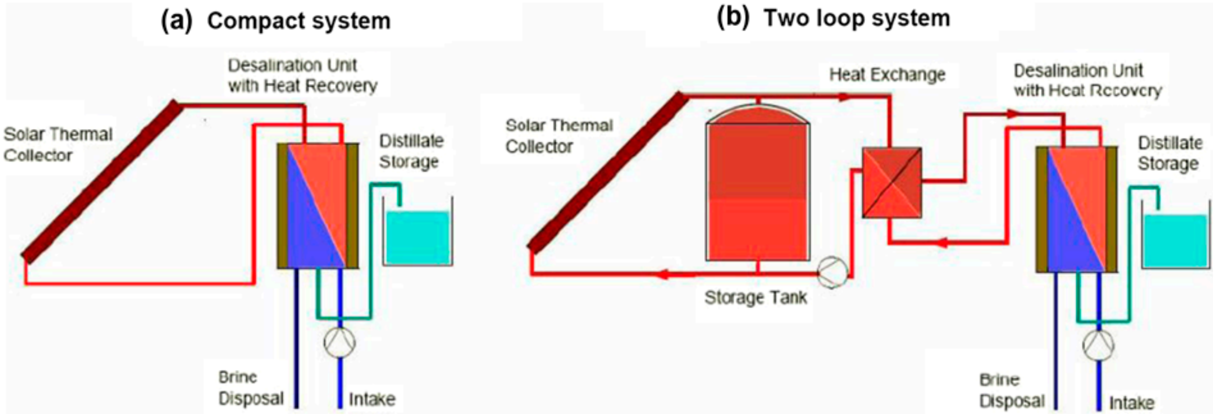

Fig. 16. Coupling schemes for a solar thermal powered MD system. (a) Compact system coupling; (b) two-loop system coupling [15].

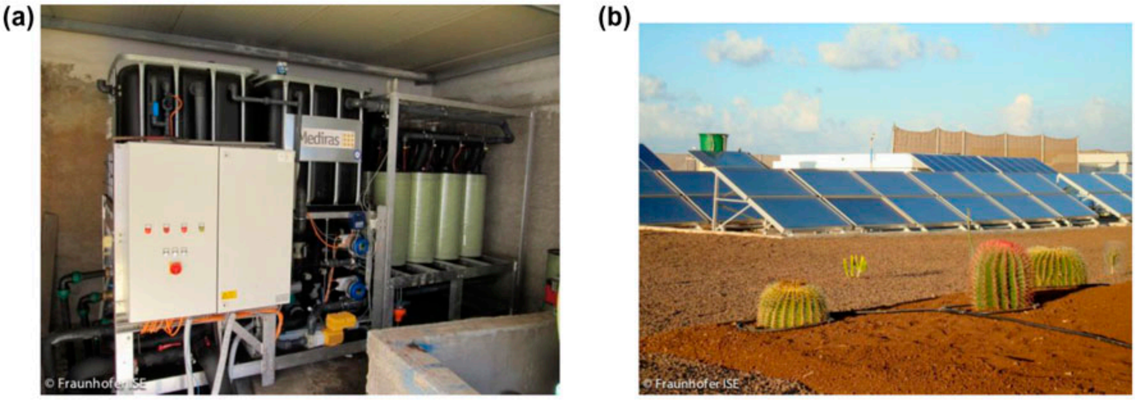

Fig. 17. (a) MD plant installed in Pantelleria (Italy) with a nominal capacity of 5 m^3/d, powered by a hybrid combination of solar energy and waste heat. (b) Solar collectors powering a 3.5 m^3/d MD unit in Gran Canaria (Spain).

many years, usually for small-scale applications. Solar stills are classified into two groups [14] in terms of energy supply: (1) passive or conventional and (2) active solar stills. The passive solar stills use solar energy as the only source of thermal energy. In active solar stills, extra thermal energy from a solar collector or any available waste heat is directed to the solar still for faster evaporation. Solar stills are the simplest devices that are used to obtain freshwater using solar energy as the sole energy supply. A solar still consists of a shallow basin with a transparent cover designed to act as a condenser (Fig. 18). Water in the basin is heated by the sun to produce vapor. The vapor produced by the evaporation is condensed on the cold surface of the roofs and the condensate is collected as product water. Until today, a significant number of variations aiming on the improvement of solar stills have been examined and several new plants have been installed.

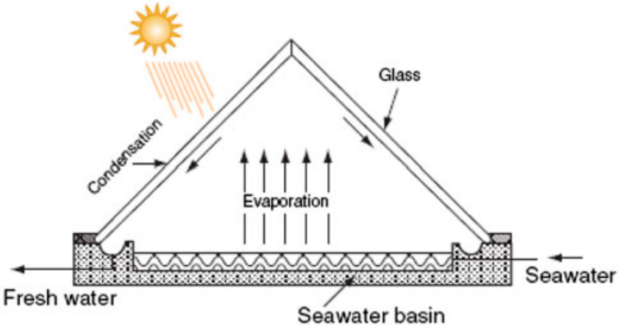

Fig. 18. A simplified schematic diagram of a solar still. Source: NREL, USA [23].

2.1.6. Solar H/DH

The H/DH process has been developed as an artificial simulator of the natural water cycle. Seawater is heated and contacted with a dry air stream, which is humidified by the natural evaporation of some water from the salty stream. The hot humid air stream is then contacted with a cold surface, where water vapor is condensed and separated from the dried air stream, which is ready for repeating the cycle. A number of different systems based on H/DH process have been developed so far, from laboratory to pilot scale [24], to commercially available units (known as multiple effect humidfication [MEH] systems) (Fig. 20). These latter are characterized by multiple H/DH cycles, where natural convection is adopted for generating the air movement, in order to minimize both thermal and mechanical energy consumption. Production capacity can vary from few 100 l/d up to several m^3/d, being the upper boundary is not conceptual but is only related by the actual availability of operating systems.

Energy requirements in H/HD systems are quite similar to MD ranging from 1 to 2 kWh$_{el}$/m^3 electrical–mechanical energy (required for feed circulating pumps and auxiliary units) and from 100 to 400 kWh$_{th}$/m^3 thermal energy (required for generating the partial evaporation of the feed stream), normally supplied in a low temperature range, i.e. 70–90˚C. Thus, also H/HD technology is particularly suitable for the coupling with solar thermal collectors, and other low-T heat sources. Electric energy requirements can be satisfied either by adding a PV system or by grid connection.

Coupling schemes can be differently designed, although mostly adopted in prototyped systems is the two-loop system coupling scheme, where solar energy is collected and stored in a primary loop and then transferred to a secondary loop by a corrosion-resistant heat exchanger where the feed stream is heated before entering the H/DH unit (Fig. 19).

Thermal energy storage is normally included in the system to guarantee more stable and continuous operations, as for solar MD and MED systems. Solar H/HD technology presents similar advantages to solar MD such as easy modularity, low-maintenance, easy operation and feasible coupling with low temperature heat sources.

Contrarily to MD, H/DH technology does not require the use of expensive membranes or high-tech materials, though the specific surfaces required for evaporation and condensation are normally quite high (in the range of 1 m^2 per l/h evaporation/condensation rate), thus occupying large volumes for installation.

2.2. Wind desalination

A number of units coupling wind turbines with desalination processes have been designed, installed and tested. The most common choice is to have stand-alone WT systems (WT) to drive RO units for seawater desalination. However, WT can also be used in conjunction with other conventional or renewable power sources (e.g. diesel, photovoltaic), these are known as hybrid systems. A small number of installations concern with the use of hybrid systems, Wind and PV technology to drive RO units.

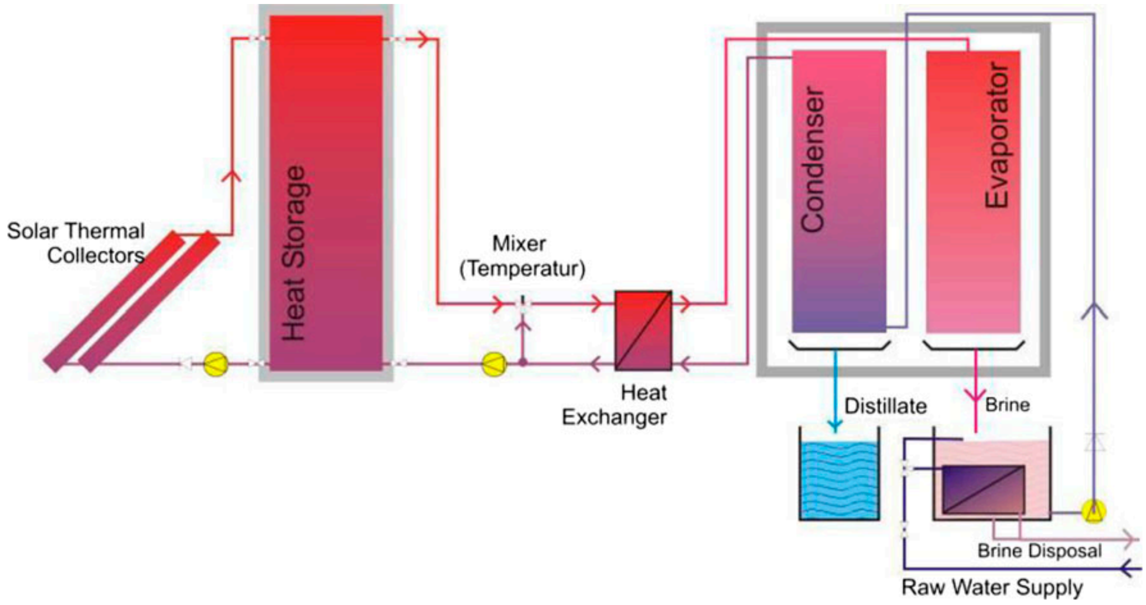

Fig. 19. Coupling scheme for a solar thermal powered H/DH system [25].

Fig. 20. View of a solar thermal powered MEH system installed in Dubai (UAE). Plant capacity 5,000 l/d and 170 m^2 solar thermal collectors [25].

2.2.1. Wind RO

A stand-alone wind RO system consists of the following equipment:

(1) Wind generator
(2) Charge controller
(3) Battery bank
(4) Inverter
(5) RO unit

The battery bank is used for power stability and as an energy supply during periods, when WT is not sufficient to drive the desalination unit. Charge controllers are used for the protection of batteries from overcharging. The inverters are used to convert the DC current from the battery output to AC, for the load. A diesel generator (DG) backup can also be used to charge the battery bank or to drive the RO unit directly. A typical diagram of a hybrid stand-alone PV/Wind/DG/RO unit is presented in Fig. 21 [5].

The size of the already installed Wind RO plants is in the range of some liters up to around 1,000 m^3/d. A significant number of units was installed and tested within EU projects (JOULE, THERMIE Programmes, etc.), in the last decade (Table 3). Since then, there is a significant market progress of the RE and desalination technologies but less support on the research and demonstration of the more mature technologies and their matching.

According to the available data from the existing installations the unit water cost from small Wind RO

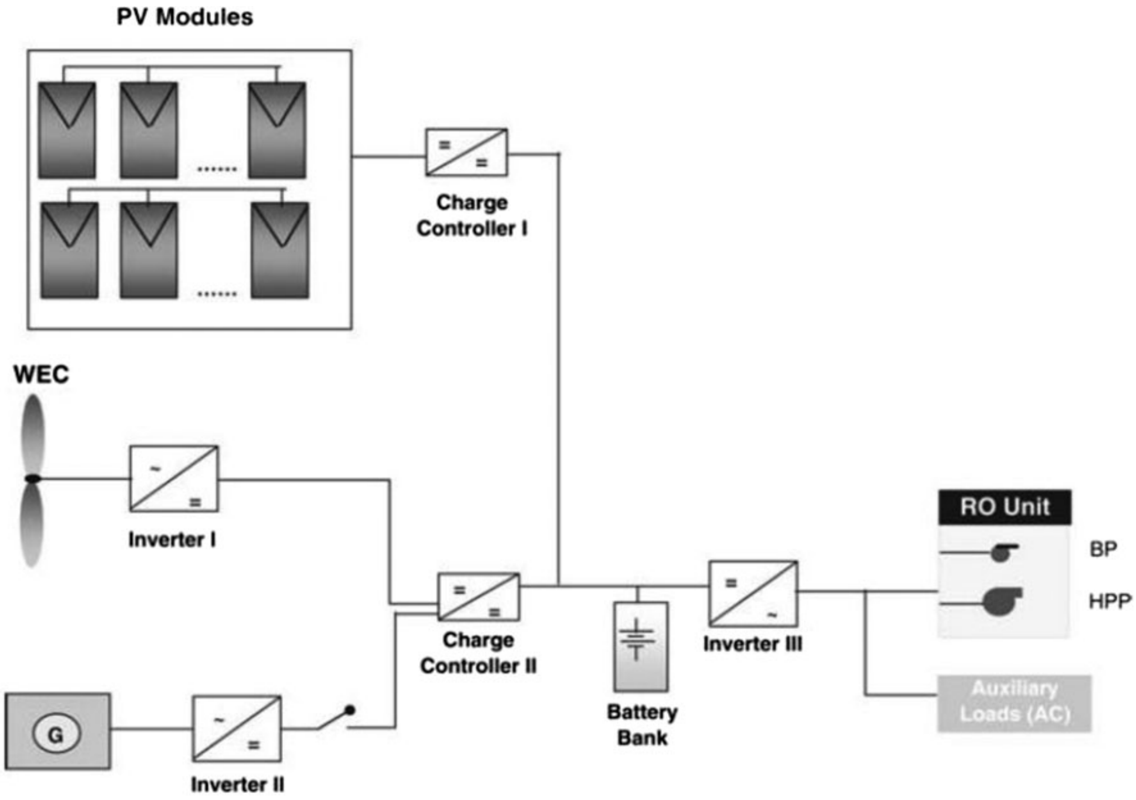

Fig. 21. Typical diagram of a hybrid RO plant [5].

systems ranges between 1.5 and 7 €/m^3, with lower values relevant to larger installations (even over 1,000 m^3/d) with grid integration of the PV system.

As mentioned before, for the RO process, ERDs are used to recover the energy from the pressurized reject brine, thereby improving the overall efficiency of the system. Their use increases the initial cost of the system but effectively reduces the energy requirement.

Small wind turbines, especially in the range of 15–100 kW nominal power are still expensive (see Table 4). However, there is a significant progress on their efficiency and market availability, during the last years.

Furthermore, there are several examples of wind-powered systems operating "grid-connected". In these cases, the RE technology has to provide the energy consumed by the desalination units via a power node connected to the grid, without the need of power back-up sources. In the case of excess of produced energy from the RES, this excess is provided to the grid with the benefit of feed-in-tariff issue (depending on the procedures and legislations of the country). This case mostly concerns with the use of a Wind Turbine or a Wind farm to cover the power requirements of RO plants.

In Australia, many desalination plants are utilizing wind farms to produce enough energy to operate nearby desalination plants. For example, the Kurnell Desalination Plant, with a capacity of producing 250,000 m^3 of drinking water per day, supplies 15% of Sydney's water needs via RO technology and is powered using "100% renewable energy" from the 140 MW Capital Wind Farm.

In Greece, in Milos Island the water needs are mainly covered by the use of a 3,600 m^3/d SWRO plant driven by an 850 kW wind turbine connected to the grid. The system has a successful operation and no water has been transferred via tankers after its installation.

For the case of Gran Canaria Island, the ITC has tested five different off-grid RE-powered RO units, either wind-powered and, reported here as a comparison, also PV-powered, since 1998. Operation under variable energy availability is managed as follows:

Table 3
WT driven RO desalination plants [5]

Location	RO capacity (m^3/h)	Electricity supply	Year of installation
Ile du Planier, France	0.5	4 kW W/T	1982
Island of Suderoog, Germany	0.25–0.37	6 kW W/T	1983
Island of Helgoland,Germany	40	1.2 MW W/T + diesel	1988
Fuerteventura, Spain	2.3	225 kW W/T + 160 KVA diesel, flywheel	1995
Pozo Izquierdo, SDAWES	8 units × 1.0	2 × 230 kW W/T	1995
Therasia Island, APAS RENA	0.2	15 kW W/T, 440Ah batteries	1995/6
Tenerife, Spain; JOULE	2.5–4.5	30 kW W/T	1997/8
Syros island, Greece; JOULE	2.5–37.5	500 kW W/T, stand-alone + grid connected	1998
Keratea, Greece PAVET Project	0.13	900 W W/T, 4 kWp PV, batteries	2001/2
Pozo Izquierdo, Spain, AEROGEDESA project	0.80	15 kW W/T, 190Ah batteries	2003/4
Loughborough Univ,UK	0.5	2.5 kW W/T, no batteries	2001/2
Milos island, Greece* OPC programme	2 x 41	850 kW W/T, grid connected	2007
Heraklia island, Greece* OPC programme	3.3	30 kW W/T off shore, batteries	2007
Delf Univ., The Netherlands	0.2–0.4	Windmill, no batteries	2007/2008

*Both plants were developed within the Operational Programme of Competitiveness of the Greek Ministry of Development.

Table 4
Cost of small wind turbines

Small wind turbines categories and cost			
SWT categories	Nominal power (kW)	Estimated hub height (m)	Estimated total cost €
Micro	0.05–1.5	10–18	350–3,500
Small	1.5–15	12–25	3,500–60,000
Small-medium	15–100	15–50	60,000–220,000

Source: CRES.

(1) Case of wind RO systems [26–30]:

    (a) When wind power increases: pitch control in wind generators.
    (b) When wind power decreases: reduction of the power consumed in desalination units and pumps (partial load operation and/or stop of units).
    (c) Transitory periods are possibly thanks to energy storage systems: flywheel for short periods (seconds) and batteries for long periods (hours).

(2) Case of PV RO systems [31,32]:

    (a) When generated power is higher than demand: power goes to batteries.
    (b) When generated power is lower than demand: additional power is supplied from batteries or the unit is operated under partial load and eventually stopped.

Furthermore, according to a study that the Wind Energy Department of CRES performed for the Municipality of a Greek island, based on parameters like the wind potential of the island and that all RO units contain ERDs, the conclusion was that a 5 MW (5000 kW) wind farm (capacity factor up to 50%) is able to cover the energy requirements of 8.500 m^3/d RO units (24 h/d operation). The total daily power required for the operation of SWRO units is 50.000,0 kWh. The yearly cost to cover all the energy requirements (feed pumps, high pressure pumps, and potable and transportation water pumps) of the RO units is estimated at 1.500.000 €. The cost for the procurement and installation of a wind turbine of around 2–2.5 MW is estimated at 1,200–1,350 €/kW.

2.2.2. Wind MVC

Evaporation with vapor compression is a thermal process that has typically been used for small- and medium-scale seawater desalination units. These units also take advantage of the principle of reducing the boiling point temperature by reducing ambient pressure, but the heat for evaporating the water comes from the compression of vapor rather than the direct exchange of heat from the steam produced in a boiler. The vapor can be compressed either by a mechanical compressor or by the use of a steam jet thermo-compressor. In most cases, a mechanical compressor is used. In general, two methods of compression are employed:

(1) Mechanical vapor compression [MVC].
(2) Thermal vapor compression [TVC].

The MVC process for seawater desalination was developed in the early 1980s. System development was motivated by the need to have a thermal desalination system that utilized solely electric power [33].

In MVC, electricity is used to power a dynamic compressor, which increases the pressure and resultant temperature of the vapor exiting from the evaporator. The re-compressed vapor can, then, be used as a motive stem for evaporation of additional seawater, thus continuously generating a distillate product (Fig. 22(a)).

MVC technology can be driven by RE technologies providing electrical power. So far, the only combination of MVC with RES concerns its matching with wind turbine(s). The wind-turbine supplies electricity to the compressor, auxiliary heater and all peripheral equipment, allowing the system to operate standalone.

Few applications have been implemented using WT to drive a MVC unit. A pilot plant was installed in 1991 at Borkum island in Germany, where a wind turbine with a nominal power of 45 kW was coupled to a 48 m^3/d MVC unit. A 36 kW compressor was required. The experience was followed in 1995 by another larger plant at the island of Rügen (Fig. 22(b)). A wind turbine with nominal power of 300 kW was coupled to a 300 m^3/d MVC unit. Additionally, a 50 m^3/d wind MVC installed within SDAWES project at Gran Canaria in Spain, while lately a wind MVC plant has been built on Symi island in Greece to cover the water needs of the area. In general, the water capacity of wind MVC units that have been installed and tested is in the range of 50 to around 500 m^3/d. The specific energy consumption of MVC units is high ranging from 9 to 20 kWh/m^3.

2.3. General overview of RES desalination installed capacity

As widely discussed in the previous paragraphs, RES desalination technologies can vary considerably depending on the process type, plant capacity, installation scenario and many other aspects, thus making it very difficult to work-out reliable general figures such as unit water cost. Furthermore, the overall system design (size of the system, type of feed water, use of

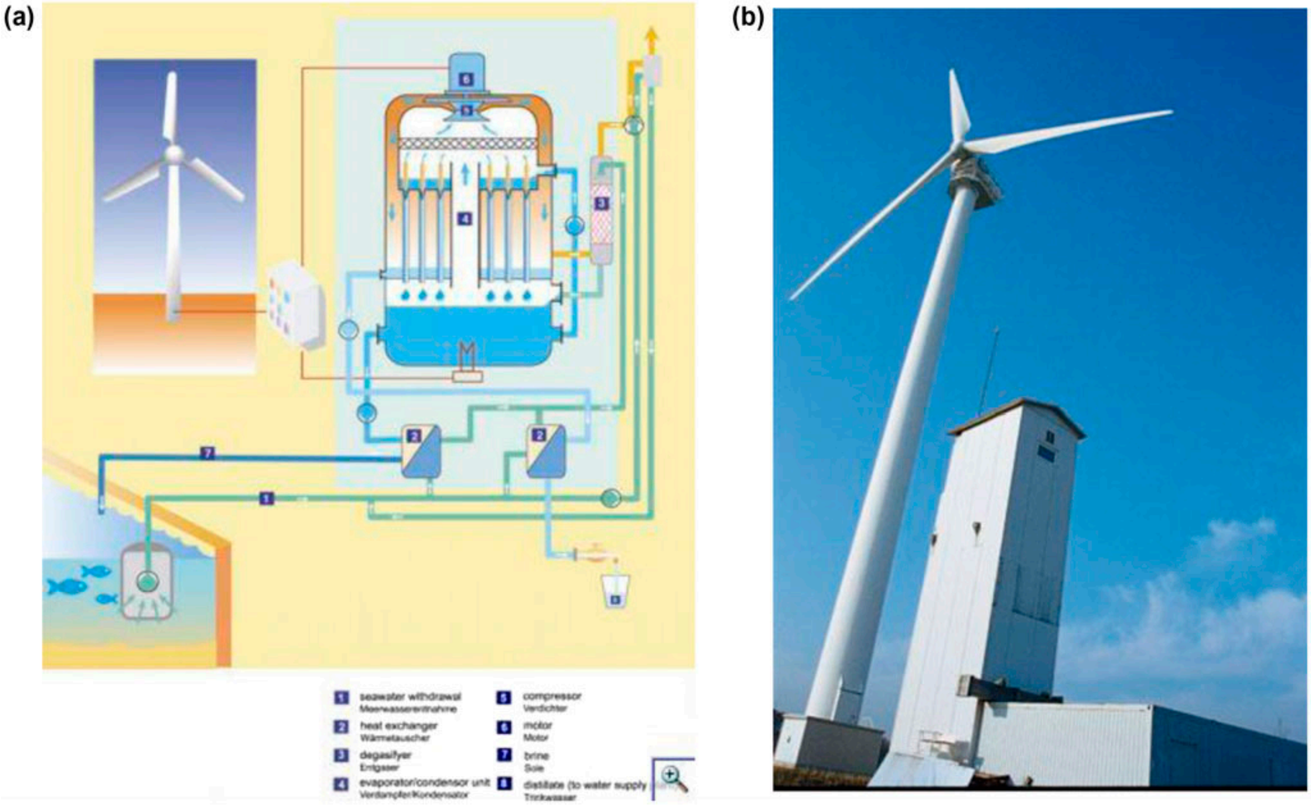

Fig. 22. (a) Diagram of a Wind MVC plant. (b) Picture of a Wind MVC plant.
Source: WME.

ERD, type of materials used, etc.) still requires a careful analysis, being in most cases a tailor-made design suitable for the particular application and characterized by a very high specificity.

The following graphs present the range of water production capacities of the most known installed RES Desalination plants, according to the total number of units (Fig. 23) and as a percentage of the total installations (Fig. 24). Such information provides a good overview of the achieved capacities and the different application scenarios, which have characterized each single technology.

Fig. 23 shows how the PV-RO coupling is the most adopted choice, being also very flexible in plant capacity. On the other side, solar MD and solar MEH plants have been proposed mainly for smaller scales, with peak capacities achieved around 5 m^3/d. Solar MED plants have also been installed in small numbers, although this technology has been considered quite promising, especially when coupled with solar CSP or poly-generative plants [6,34]. Wind-powered MVC and RO units have been installed and tested mainly for larger scale applications, generally above the limit of 5 m^3/d, while PV-ED and hybrid RO systems still represent a minor example of operating plants.

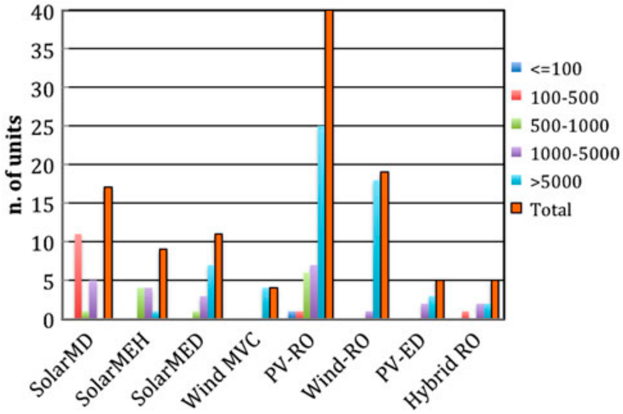

Fig. 23. Range of water capacities (in l/d) of the most known installed RES desalination plants according to the total number of units.

3. Stand-alone RES desalination applications under study

3.1. *Analyses of scenarios and critical aspects of the operations*

For the needs of this study a questionnaire has been developed and distributed to the operators or

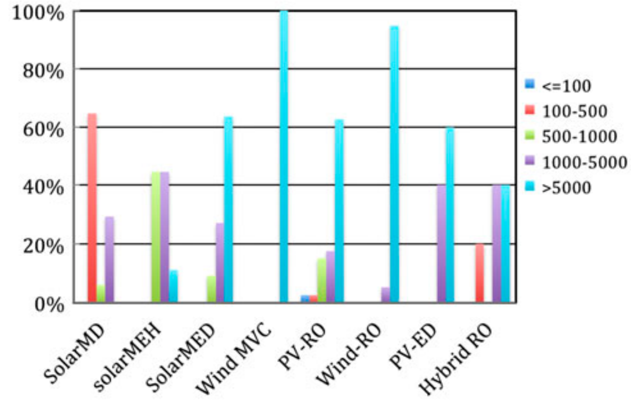

Fig. 24. Range of water capacities (in l/d) of the most known installed RES desalination plants as % of the total number of units.

responsible persons from the organizations operating RES desalination units. The aim of the questionnaire was to investigate the main potentials and limitations made evident by the long-term operations of the systems, looking in particular at the technological barriers, possibilities of scale up and the onerosity of ordinary and extra-ordinary maintenance.

The systems under study concern technologies such as PV-RO, hybrid (Wind, PV) RO, PV-ED and solar MD for brackish and seawater desalination. These units are either installed within the premises of the responsible research organizations or in remote areas of North Africa and Middle-East countries to cover irrigation needs or fresh water requirements of small villages. Table 5 presents the sample of units under study.

The first, most important, outcome of the questionnaire was that, based on the collected data, none of the problems mentioned by the operators were related to the coupling of the two technologies.

Most of the RES, RO and ED systems (PV RO, WIND RO) contain energy storage systems (batteries), charge controllers and inverters. Even if some of the units are operating under difficult weather circumstances at remote areas of North Africa countries (Morocco, Tunis, etc.) or Middle-East (Jordan), problems with the battery storage systems or other power supply equipment were not mentioned. From the available data, it seems that the maintenance requirements of the systems laid on the cleaning of the PV panels, mainly in the North Africa and Middle-East areas, and on the economic difficulties of local communities to replace the RO modules and pumps.

On the other side, solar thermal systems (solar MD) demonstrated a very stable operation, though, also in this case, the main maintenance problems were related to the cleaning operation of solar collectors (and PV panels, when present) and to the failure of some of the MD modules, due to internal leakages (which affected the product quality) or formation of fouling or scaling, which somehow reduced the flux and the capacity of the unit. At the same time, some systems, operating under well-controlled feed conditions, have operated for months or years keeping very high standard of the produced water (TDS below 100 ppm) with relatively constant specific energy consumptions.

The chemical cleaning of the membranes, in all the cases, occurred once per year. Nothing unusual in the operation and maintenance of the power supply or desalination systems is mentioned. The quality of the permeate water from all units remained the same after several years of operation. In few cases, a slight increase on the permeate conductivity is mentioned but at the permissible limits of potable water.

In most cases, the operation of the systems characterized as successful and important for the local communities. For the scientists and technologists the research work on pilot units, the opportunity of system's optimization, the collaboration with other scientists and networks as well as the promotion of their work form a vast basis for further development of the technology and the market.

Summarizing the main issue and/or problems declared by the operators, the following list can give a good example of what "can go wrong" in RES desalination stand-alone systems:

(1) Electronic devices breakdown;
(2) Damage of the small wind turbine after extremely and continuously high wind conditions;
(3) Problems with the valves for ERDs and refilling pump;
(4) Problems with the booster pump;
(5) Economic difficulties to replace the modules of RO units after several years of operation
(6) Blockage of circulation pumps in MD units;
(7) Failure in the sensors and/or automatic controls for the operation of the system under safe conditions,
(8) Fouling or internal leakages of membrane modules, requiring maintenance or substitution.

3.2. Lessons learnt

Numerous RES desalination stand-alone plants have been installed, most of them for demonstration

Table 5
Examples of RES desalination installations under study

a/a	Location	Responsible organization	RES desalination technology	Desalination capacity	PSS nominal power	Year of install.
1	Aqaba, Jordan	NERC	PV-BWRO	30 m^3/d	16.8 kWp	2005
2	Jordan Valley, Jordan	NERC	PV-BWRO	20 m^3/d	10.4 kWp	2010
3	CRES Keratea, Greece	CRES	PV/Wind-SWRO	3 m^3/d	4 kWp PV, 900 W WT	2004
4	Cyprus, Geroskopous	Fraunhofer ISE	PV BWRO	5 m/d	7.65 kWp	2011
5	Pozo Izquierdo, Gran Canaria	ITC	PV EDR (BW)	95 m^3/d	5.6 (for pumps) + 3.7 (for stacks) kWp	2010
6	Khar Ghilene, Tunisia	ITC	PV BWRO	50 m^3/d	10.5 kWP	2006
7	Amellou, Morocco	ITC	PV BWRO	24 m^3/d	4 kWp	2008
8	Tangarfa, Morocco	ITC	PV BWRO	12 m^3/d	2.5 kWp	2008
9	Tasekra, Morocco	ITC	PV BWRO	24 m^3/d	4 kWp	2008
10	Azla, Morocco	ITC	PV BWRO	24 m^3/d	4 kWp	2008
11	Gran Canaria, Spain	Fraunhofer ISE	Solar MD	150 l/d	75 Wp PV 6.5 m^2 solar thermal	2004
12	Morocco	Fraunhofer ISE	Solar MD	150 l/d	80 Wp PV 6 m^2 solar thermal	2005
13	Aqaba, Jordan	Fraunhofer ISE	Solar MD	1 m^3/d	12 m^2 PV 72 m^2 solar thermal	2005
14	Palermo, Sicily	Solar spring/ University of Palermo	Solar MD	150 l/d	12 m^2 solar thermal	2010
15	Monterey, Mexico	Fraunhofer ISE/solar spring	Solar MD	150 l/d	80 Wp PV 7 m^2 solar thermal	2010
16	Pantelleria, Sicily	Fraunhofer ISE /University of Palermo	Solar + waste heat MD	5 m^3/d	40 m^2 solar thermal + waste heat	2010
17	Gran Canaria, Spain	Fraunhofer ISE	Solar MD	3,5 m^3/d	180 m^2 solar thermal	2011

Notes: SW: seawater, BW: brackish water, PSS: power supply system, PV: photovoltaic, WT: wind turbine.

projects and consequently of small capacity. The matching of the desalination process to a RES is not simple, mainly because desalination process is best suited for continuous operation. Unpredictable and non-steady power input forces the desalination unit to operate in non-optimal conditions and this may cause operational problems, unless well designed energy storage systems are adopted for buffering energy supply fluctuations. Besides, no technical problems in the matching of the two technologies have been encountered. Additionally no problem has been mentioned regarding the quality and sufficient quantity of the produced water.

Proper selection of technologies, matching, optimum sizing, and selection of material, sufficient automation of the system, and local people acceptance and participation is normally the base of a successful installation. Capacity building issues is of high importance for the operation, promotion and dissemination of RES desalination technologies.

Researchers are still in the process of optimizing the combinations of the two technologies. Final success will be achieved with the development of reliable, market-available systems, which will have the capability to provide sufficient quality and quantity of water at a reasonable cost. This is particularly addressed to the availability of specific components for small scale units, such as ERDs for RO, PV control systems and charge controllers suitable for the operation under harsh conditions. Finally, the reduction of the effect of the economy of scale on the cost of produced water will play a fundamental role in the achievement of a cost-competitiveness of these technologies.

4. RES desalination market progress and barriers

The matching of RES with desalination is a slowly growing market and this is mainly due to the typically “high cost” of the produced water. Parameters like the size of the unit, the energy consumption and availability and other factors should be considered for the final decision of technology selection. Nowadays, there is small market of commercially available units, typically constructed and commissioned by small and young start-up companies. Advanced R&D activities are still carried out for the coupling of solar energy with MED technology, although several industrial pilot projects have recently started for the construction and operation of relatively large solar MED plant, especially in the Middle East region. A niche sector is also visible for the PV-ED (or EDR) technology, which is growing in interest due to recent developments of ED and Ion Exchange Membrane industry. Finally, the coupling between RO and wave/tidal energy is still at a "concept idea" level of development, being not represented by any pilot unit, at least to our knowledge.

In general, the need of supplying potable or fresh water to remote areas is huge. However, even if there is a small RES desalination market able to provide commercial modular systems, such as PV RO, Wind-RO, solar MD, etc. it seems that the majority of the RES desalination installation have been so far installed and operated within EU or National projects. However, the barriers seem to be mostly economical and political rather than technical.

Unfortunately, the importance to invest and to provide a suitable level of life in remote and, most of the times, poor areas of the planet seems low. However, though the cost of the unit water produced from RES desalination systems in small scales is still high, it is normally lower than other alternatives, such as water transportation, very long water ducts, etc. which can also lead to problems of poor quality of distributed water.

5. Conclusions

Keeping in mind the climate protection targets and strong environmental concerns, future water desalination technologies around the world will be increasingly powered by solar, wind and other natural energy resources. As conventional energy costs will expectedly increase on the short term and water availability will decrease due to the implications derived from climate change, the future of RE-powered desalination is very promising for environmental and economic reasons; it is, in fact, already a competitive alternative where water costs are very high.

A survey analysis has been performed on the operation of some of the most important examples of RES desalination technologies, focusing on potentials and limitations of each one and on any possible barrier (technological, economic, socio/political, etc.) which could obstacle further development. The survey shows how the coupling between RES and desalination technologies does not present itself any real technological barrier, though some limitations arose when looking at the life-time, robustness and cost of specific components required for the construction and efficient operation of these processes.

Hopefully, such environmentally friendly systems should be soon potentially available at competitive costs. However, to achieve that, more research has to be done on the new generation products, such as ERDs, new generation small wind turbines, energy storage systems (batteries, supercapacitors) and, on the development of more advanced control and monitoring systems in order to develop autonomous systems able to offer fresh water to remote areas by a reliable and economic way. Demonstration/pilot activities of the new or improved RES desalination combinations in a real environment, with the collaboration of research organizations and the market (major companies, SMEs, etc.) and with the contribution of all stakeholders is of vital importance.

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List of abbreviations

BW	—	brackish Water
CSP	—	concentrated solar power
DG	—	diesel generator
ED	—	electrodialysis
EDR	—	electrodialysis reversal
ERD	—	energy recovery device
H/DH	—	humidification/de-humidification
MD	—	membrane distillation
MED	—	mutli effect distillation
MEH	—	multiple effect humidfication
MVC	—	mechanical vapor compression
PSS	—	power supply system
PV	—	photovoltaic
RE	—	renewable energy
RES	—	renewable energy sources
RO	—	reverse osmosis
SW	—	sea water
TDS	—	total dissolved solids
WT	—	wind turbine

References

[1] E. Tzen, Wind energy powered technologies for freshwater production: Fundamentals and case studies, sustainable energy developments 2, renewable energy applications for freshwater production, Taylor & Francis Group, Abingdon, ISBN 9 780415 620895, 2012.

[2] G. Micale, A. Cipollina, L. Rizzuti, Seawater desalination for fresh water production, in: A. Cipollina, G. Micale, L. Rizzuti (Eds.), Seawater Desalination, Springer, New York, NY, 2009.

[3] G. Zaragoza, A. Ruiz-Aguirre, E. Guillén-Burrieza, Efficiency in the use of solar thermal energy of small membrane desalination systems for decentralized water production, Appl. Energy 130 (2014) 491–499. http://dx.doi.org/10.1016/j.apenergy.2014.02.024.

[4] Personal communication with Mr. M. Sigalas, PHOTOVOLTAIC—Renewable Energy Applications, Athens, Greece, 2014.

[5] E. Tzen, Wind and Wave Energy for Reverse Osmosis, in: A. Cipollina, G. Micale, L. Rizzuti (Eds.), Seawater Desalination, Springer, New York, NY, 2009.

[6] F. Calise, A. Cipollina, M. Dentice d'Accadia, A. Piacentino, A novel renewable polygeneration system for a small Mediterranean volcanic island for the combined production of energy and water: Dynamic simulation and economic assessment, Appl. Energy (2014), in press, http://dx.doi.org/10.1016/j.apenergy.2014.03.064.

[7] E. Tzen, G. Zaragoza, D-C Alarcón Padilla, Solar desalination, in: A. Sayigh (Ed.), Comprehensive Renewable Energy, vol. 3. Elsevier, Oxford, 2012, pp. 529–565.

[8] E. Tzen, PRODES Project, From CRES Seminar presentations, Athens, Greece, 2010.

[9] Centre for Renewable Energy Sources, Desalination Guide using Renewable Energies, ISBN 960-90557-5-3, CRES, Greece, 1998.

[10] B. Peñate, F. Círez, F.J. Dominguez, V. Subiela, L. Vera, Design and testing of an isolated commercial EDR plant driven by solar photovoltaic energy, Desalin. Water Treat. 51 (2013) 1265–1271.

[11] I.C. Watson, O.J. Morin Jr., L. Henthorne, Desalting Handbook for Planners, third ed., U.S. Department of the Interior Bureau of Reclamation, Denver, CO, 2003.

[12] E. Zarza, Solar thermal desalination Project Phase II Results & Final Project Report, PSA/CIEMAT: Secretaria General Technica del Ciemat, 1994.

[13] D.C. Alarcón-Padilla, L. García-Rodríguez, J. Blanco-Gálvez, Design recommendations for a multi-effect distillation plant connected to a double-effect absorption heat pump: A solar desalination case study, Desalination 262 (2010) 11–14.

[14] J.H. Lienhard, M.A. Antar, A. Bilton, J. Blanco, G. Zaragoza, Solar desalination, in: Annual Review of Heat Transfer, vol. 15, Begell House Inc., New York, NY, 2012, pp. 277–346.

[15] J. Koschikowski, M. Wieghaus, M. Rommel, Membrane distillation for solar desalination, in: Seawater Desalination, A. Cipollina, G. Micale, L. Rizzuti (Eds.), Springer, New York, NY, 2009, pp. 165–187.

[16] A. Kullab, A. Martin, Membrane distillation and applications for water purification in thermal cogeneration plants, Sep. Purif. Technol. 76 (2011) 231–237.

[17] A. Cipollina, M.G. Di Sparti, A. Tamburini, G. Micale, Development of a membrane distillation module for solar energy seawater desalination, Chem. Eng. Res. Design 90 (2012) 2101–2121.

[18] J. Koschikowski, M. Wieghaus, M. Rommel, Solar thermal-driven desalination plants based on membrane distillation, Desalination 156 (2008) 295–304.

[19] R. Schwantes, A. Cipollina, F. Gross, J. Koschikowski, D. Pfeifle, M. Rolletschek, V. Subiela, Membrane distillation: Solar and waste heat driven demonstration plants for desalination, Desalination 323 (2013) 93–106.

[20] J.H. Hanemaaijer, J. van Medevoort, A.E. Jansen, Memstill membrane distillation—A future desalination technology, Desalination 199 (2006) 175–176.

[21] K. Zhao, W. Heinzl, M. Wenzel, S. Büttner, F. Bollen, G. Lange, S. Heinzl, N. Sarda, Experimental study of the memsys vacuum-multi-effect-membrane-distillation (V-MEMD) module, Desalination 323 (2013) 150–160.

[22] R. Porrazzo, A. Cipollina, M. Galluzzo, G. Micale, A neural network-based optimizing control system for a seawater-desalination solar-powered membrane distillation unit, Comput. Chem. Eng. 54 (2013) 79–96.

[23] T.E. Karen, Desalination of Village Scale, Renewable Energy Powered Desalination, NREL, Denver, CO, 1997.

[24] H. Mueller-Holst, Solar thermal desalination using the multiple effect humidification (meh)-method, in: L. Rizzuti, H. Ettouney, A. Cipollina, (Eds.), Solar Desalination for the 21st Century, NATO Security through Science Series, Springer, New York, NY, 2007.

[25] H. Mueller-Holst, Lecture Material of the PRODES Course on Desalination with Renewable Energy, Palermo, 2009.

[26] V. Subiela, J.A. de la Fuente, G. Piernavieja, B. Peñate, Canary Islands Institute of Technology (ITC), experiences in desalination with renewable energies (1996–2008), Desalin. Water Treat. 7 (2009) 220–235.

[27] V.J. Subiela, J.A. Carta, J. González, The SDAWES project: Lessons learnt from an innovative project, Desalination 168 (2004) 39–47.

[28] J.A. Carta, J. González, V.J. Subiela, The SDAWES project: An ambitious R&D prototype in wind-powered desalination, Desalination 161 (2004) 33–48.

[29] J.A. Carta, J. González, V.J. Subiela, Operational analysis of an innovative wind powered reverse osmosis system installed in the Canary Islands, Sol. Energy 75 (2003) 153–168.

[30] B. Peñate, F. Castellano, A. Bello, L. García-Rodríguez, Assessment of a stand-alone gradual capacity reverse osmosis desalination plant to adapt to wind power availability: A case study, Energy 36 (2011) 4372–4384.

[31] V.J. Subiela, B. Peñate, F. Castellano, F.J. Rodríguez, Solar PV powered RO systems, in: Renewable Energy Applications for Freshwater Production, CRC Press/Taylor & Francis Group, Abingdon, (ISBN: 978-0-415-62089-5), July 2012, pp. 135 –260.

[32] Baltasar Peñate, J. Vicente Subiela, Fayna Vega, Fernando Castellano, F. Julián Domínguez, Vanesssa Millán, Uninterrupted 8-year operation of the autonomous solar photovoltaic reverse osmosis system in Ksar Ghilène (Tunisia), Desalin. Water Treat. (2014), in press.

[33] Ettouney, H., Wilf M., Commercial desalination technologies—An overview of the current status of applications of commercial seawater desalination processes, in: Seawater Desalination, A. Cipollina, G. Micale, L. Rizzuti (Eds.), Springer, Berlin, 2009.

[34] S. Casimiro, J. Cardoso, C. Ioakimidis, J. Farina Mendes, C. Mineo, A. Cipollina, MED parallel system powered by concentrating solar power (CSP). Model and case study: Trapani, Sicily, Desalin. Water Treat. (2014), accepted for publication.