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Desalination by using alternative energy: Review and state-of-the-art

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Abstract

Energy is a critical parameter for economic and of vital importance in social and industrial development, as it is also quality water. Numerous low-density population areas lack not only fresh water availability, but in most of the cases electrical grid connection or any other energy source as well, except for renewable energy sources, mostly referring to solar radiation. For these regions desalination is a moderate solution for their needs. In using RE desalination there are two separate and different technologies involved: energy conversion and desalination systems. The real problem in these technologies is the optimum economic design and evaluation of the combined plants in order to be economically viable for remote or arid regions. Conversion of renewable energies, including solar, requires high investment cost and though the intensive R&D effort technology is not yet enough mature to be exploited through large-scale applications. This paper presents a review of the highlights that have been achieved during the recent years and the state-of-the-art for most important efforts in the field of desalination by renewable energies, with emphasis on solar energy applications.

Keywords: Desalination; Alternative energy; Review

1. Introduction

Water and energy are two of the most important topics on the international environment and development agenda. The social and economic health of the modern world depends on sustainable supply of both energy and water. These two critical resources are inextricably and reciprocally linked: the production of energy requires large volumes

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of water while the treatment and distribution of water is equally dependent upon readily available, low-cost energy. The ability of nations to provide both clean, affordable energy and water is being seriously challenged by a number of emerging issues.

Through the natural water cycle, one may have the wrong impression that fresh water is a renewable item, and in some way it is, even though the availability of quality fresh water resources is decreasing dramatically due to the population increase, the irrational waste and especially to severe contamination of the existing resources. There is a world-wide crisis concerning availability of good quality water, and this goes to local, regional and national levels, despite the huge amount of water covering the earth's surface. This situation leads to the application of cleaning methods or to desalination of brackish and seawater.

In most of the arid, semi-arid and remote regions fresh water is very scarce. This is especially true for the Mediterranean basin and the Middle East regions where many big cities and small villages suffer from lack of quality fresh water but, at the same time, they are blessed with abundant salt-water sources. In seawater desalination the trend refers mainly to large centralized or dual-purpose desalination plants, as being more economical and suitable for large density population areas, ignoring through this practice small poor communities. However, numerous low-density population areas lack not only fresh water but, in most the cases, electrical power grid connections as well. For these regions renewable energy desalination is the only solution.

Since ancient times humans have used renewable energy sources (RES), but the remarkable development of renewable systems has taken place after the petroleum crisis of 1973. At present, the increasing preoccupation for the environment has consequently increased the interest for the use of renewable energies. Naturally, one has to consider the existing main limitations, related to the temporal and space-dependent character of these resources, the high land requirements and investment costs of renewable energy facilities.

Apart from the referred reasonable arguments for the use of RES towards the emerging and stressing energy problems, there is a number of reasons related to the more specific issue, the one of the suitability of RES for seawater desalination:

- Arid regions are often remote, coastal areas or little islands where renewable energy sources are available and conventional energy supply is not always possible or at least easy to implement. In these cases RES represent the best energy supply option for autonomous desalination systems.
- Climatic reasons lead to remarkable agreement on a time-basis, between the availability of RES, especially when referring to solar energy, and the intensive demand of water. Furthermore, often freshwater demand increases due to tourism, which is normally concentrated at times when the renewable energy availability is high.
- Both renewable energy systems and desalination refer to self-sufficiency and local support. The operation and maintenance of related systems in remote areas are often easier than conventional energy ones. Furthermore, the implementation of RES-driven desalination systems enforces sustainable socioeconomic development by using local resources.
- Renewable energies allow diversification of energy resources and help to avoid external dependence on energy supply. This has to be seen through the prospect of the least developed countries, where major water shortage problems exist, considering as well the fact that seawater desalination processes are highly energy-consuming methods.

However, present situation does not reflect the obvious advantages of RES and desalination conjunction. More specifically, RES-driven desalination systems are scarce, presenting usually limited capacity. Accordingly, they only represent about

0.02% of the total desalination capacity [1]. The reasons for this are related to various, often correlated, aspects:

- *Technology*: The use in desalination systems of alternative energy sources imposes the conjunction of two separate and different technologies: the energy conversion and the desalination systems. Both are considered mature to a lesser or greater degree, even though there are still significant margins regarding the efficiency increase, as well as volume and costs decrease. A real challenge for these technologies would be the optimum technological design of combined plants through a system-oriented approach.
- *Cost*: Exploitation of RES and development of desalination plants represent capital-intensive installations. By this time, renewable energy technologies are not considered totally mature and the various system components are still expensive. Even though prices decrease continuously, still in many cases they are prohibiting for commercialization.
- *Availability*: Renewable energies are unlimited, being though transient, thus presenting intermittent character, leading to limitations concerning the maximum exploitation capacities per time unit. Furthermore, the geographical distribution of RES potential does not always comply with the water stress intensity at a local level.
- *Sustainability*: In most of the cases, the maturity of the associated technologies does not match the low level of infrastructures which often characterizes places with severe water stress. Experience has shown that several attempts to integrate advanced desalination solutions in isolated areas failed due to lack of reliable technical support.

Through the above mentioned framework, the following discussion concentrates on the main RES-driven desalination concepts, aiming to light up their prospective characteristics and trace the problems arising. The criteria of analysis refer amongst others to RES availability, technological maturity, simplicity, availability of local resources for handling and maintenance, possibility to ensure a given level of fresh water production, suitability of the system to the characteristics of the location, efficiency, etc.

2. Matching renewable energies with desalination units

Renewable energies and desalination plants are two different technologies, which can be combined in various ways. The interface between the renewable energy system and the desalination system is met at the place/subsystem where the energy generated by the RE system is promoted to the desalination plant. This energy can be in different forms such as thermal energy, electricity or shaft power. Fig. 1 shows the possible combinations. One has to note that in this figure, there have been introduced some changes regarding relevant references [2]. These changes concern the insertion of direct solar distillation (SD), humidification–dehumidification (HD) and membrane distillation (MD) systems.

Renewable energy-driven desalination systems fall into two main categories: thermal processes and electromechanical processes. As regards the energy source, a desalination plant powered by renewable energy is likely to be a stand-alone system at a location which has no electricity grid. Stand-alone systems are often hybrid systems, combining more than one type of renewable energy sources, for instance, wind and solar energy or including a diesel generator. In order to ensure continuous or semi-continuous operation independent of weather conditions, stand-alone systems usually include a storage device.

In recent years, due to intensive R&D efforts and to operation experience gained, advances in conventional desalination plants, steam or electrically driven, refer to a significant efficiency increase and reduction of cost [3,4]. On the other

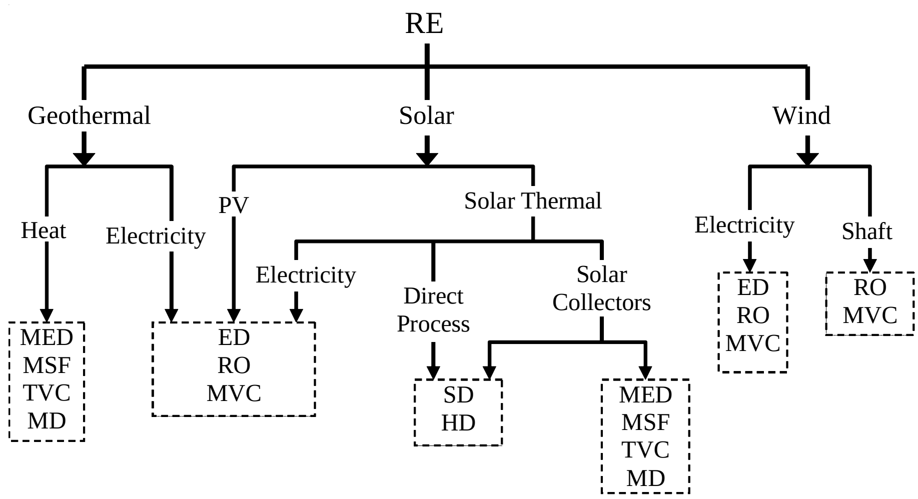

Fig. 1. Possible technological combinations of the main renewable energies and desalination methods.

hand, the situation with renewable energy-driven desalination systems is quite different. At present time, these systems evolve through the R&D stage, or they are implemented as pilot plant size applications, presenting, in general, capacities from a few m^3 up to 100 m^3. There have also been some demonstration plants of medium size, mainly solar-powered, but a minority of those has presented successful operation characteristics [4,5].

Not all the combinations of RES-driven desalination systems are considered to be suitable for practical applications; many of these possible combinations may not be viable under certain circumstances. The optimum or just simple specific technology combination must be studied in connection to various local parameters as geographical conditions, topography of the site, capacity and type of energy available in low cost, availability of local infrastructures (including electricity grid), plant size and feed water salinity. General selection criteria may include robustness, simplicity of operation, low maintenance, compact size, easy transportation to site, simple pre-treatment and intake system to ensure proper operation and endurance of a plant at the often difficult conditions of the remote areas.

Fig. 2 shows that the most popular combination is the use of PV with reverse osmosis [6]. Table 1 gives an overview of recommended combinations depending on several input parameters, noting though that other, additional combinations are also possible [4]. Indeed, PV is considered a proper solution for small applications in sunny areas. For larger units, wind energy may be more attractive as it does not require anything like much ground. This is often the case on islands where there is a good wind regime and often very limited flat ground.

The general tendency is to combine thermal energy technologies (solar thermal and geothermal energy) with thermal desalination processes and electromechanical energy technologies with desalination processes requiring mechanical or electrical power. Therefore, the following combinations are the options most commonly used when desalination units are powered by renewable energy [4]:

- PV or wind-powered reverse osmosis, electrodialysis or vapour compression;
- Solar thermal or geothermal energy and distillation processes.

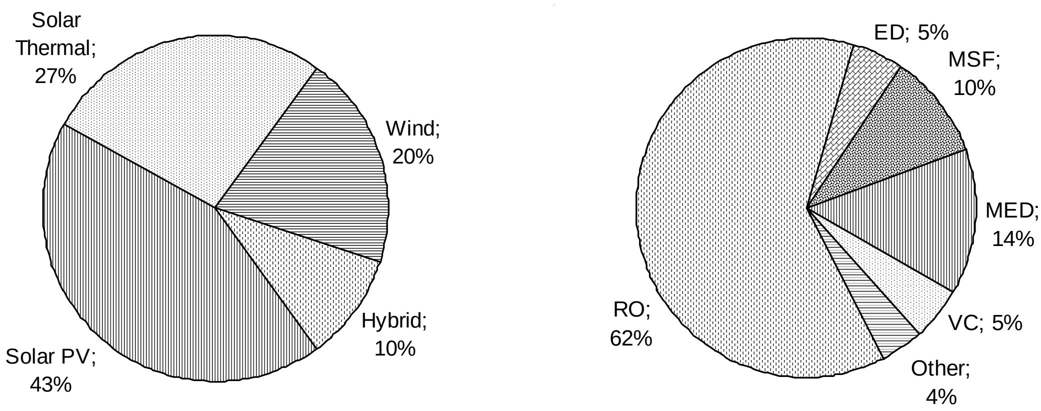

Fig. 2. Renewable energy-driven desalination processes and energy sources.

Table 1
Recommended renewable energy–desalination combinations

Feed water quality	Product water	RE resource available	System size			Suitable combination
			Small ($1–50\ m^3d^{-1}$)	Medium ($1–50\ m^3d^{-1}$)	Large ($1–50\ m^3d^{-1}$)	
Brackish water	Distillate	Solar	*			Solar distillation
	Potable	Solar	*			PV–RO
	Potable	Solar	*			PV–ED
	Potable	Wind	*	*		Wind–RO
	Potable	Wind	*	*		Wind–ED
Seawater	Distillate	Solar	*			Solar distillation
	Distillate	Solar		*	*	Solar thermal–MED
	Distillate	Solar			*	Solar thermal–MED
	Potable	Solar	*			PV–RO
	Potable	Solar	*			PV–ED
	Potable	Wind	*	*		Wind–RO
	Potable	Wind	*	*		Wind–ED
	Potable	Wind		*	*	Wind–MVC
	Potable	Geothermal		*	*	Geothermal–MED
	Potable	Geothermal			*	Geothermal–MED

Although there do not exist any extensive references concerning the real cost of water produced by these installations, prices that have been theoretically calculated [7–9] for large capacities are higher than these from conventional desalination plants. In any case one has to wonder whether this is the main problem for RES-driven desalination installations being scarce, as a glass of drinking water in remote and arid regions is actually precious and cost can be considered a matter of minor weight.

The following analysis presents, in more detail, the potential RES-driven desalination systems. Emphasis is paid to the systems with the higher prospects on a research and technological basis. Evidently, these systems comprise the most promising practical solutions within the medium-term time period.

3. Thermal solar desalination

3.1. Desalination powered by thermal solar energy

Thermal solar energy is considered to be one of the most promising applications of renewable energies to seawater desalination, as it is suitable for arid and sunny regions. A thermal solar distillation system usually consists of two main parts, the collecting device and the distiller. Solar thermal desalination processes are characterized as direct processes when all parts are integrated into one system, while the case of indirect processes refers to the heat coming from a separate solar collecting device, usually solar collectors or solar ponds.

Solar stills belong to the case of direct processes, and due to the interest they present, they will be discussed thoroughly below. The low efficiency of the still, mainly due to the high heat loss from its glass cover, has led many researchers through the survey of design concepts that would decrease the loss of latent heat of condensation at the glass cover or furthermore would partly recover this energy. Thus, the idea of utilizing latent heat of condensation via multi-effect solar stills has come out. The basic principle imposes the use of condensation heat of the vapour from the n-th effect, for the evaporation of water at the $n + 1$st effect. Actually, one should talk of direct processes utilizing humidification–dehumidification techniques through a broad area of design solutions [10–14], leading eventually to significantly improved performance, compared to a simple solar still.

The indirect-type stills are based on the fact that heat is provided only at the first stage of such a multi-effect unit, thus the use of external heat source is possible. Conventional solar thermal collectors, corrosion-free collectors developed for the specific application [15,16] or even evacuated tube collectors [17] have been used as the external heat source.

Within the category of indirect processes installations based on conventional thermal desalination technology, as MED and MSF, are also included. For reasons related to the complexity and the cost of desalination units, these plants are usually of greater size. Even though during last years the development of such installations has been rather abandoned, several MED and MSF pilot plants have been designed and tested during the past, especially in late 90s. These installations have been driven by a flat plate, parabolic trough or vacuum solar collectors [17–19]. The evaluation of these plants has shown that MED has greater potential than MSF for designs with high performance ratio and, moreover, the MED processes appear to be less sensitive to corrosion and scaling than the MSF processes [4].

Solar thermal energy can be used, in principle, for the production of electricity or mechanical energy. Evidently, the process of thermal energy conversion is accompanied with a decreased efficiency. During the past, only single attempts are reported, as the case of a solar-assisted freezing plant powered by a point-focusing solar collector field [20], a cogeneration hybrid MSF–RO system driven by a dual-purpose solar plant [21], and an RO plant powered by flat-plate collectors with freon as the working fluid [22].

Finally, special reference has to be given to the solar pond-powered desalination plants, selected by some authors as amongst the most cost-effective systems [23,24]. With relevance to this concept, different plants were implemented coupling a solar pond to an MSF process [21,25–27].

3.2. Solar stills

In solar distillation there exists a huge amount of bibliography describing all possible configurations of solar stills, including theories, models and experimental results. Usually they are limited to each special still design, while some of them propose comprehensive reviews and cost analysis [8,10,28]. Most of the studies try to increase the efficiency by using latent heat of condensation or coils to preheat the feed water and increase vapour condensation [29], separated evaporation and condensing zones [30,31], capillary film techniques [32]. Others try to increase feeding water temperature by various techniques, as connection with solar collectors [33], use of intermediate storage in connection to collectors [34], or integration of solar still in a multi-source, multi-use environment [35].

Conventional simple greenhouse-type solar distillation plants present specific disadvantages as low efficiency, high initial capital cost (counterbalanced in part by lower operational cost), large installation surface areas, vulnerability to extreme weather conditions (especially plastic covered stills), risk of formation of algae and scale on the black surface and need for special care to avoid problems related to dust deposition on the transparent cover.

At present time, only a few small solar distillation plants exist world-wide, referring amongst others to the case of India. Despite the considerable number of plants developed in the past, including as well plants still existing, there are not available, at least published, analytical information about real operation conditions, cost of produced water, cost of installation, operation and maintenance or any other problem raised, i.e. information potentially important for the optimum design of new installations.

Solar distillation plants are not commercialized yet, except for a few individual units. In fact, in many cases, one may use the term of semi-empirical devices, thus characterizing the design level. Constructions are made with locally available materials resulting in economic figures variation from region to region. On the other hand, the overall economics and operation conditions are of major importance to be known.

Considering the above mentioned status of solar stills, the main question/problem that arises could be formulated as follows: What must be done for further development, in order solar distillation plants to become viable and reliable installations for small communities?

Through this approach, the following priority actions arise:

- To formulate a well-designed prototype still, and investigate the applicability of optimum design and mathematical models that are widely applied in solar stills. Some authors have developed simple models to predict daily output depending on geometry of construction and operational parameters of the still, being applicable though to a wide range of single solar still configurations [34,36]. This has to be extended for the case of multiple solar stills, as well.
- To find the best materials of construction. The term best should refer to materials that combine long life of the stills, resistant behaviour (e.g., no corrosion in fresh and salt water) with the lower cost possible. This can be achieved only if global information is available.
- To study and find the optimum operational conditions in order to avoid scale formation and algae deposits into the basin and onto the black surface, thus improving absorptivity of solar radiation.
- To construct small plants in poor small communities and collect all possible information about construction, operation and maintenance, providing at the same time water to the people of dry regions.
- To elaborate a reliable economic evaluation of a solar distillation plant. This should lead to an optimum economical characterization of the system, comprising criteria of location, necessary equipment size, labour cost and energy analysis. This type of analysis is considered to be complex and time consuming, mainly due to the detailed meteorological data need.

Despite the problems and priority actions referred, even through an existing semi-empirical design level, solar distillation plants may be the only solution for some small communities where the only item that counts is fresh water production.

3.3. Humidification–dehumidification

As it has already been mentioned, the humidification–dehumidification (HD) principle has been developed while trying to solve the major problem of solar stills, that is the energy loss in the form of latent heat of condensation. Solar desalination based on the HD principle results in an increase in the overall efficiency of the desalination plant and therefore appears to be the best method of water desalination with solar energy. At present time, the HD desalination process is considered a promising technique for small-capacity, solar-driven desalination plants. Through this approach, one has to note the relevant significant bibliography, as well as the fact of various experimental units based on the principle of solar powered HD being constructed in different parts of the world (for an comprehensive review see [38,39]).

The process presents, indeed, several attractive features, including operation at low temperature, ability to combine with renewable energy sources (i.e. solar, geothermal), modest level of technology employed, simplicity of design and ability to be manufactured locally. Furthermore, it has the advantage of separating the heating surface from the evaporation zone, therefore, the heating surface is relatively protected from corrosion or scale deposits [11].

The basic operation principle of the HD process is the evaporation of seawater and condensation of water vapour from the humid air taking place inside the unit at ambient pressure, while there is continuous humid air flow from the evaporator to the condenser including recovery of latent heat of condensation for the preheating of the feed water (Fig. 3). More thoroughly, when circulating air comes in contact with hot saline water in the evaporator, a certain quantity of vapour is extracted by the air. Part of the vapour

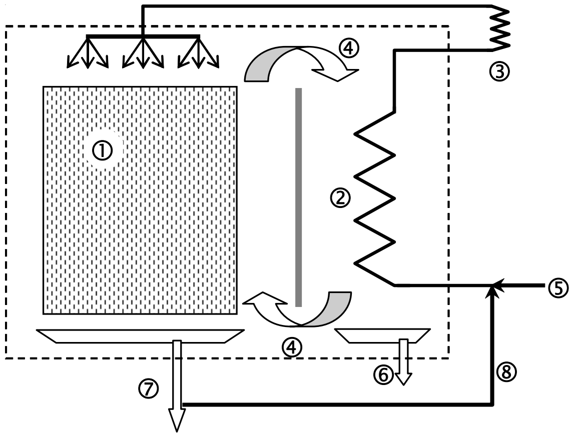

Fig. 3. General layout of an HD unit:1 evaporation area, 2 condensation area, 3 heat source, 4 air circulation, 5 feed saline water, 6 distillate, 7 brine, 8 brine recirculation reflux.

mixed with air may be recovered as condensate, by bringing the humid air in contact with a cooling surface in another exchanger, in which saline feed water is preheated by the latent heat of condensation. On the basis of this principle, there have been proposed several configurations, differing through the following points: the overall arrangement of the main unit (open-air closed-water cycle and open-water closed-air cycle), the circulation of the humid air between the evaporator and the condenser (natural or forced), the packing material placed in the evaporator (Raschig rings, tissues, fleece, stems) and the way to bring the heat to the unit (heating of the feed water or heating of the circulating air) [38,39].

The first specific bibliographic reference to the HD desalination is set by the year 1966 and concerns a pilot plant of 5000 US gallons (14.3 m^3) per day. It was called "Humidification Cycle Distillation". The plant consisted of a condenser tower, an evaporator tower with Raschig rings and long, plastic solar collectors [40]. A second reference, in 1968, presents the parametric analysis of two experimental units, of 3 $L.d^{-1}$ and 196 $L.d^{-1}$ capacities, equipped with surface condenser and with Raschig rings as the packing material in the evaporator. Nevertheless, by the early 1960's, the multi-effect humidity approach (MEH) has been introduced, referring to the distillation by natural or forced circulation of an air loop saturated with water vapour [41]. It has to be noted that the term "multiple effect" does not necessary refer to well distinguished stages, but to the fact that evaporation and condensation happen continuously over the whole temperature range between the condenser inlet and evaporator outlet.

Since its introduction, the MEH process has been evolved and various configurations have been investigated in different countries. Veza and Ruiz [42] suggested the use of an external cooler in a direct, forced circulation process without latent heat recovery. Investigation of an integrated collector, evaporator, and condenser [43] has shown that the efficiency of these desalination units can be significantly higher than that of a single-basin-still, while other studies refer to typical water production not more than 6 L.m^{-2}d^{-1} [44], accompanied though to gain output ratio (GOR) values higher than 3 [45]. One may also note the existence of studies proving the positive influence of the increase of the water temperature at the inlet to the evaporator of the MEH units, as well as of air-circulation, on the desalination productivity [46]. A more consistent and systematic investigation of forced or natural circulation units has been attempted by Farid et al., reporting as well the development of a rigorous detailed model that can be used to describe the performance of the desalination units working on the humidification–dehumidification principle [47–49].

Important can be considered the work referring to the investigation of long-term performance and the optimization of a compact, natural circulation, thermal solar-driven HD plant, constructed on the basis of the design originally developed by the University of Munich [50]. Two prototype plants were installed and measured from October 1992 to March 1997 in the Canary Islands [51]. The performance of the units has been improved over the years and an average daily production of 11.8 L.m^{-2}.d^{-1} has been obtained from the systems without thermal storage, on an average gain output ratio (GOR) between 3 and 4.5. From this work an improved concept has come out, including a conventional heat storage tank and heat exchanger between the collector and the distillation circuit, so as to enable 24-h operation of the distillation module [52]. Within the framework of the same project (SODESA), a new collector with corrosion-free absorbers was developed [15].

The solar multiple condensation evaporation cycle (SMCEC) concept has been proposed as well suited for developing countries with extended rural areas, because of its simplified design, low maintenance, extended life time and low capital cost [53]. The three main parts of the SMCEC desalination unit (solar collector, condensation tower and evaporation tower filled with thorn trees), were optimized through ~~a~~ detailed modelling, simulation and experimental validation.

Other relevant works present systems of closed water circulation in contact with ~~a~~ continuous flow of cold air in the evaporation chamber [54], open-air cycle systems [55] characterized by ~~a~~ high power requirement for air circulation, as well as a solar operated HD desalination system driven by a solar pond [56]. Recently, Nafey et al. presented an experimental and numerical investigation concluding that the productivity of HD systems is strongly affected by the saline water temperature at the inlet the humidifier, the dehumidifier cooling water flow rate and the recirculation air flow rate [57]. In addition, Ettouney presented a critical analysis of the four main configurations of the dehumidification process, concluding to the need to fully optimize these configurations in order to define the best design and operating conditions [58].

3.4. Membrane distillation

Membrane distillation (MD) is a thermally driven, membrane-based process. It first appeared at the end of 60s, and it constitutes the most recent development in the field of thermal desalination processes. The process takes advantage of the temperature difference between a supply solution, coming in contact with the surface, on one side, of the readily selected micro-porous membrane, and the space, on the other side of the membrane (Fig. 4). This temperature difference results in a vapor pressure difference, leading to the transfer of the produced vapor, through the membrane, to the condensation surface. The overall process is based on the use of hydrophobic membranes, permeable by vapor only, thus excluding transition of liquid phase and potential dissolved particles [59,60].

In a typical MD system, the feed water (e.g., 25°C inlet temperature) passes through the condenser channel, from its inlet to its outlet, while warming up (e.g., 65°C outlet temperature). The hot feed solution (e.g., T_{high} = 80°C inlet temperature) is directed along this membrane, passing the evaporator channel from its inlet to its outlet, while cooling down (e.g., T_{low} = 40°C evaporator outlet temperature). The input heat, necessary to achieve the required temperature gradient between the two channels (e.g., 80 – 65°C = 15°C), is introduced into the system between the condenser outlet and the evaporator inlet, by the heat medium.

The basic requirements for the membrane refer to the negligible degree of liquid phase permeance, while the opposite is required for the air phase, as well as to low thermal conductivity, sufficient but not excessive thickness, long-time resistance to the seawater contact, low water absorbency, and adequate level of porosity (70–80%). Materials that have been used on a research level are PTFE, PVDF, PE and PP. Typical sizes for the porosity are 0.06–0.85, for the pore sizes 0.2–1.0 μm and for thickness 0.06–0.25 mm.

Despite the fact that the process has been known for a considerable number of years, and the existing interest for commercial exploitation in desalination applications, the high cost and the problems associated with the use of membranes have prohibited the development of commercial products. On the other hand, there has been imple-

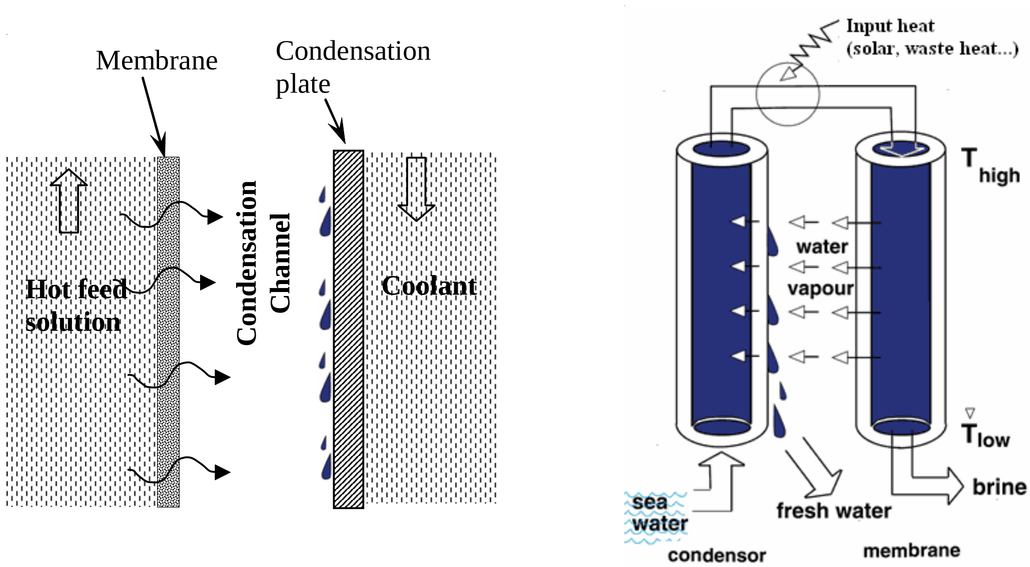

Fig. 4. Principle of the MD process (left) and schematic diagram of a typical MD system (right).

mented considerable research activity, as depicted through the existing relevant bibliography. Suggestively, studies [61–71] are referred, as well as a remarkable evaluation of the results obtained up to now [72]. The relevant studies conclude that the feed water salt concentration has a very small effect on the permeate flux and thermal efficiency. On the contrary, increasing the inlet temperature of the hot solution has a major effect on the permeate flux. For instance an increase from 40 to 80°C would increase the flux by nearly an order of magnitude and the thermal efficiency by 12%. The selectivity of membrane desalination is higher than this of any other membrane desalination process, and the produced water, as measured through the experiments, is proven to be purer even than the water produced by MSF.

Within the field of desalination processes, one has to point out the MD process taking place on atmospheric pressure, and on temperatures not exceeding 80°C, raising energy demand to that of thermal energy only. For this reason, MD is a process with several advantages regarding the integration into a solar, thermally-driven, desalination system. In addition, integrating membrane distillation with other distillation processes seems to be promising, for example by using MD as a bottoming process for MSF or ME, so that the hot reject brine from MSF or ME could operate as the feed solution for the MD plant [73].

In bibliography specific reports to solar, thermally driven, MD systems are detected. Bier and Plantikow present the results for a prototype of an autonomous solar MD system, powered by a 51 m^2 collector field, and being installed on 1993 on the Island of Ibiza, Spain. A distillate production of 40–85 l/h is reported for feed water flows of 0.8–1.7 m^3/h [74]. Koschikowski et al. discuss the design and development of a stand-alone MD system powered by 5.9 m^2 of corrosion-tie, seawater-resistant, thermal collectors. The maximum of distillate gain during the test period of summer 2002 was about 130 l/d under the meteorological conditions of Freiburg (Germany) [75]. Recently, the same authors presented the first results from the on-going tests of a new compact, thermal solar-powered MD unit, installed in the Canary Island, showing that distillate production rates of about 25 l m^{-2} d^{-1} are realistic [76].

A modified air gap MD process (Memstill process) aiming at presenting a low-cost alternative solution to both large- and small-scale RO, MSF and MED practices, was developed by a consortium of nine parties. According to the author, MEMSTILL® houses a continuum of membrane evaporation stages in an almost ideal counter current flow process, making it possible to achieve a very high recovery of evaporation heat [77]. Kullab et al. present results from the investigation of a stand-alone air-gap MD unit integrated with non-concentrating solar collectors, aiming to the development of a commercial prototype for mass production. Scaling-up of the MD unit was accomplished on the basis of experimental data obtained from the prototype and a simulation was performed for a specific case study [78].

In summary, MD desalination seems to be a highly promising process, especially for situations where low-temperature solar, waste or other heat is available. When operating between the same top and bottom temperatures as MSF plants, MD with heat recovery can operate at performance ratios about the same as the commercial MSF plants, but with much lower pumping power consumption. MD systems are very compact, similar to RO ones, and at least 40-fold more compact than other distillation desalination systems such as MSF. It is obvious though that a more intensive research and development effort is needed, both in experimentation and modelling, focused on key issues such as long-term liquid/vapour selectivity, membrane aging and fouling, feedwater contamination and heat recovery optimization. Scale-up studies and realistic assessment of the basic working parameters on real pilot plants, including cost and long-term stability are also considered to be necessary.

4. Electromechanical processes

4.1. PV-driven RO and ED processes

There are mainly two PV driven membrane processes, reverse osmosis (RO) and electrodialysis (ED). The first one (RO) is a pressure-driven membrane process where a feed stream flows under pressure through a semi-permeable membrane, separating two aqueous streams, one rich in salt and the other poor in salt. Water will pass through the membrane, when the applied pressure is higher than the osmotic pressure, while salt is retained. As a result, a low salt concentration permeate stream is obtained and a concentrated brine remains at the feed side. ED is an electricity-driven process where an ionic solution is pumped through anion- and cation-exchange membranes arranged in an alternating pattern between an anode and a cathode. When an electrical potential is applied between the two electrodes, the cations migrate towards the cathode but are retained by positively charged anion-exchange membranes, while the anions migrate towards the anode and are retained by cation-exchange membranes. The described phenomenon results in ion concentration in alternate compartments (concentrate or brine compartment), while other compartments simultaneously become depleted (dilute compartment). Comparing RO and ED, one could say that in reverse osmosis the water is transported through the membrane and the electrolytes are retained, while in electrodialysis the electrolytes are transported through the membrane and water is more or less retained [79,80].

From a technical point of view, PV as well as RO and ED are mature and commercially available technologies at present time. Besides that, RO represents 42% of world-wide desalination capacity and more than 88% of membrane processes production [81]. The feasibility of PV-powered RO or ED systems, as valid options for desalination at remote sites, has also been proven [82]. Indeed, there are commercially available stand-alone, PV powered desalination systems [83]. The main problem of these technologies is the high cost and, for the time being, the availability of PV cells.

With regard to the process selection, the choice of the most relevant technology mostly depends on the feed water quality, level of technical infrastructures (availability of skilled operators and of chemical and membrane supplies) and user requirement:

- Both RO and ED can be used for brackish water desalination, but RO constitutes a more realistic choice for seawater desalination, since it presents higher energy efficiency than ED when feed water salinity is higher than, let us say, 2000 ppm. ED is preferable for brackish water desalination, due to its relatively higher efficiency and robustness.
- Considering the feed water quality, pre-treatment is often more strict in the case of RO, since RO membranes are very susceptible to fouling. On the other hand, as ED only removes ions from the water, additional measures may be required (disinfection, removal of particles, etc.) [84,85].
- Considering the energy supply, RO presents lower energy consumption but ED shows better behaviour considering intermittent or fluctuating electrical power, as a consequence of changes in solar resource intensity.

Several RO or ED desalination systems driven by PV have been installed throughout the world in the last decades, most of them being built as experimental or demonstration plants. An overview of technology options with reference to existing systems is given in [19]. Some authors present experimental or simulation results [86–91], while some others concentrate on cost analysis [92–94].

The challenge for the near future seems to be the development of small, autonomous, modular, flexible and reliable units, offering operation and maintenance at reasonable cost, in order to serve the segment of isolated users [80]. On that level, the development of battery-less systems, as well as the use of recovery devices, is of special importance.

Obviously, batteries increase the overall productivity of the PV system in an intermittent electrical power context induced by fluctuating solar radiation. However, they require careful maintenance and, hence, higher skills for sustainable operation, conditions which are proved to be difficult at remote sites. For this reason, intermittent operation of direct connected PV–RO and PV–ED plant may be a promising option. This requires modification of common design rules for the electronics and the water processing part of the plant.

The battery-less option has been discussed by some authors in PV desalination applications [95,96]. Recently, Richards et al. presented results from field performance test of a 1000 l/d PV powered hybrid ultrafiltration–nanofiltration or RO system. The system operates without batteries, and is designed to desalinate groundwater of marginal and brackish water [97]. Advantages of battery-less systems with electronic power converters are simplified configuration, compact design, improved robustness and long life of all components of the power supply sub-system. Disadvantages are higher cost and possible availability problems of power electronics, longer periods in 'stand by' mode with related risks of membrane fouling, critical importance of optimized sizing of sub-systems.

Another promising option is that of the energy recovery devices. Pelton wheel turbines and pressure exchangers are commonly used in RO desalination to recover part of the feed pressure, but both systems have been available for large plants only. However, some authors have recently reported applications in which hydraulic motors and a Spectra Clark Pump were used to recover energy for smaller plants [96,98]. According to their conclusions, these systems may ensure higher efficiency over a wide range of flow rates and look-very promising for PV–RO plants. Nevertheless, conclusions from long-term operation in real conditions still have to be reported, in particular concerning fouling and scaling phenomena.

4.2. Wind power and hybrid wind power–PV

The electrical or mechanical power generated by a wind turbine can be used to power desalination plants. Like PV, wind turbines represent a mature, commercially available technology for power production. A comprehensive review of wind technology has been proposed by Ackermann et al. [99]. Wind power is an interesting option for seawater desalination, especially for coastal areas presenting ~~a~~ high availability of wind energy resources. Wind turbines may, for instance, be coupled with RO and ED desalination units. According to some authors, wind powered RO plants appear to be one of the most promising alternatives of renewable energy desalination [100].

Several simulation studies show the feasibility of wind powered desalination technologies, through the analysis of different types of membranes and feed water quality levels [101–103]. There are also several installations powered by wind turbines, either connected to a utility network or operating in a stand-alone mode. Most of them have been installed at Canary Islands, Spain: a 200 m^3/d wind–RO plant for brackish water desalination [104], a 56 m^3/d hybrid diesel–wind–RO plant providing fresh water and electricity for local people [19], a battery-less wind–RO [105] and a wind–ED experimental plant [106]. Based on the long-term experience accumulated at Canary Islands, the Canary Islands Technological Institute developed the concept AEROGEDESA, referring to a compact, stand-alone wind–RO system with capacities between 5 and 50 m^3/d. Furthermore, experimental investigation of a shaft power-driven wind–RO system has been reported by the same Institute [19].

Besides that, several other wind–RO desalination plants have been reported in the literature [107–112] as well as some mechanical VC installations powered by wind turbines [22,113,114]. In a recent paper, Carta et al. have presented a fully autonomous, battery-less system which consists of a wind farm supplying the energy needs of a group of eight RO modules [115]. The main innovation of this system refers to the implementation of an automatic operation strategy, controlling the number of RO modules that have to be connected in order to match the variable wind energy supply.

The idea to use hybrid wind–solar systems for desalinization is based on the fact that, for some locations, wind and solar time profiles do not coincide. Obviously, the opportunity to install such a hybrid system has to be carefully investigated by means of simulation [116], using typical metrological data. Finally, it is to be noted that some small-scale experimental pilot plants of this type are reported in the literature [88,99,117,118].

5. Desalination powered by geothermal energy

Even though geothermal energy is not as common in use as solar (PV or solar thermal collectors) or wind energy, it presents a mature technology which can be used to provide energy for desalination at a competitive cost. Furthermore, and comparatively to other RE technologies, the main advantage of geothermal energy is that the thermal storage is unnecessary, since it is both continuous and predictable [119]. A high-pressure geothermal source allows the direct use of shaft power on mechanically driven desalination, while high temperature geothermal fluids can be used to power electricity-driven RO or ED plants. However, the most interesting option seems to be the direct use of geothermal fluid of sufficiently high temperature in connection to thermal desalination technologies [4].

The first geothermal energy-powered desalination plants have been installed in the United States by the 70s [120,121], through the testing of various potential options for the desalination technology, including MSF and ED. Ophir presents an economic analysis showing that high-temperature geothermal desalination plants could be a viable option [122]. Karytsas proposed a technical and economic analysis of an MED plant, with a capacity of 80 m^3/d, powered by low-temperature geothermal source and installed in Kimolos, Greece [123]. Bourouni et al presented results from an experimental investigation of two polypropylene made HD plants powered by geothermal energy [124]. Recently, Bouchekima discussed the performances of a hybrid system, consisting of a solar still in which the feed water is brackish underground geothermal water [125].

Finally, the availability and/or suitability of geothermal energy, and other RE resources, for desalination, are given by Belessiotis and Delyannis [126].

6. Conclusions

The use of renewable energies for desalination appears nowadays as a reasonable and technically mature option towards the emerging and stressing energy and water problems. However, and despite intensive research world-wide, the actual penetration of RES-powered desalination installations is too low.

During the recent past, there has been a rather intense attempt to develop effective large-scale desalination plants, mainly powered by renewable sources. Through this activity, considerable experience has been gained, even if this option appears to have entered a phase of relative stagnation.

Yet, numerous low-density population areas lack not only fresh water but, in most of the cases, electrical power grid connections as well. For these regions renewable energy desalination is often the only solution. Through this situation there is a growing interest for the development of small-scale autonomous solutions, also confirmed by the respective bibliography.

Thus, what is important now is to move towards the development of integrated solutions, ensuring reliability, robustness, sustainability in terms of local resources and effective performance at acceptable cost. From this point of view, there have been detected some promising technological options that have to be studied more thoroughly aiming to achieve optimum operation and overcome specific construction and operational problems. Amongst the issues to be investigated, one may mention the following:

- The humidification–dehumidification process presents several attractive features, including the ability to combine with low temperature renewable energy sources, modest level of technology employed, simplicity of design and, most of all, relatively high efficiency compared to other thermal processes. Thus, it is of great importance to work further on problems related to material optimization and on the establishment of realistic cost figures in actual operation conditions.
- MD desalination seems to be a highly promising process, especially for situations where low-temperature solar, waste or other heat is available. It is obvious though that a more intensive research and development effort is needed, both in experimentation and modelling, focused on key issues such as long-term liquid/vapour selectivity, membrane aging and fouling, feed water contamination and heat recovery optimization. Scale-up studies and realistic assessment of the basic working parameters on real pilot plants, including cost and long-term stability are also considered to be necessary.
- PV and wind powered desalination technologies appear to be a rather mature option from a technological point of view. The challenge here would be to propose more efficient and sustainable solutions though system integration and subsystem packaging. Upon this, the issue of storage becomes of critical importance, having to cope with the intermittent and fluctuating character of the renewable source. Concerning storage, three main options are discussed: improved or new storage technologies (potentially including hydrogen), optimal management of modular type desalination units according to the energy availability, and implementation of new control strategies, supported by appropriate electronics, allowing battery-less operation. Concerning efficiency, a promising option appears to be the use of recovery devices, designed specifically for small scale applications.

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