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Renewable Energy-Driven Desalination: New Trends and Future Prospects of Small Capacity Systems

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Abstract: New trends and future prospects for small capacity systems of Renewable Energy-driven DESalination (REDES) are reviewed and assessed in this paper over a nominal desalination capacity range of 3–1000 m^3/d. A thorough literature review is reported in order to evaluate current research and developing activities. Outstanding commercial prospects in the near future are identified for two off-grid REDES technologies under development. First, wave energy converters with direct coupling to seawater desalination. Second, solar micro gas turbines with biofuel backup coupled to reverse osmosis (RO) desalination and/or zero liquid discharge water treatment. These systems, as well as mature REDES plants (namely PV/RO and wind turbines/RO), will benefit from forthcoming advances in energy efficiency in the RO process itself. The Closed Circuit RO desalination (CCRO^{TM}) concept may be a key configuration for enhancing RE-driven RO desalination. Additionally, opportunities for innovation in seawater RO desalination with variable power consumption are highlighted. On the other hand, our conclusions highlight opportunities for developing novel portable REDES systems based on solar membrane distillation with a portable linear Fresnel concentrator manufactured by SOLATOM. Additionally, the concept of portable systems could foster the commercial development of microbial desalination cells combined with solar PV energy and RO powered by tidal currents.

Keywords: solar desalination; seawater desalination; renewable energies; wave energy; wind driven desalination; microbial desalination cells; reverse osmosis

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1. Introduction

Isolated communities in extreme arid regions with no grid available require the development of desalination technologies driven by renewable energy (RE) sources regardless of the costs and energy efficiency. Nevertheless, only the most energy efficient and cost-effective systems will have market opportunities against mature competing technologies such as reverse osmosis (RO) driven by wind and/or solar photovoltaic (PV) energies.

This paper reviews and assesses the most relevant new trends in RE-powered DESalination (REDES), focusing on off-grid systems within a nominal capacity up to 1000 m^3/d in order to identify technologies with the best future market prospects.

The REDES technologies that existed prior to the last decade suffered from slow progress in terms of technology development—i.e., maturity and reliability. In addition, improvements in the main parameters of fresh water production, namely energy consumption and capital expenses, among others, have been significant. They are mainly attributable to an evolution in the cost and efficiency of solar energy systems. Moreover, experience gained in operating RO systems out of their nominal capacity will make REDES systems more and more able to fit power production and consumption profiles. References [1–4] describe experimental research on configurations of RO desalination systems that allows for the regulation of water production and the corresponding consumption to fit the energy generation curve. This is essential to increase the operation hours of the desalination plants, thus improving their cost efficiency. There are two main options—to install several RO plants working in parallel or to design a single RO plant with several trains of different capacity that are able to be operated independently to allow for the operation of the plant at partial loads.

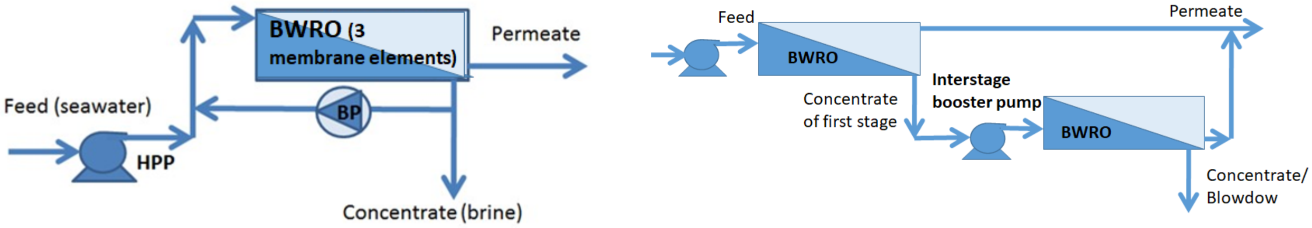
Reports on the prospects of REDES can be found in [5–8]. With regard to those publications, this paper aims to provide complementary information and discussions. In addition, some papers focused on the description of existing REDES technologies are suggested for further reading as follows. The status of conventional REDES is reported in [9] concerning solar photovoltaic (PV) and wind systems and in [10] considering solar thermal energy. Complementary information dealing with the main advances in REDES within the first decade of the 21st century is provided in [11]. Additionally, a summary of the development of wind-driven desalination into a mature technology can be found in [12]. Moreover, in relation to solar thermal energy, the development of solar thermal power cycles for driving RO desalination at a medium capacity range based on organic Rankine cycles is described in [13]. Small capacity membrane distillation directly driven by solar thermal collectors is reviewed in [14] and conventional distillation plants coupled with solar thermal conversion systems can be found in [15].

Based on the expertise acquired by the authors on REDES, the main innovations from the last decade that could be applicable for enhancing REDES have been preselected for discussion in this paper from among those reported in the literature. The figure of merit for selecting the desalination process to be driven by REs is the energy efficiency, since the costs of technologies under development are not representative of those that will be achieved when they are fully developed. Concerning desalination processes with electricity/shaft power consumption, RO exhibits the best energy efficiency for seawater desalination applications regardless of the system capacity. This is also a suitable selection for drinking water production from brackish water resources. The latest research trends in the RO process are studied. Furthermore, recent technological advances in thermal-driven desalination mainly consist of enhancing the energy efficiency of the commercial products of membrane distillation (MD) rather than industrial distillation technologies; thus, other distillation processes are discarded for coupling with REs. In addition, this paper addresses highly innovative energy resources as follows. The chemical energy of wastewater is considered a sustainable energy source that can be directly coupled with electrodialysis by means of microbial desalination cells (MDCs). Furthermore, opportunities to exploit energy from salinity gradients by integrating such systems in RO plants are also analyzed. Finally, the future prospects of innovative REDES for small capacity systems are assessed.

Sections 1.1–1.3 describe the aforementioned new research trends with potential applications in REDES, advances in RO desalination, and recently developed sustainable energies, namely salinity gradients and the chemical energy of wastewater. Sections 2–4 assess the key concepts for developing innovative REDES technologies with significant market prospects, potential advances in RO desalination, MDCs, and highly innovative RE-desalination technologies currently under development based on solar and wave energies. Lastly, Sections 4 and 5 point to new trends that will likely result in a new generation of REDES plants that are able to compete with existing mature technologies.

1.1. Innovative Configurations of RO Desalination

As the most important effect on the specific electricity consumption in SeaWater Reverse Osmosis (SWRO) desalination is caused by the plant configuration, this is the first issue to be assessed. Lin and Elimelech [16] thoroughly explain the concept of staged SWRO configurations. They consist of several RO processes coupled in series, with the concentrate of one stage being the feed for the next. In seawater RO desalination, each stage comprises a set of 7–8 membrane elements coupled in series within each pressure vessel. In a desalination plant, a set of pressure vessels is coupled in parallel to meet the water demand. A conventional SWRO desalination plant consists of a single stage. The main electricity consumption is typically 2.0–2.3 kWh/m^3 in Atlantic seawater conditions. If the permeate produced requires further treatment in a second pass of brackish water RO membranes, it results in an additional consumption of about 0.3–0.5 kWh/m^3. The technical limit of specific electricity consumption corresponds to an unlimited number of stages operated with a negligible driving force, i.e., the pressure gradient minus the osmotic pressure gradient at the opposite sides of the RO membrane. The authors of the abovementioned paper compare the single stage configuration normally used in SWRO with configurations with two stages and a closed circuit desalination (CCD) layout, which was proposed by R. Stover [17] and developed by Desalitech. Brackish water desalination systems based on the CCD configuration (CCRO^{TM}) represent the most relevant commercial development of RO desalination in the last decade. Nevertheless, regarding the CCD concept for seawater desalination, brine energy recovery is the main bottleneck for achieving a significant decrease in its the energy consumption below that of the two-staged SWRO technology. Figure 1a shows the CCD concept applied to brackish water desalination. The system operates in batches thanks to the on/off valves corresponding to the feed inlet and the concentrate outlet. Feed flow (brackish water) is recirculated within pressure vessels in parallel that consist of only three membrane elements. Therefore, the brackish water flow progressively increases the salinity until the concentrate valve is opened for discharging and the feedwater valve is opened to start a new desalination process. Both valves remain closed while the feedwater is recirculating. Solvent extraction up to 90% can be achieved in brackish water desalination with lower energy consumption and investment cost [16,17] in comparison to a conventional configuration—depicted in Figure 1b. The relatively low operating pressure (below 25 bar) required in brackish water desalination in comparison with that of seawater desalination (normally 52–64 bar) results in scarce use of energy recovery devices. Therefore, discontinuous operation of the CCD concept does not become a barrier to this application.



(**a**) (**b**)

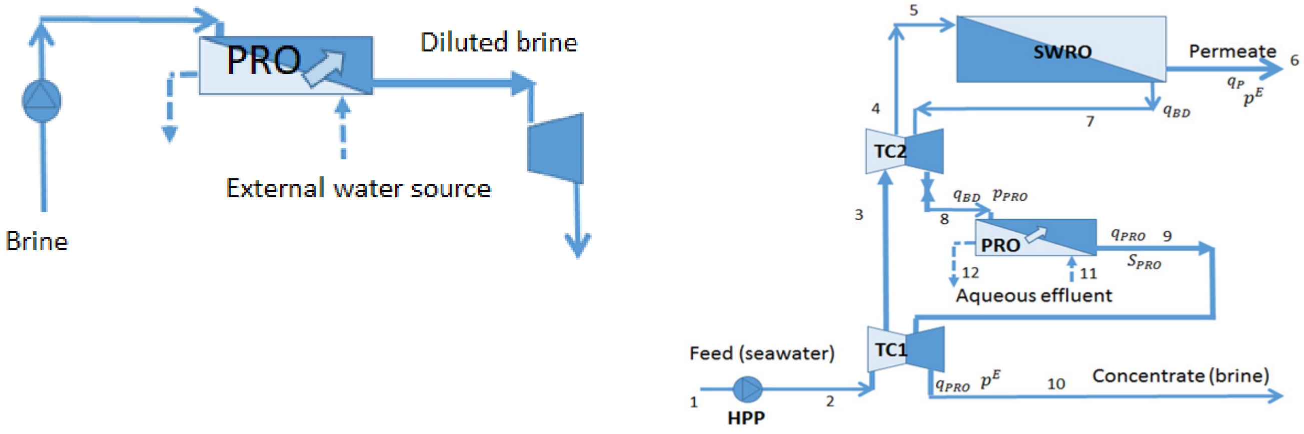
Figure 1. Conceptual diagrams of two configurations of brackish water reverse osmosis (BWRO) systems: (**a**) closed circuit desalination (CCD); (**b**) conventional desalination configuration.

1.2. Processes Driven by Salinity Gradients

Power production from a salinity gradient could be performed by means of either pressure retarded osmosis or reverse electrodialysis. Both processes could be coupled with SWRO desalination plants:

- *Pressure Retarded Osmosis (PRO)*. The PRO process consists of the spontaneous passing of water through a semipermeable membrane from a low concentration solution at around ambient pressure to a pressurized high-concentration solution. The process is technically feasible if the pressure in the high-concentration channel with respect to the low salinity channel is lower than the difference in osmotic pressure between them. Power generation is mainly due to the flow increase in the high-concentration channel, since the water flow transferred through the membrane increases its pressure. The useful output of the PRO system is the pressurized flow of diluted brine, which could drive either:
    - ○ a hydraulic turbine to produce shaft power/electricity (see Figure 2a) or

  - an energy recovery device—i.e., a turbocharger or isobaric chamber—coupled with the seawater feed flow of the desalination plant (see Figure 2b).



(**a**) (**b**)

Figure 2. Energy production from pressure retarded osmosis by pressurizing water transferred through the membrane elements. (**a**) Conceptual diagram of electricity production. (**b**) A possible combination of PRO and RO desalination with two turbo chargers (TC) as energy recovery devices.

Studies and literature reviews on this topic include [18,19], among others. Despite the current scarcity of precommercial and commercial membrane elements, there is significant research activity on the development of membranes, such as the groundbreaking work given in [20–22]. Moreover, some of the first interesting proposals of desalination configurations were reported by Kim et al. [23] and Sakai et al. [24].

- Reverse ElectroDialysis (RED). The RED process is the inverse concept of electrodialysis and generates electricity from spontaneous ion migration. The RED technique is elaborately described in the pioneering papers [25–28]. Additionally, refer to [29–31] for some recent representative literature in relation to system design, numerical simulation, and an interesting case study, respectively.

On the other hand, forward osmosis (FO) is based on the spontaneous water extraction from seawater by a draw solution when a semipermeable membrane separates both of them. The process operates at ambient pressure. Water transferred to the draw solution should be separated by a desalination process. The draw solution flow at each point of the membrane surface must have higher osmotic pressure than that of the feed flow circulation at the opposite side of the membrane, which consists of seawater that is progressively concentrated. Therefore, RO is not useful for desalinating the draw solution. No processes that can compete with conventional desalination have been identified.

1.3. Microbial Desalination Cells (MDCs)

Microbial desalination cells consist of a microbial fuel cell and an electrodialysis (ED) desalination cell. The smallest unit consists of a central chamber containing a saline solution (feed solution) separated by anionic and cationic membranes from the respective electrode compartments. The energy source is wastewater placed in the compartment of the anode electrode by means of the chemical energy of organic matter degraded by microorganisms. Electrons delivered in such a process drive the ED cell where ions migrate to the respective electrodes through membranes. Thus, the salinity of the central chamber progressively decreases. Figure 3 depicts the conceptual diagram of the desalination process carried out by a MDC. To date, there are no commercial products of this type available.

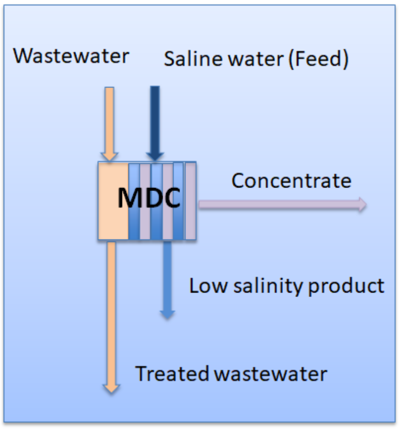


Figure 3. Conceptual diagram of a desalination process by means of a MDC.

Excellent reviews on MDCs are reported in [32,33] that thoroughly study the desalination process and other bioelectrochemical systems [34]. Additionally, FO integrated within MDC to enhance the desalination process has been described and is referred to as Osmotic MDC (OsMDC) [35]. As a complementary analysis, this paper aims to assess MDCs from the point of view of conventional desalination processes. Since technical descriptions of MDCs, experimental setups, and procedures are outside the scope of this paper, readers interested in these topics are encouraged to find related information in the following papers: bipolar membrane MDCs [36], ion exchange membranes [37], applications and working conditions [38], operational assessment of a MDC over 900 h [39], temperature effect [40], modeling [41], use of ion exchange resins [42], pH imbalance [43], and series connections of MDCs [44].

The main identified technical bottlenecks of MDCs are:

- Large volume of the anode solution required in comparison to that of seawater/brackish water to be treated.
- Long start-up period.
- Decreasing of the pH of the anodic compartment, thus causing damage on the adjacent membrane.
- Toxic waste.
- Low voltage achieved, which results in a very slow desalination process.

Relevant papers that solve said bottlenecks of MDC technology development are the following: Meng et al. [45] test an advanced MDC with significant improvements to the start-up period and maintain the anodic pH; Al Hinai et al. [46], Qu et al. [47], and Chen et al. [43] focus on avoiding pH imbalance; Liang et al. [48] analyze photo-electrochemical interactions in a modified design MDC; Sophia and Bhalambaal [49] use coconut shell carbon in the anode to increase salt removal; Mier et al. [50], Borràs et al. [51], and Ma and Hou [52] describe the latest developments in electrode materials; Greenman et al. [53] address biofilms with anodic electrodes; Kokabian and Gude [54] propose and test biocathodes to increase sustainability by avoiding toxic chemicals; Barahoei et al. [55] successfully assess microalgae as biocathodes; and Zhang and He [56] propose applying an external voltage in order to accelerate the salt removal as part of their scaling-up analysis.

The experimental data available so far seem to suggest that MDCs in the near future will mainly be used for producing low salinity water from seawater instead of fresh water, due to the technical bottlenecks discussed by Mehanna et al. [57]. Therefore, the design of seawater desalination applications requires the coupling of MDC with another desalination process. On the contrary, brackish water desalination does not exhibit such a problem.

The combination of MDCs prior to a RO or an electrodialysis process has been proposed as a way to significantly reduce the energy consumption of seawater desalination [36,58]. To this end, the Spanish company FCC-Aqualia coordinated the H2020 project

MIDES [58], an existing prototype of MDC that has a capacity of 1 m^3/d. The desalination process achieves productivity of 12.5 $L/m^2 \cdot h$.

Wen et al. [59] propose a system based on membrane capacitive deionization after MDC treatment to complete the desalination process. Furthermore, Shehab et al. [38] incorporate the electrodeionization process into the MDC. Concerning other processes, Morel et al. [60] and Zhang et al. [61] implemented ion exchange resins within the MDC. Finally, Yuan et al. [62,63] proposed the use of MDC together with the forward osmosis (FO) process.

In addition, it should be highlighted that an added bonus of developing MDC technology is the simultaneous processes of salinity decrease in the feed solution and wastewater treatment. The latter could be improved with the use of an aerobic biocathode (bacterial catalysts) [64] or could be complemented by a post-aerobic process [56]. Moreover, Mehanna et al. [65] suggest that MDC technology can be used for both water desalination and hydrogen gas production. Li et al. [66] propose the removal of nitrogen in municipal wastewater or metal in industrial wastewater. Finally, Zamanpour et al. [67] experimentally assess microalgae cultivation integrated within MDCs.

Cao et al. [68] describe a pilot system capable of reducing feed salinity up to 90%. This result was based on experimental analyses with initial salt concentrations of 5, 20, and 35 g/L. The results are remarkable, not only because the desalination process required no external energy source but also due to the unconventional use of the ED process with high salinity. Note that the conventional ED process is not normally recommended for desalinating saline water over 6 g/L. This is due to its high energy consumption, which increases with the salt concentration. In addition, Chen et al. [69] among others report on an advanced prototype of a MDC that consists of a membrane stack instead of a single saline chamber. This is referred to as a stacked microbial desalination cell (SMDC). The ratio of salt concentration reduction was 70%, which was obtained when using a feed solution of 20 g/L. The authors of the abovementioned study analyzed the effect of the number of chambers in the stack. Moreover, Jacobson et al. [70] refer to their previous experimental results in which 99% TDS removal was obtained from a feed saline solution of 30 g/L.

Most of the experimental tests carried out with MDCs have used saline solutions of NaCl. This makes it difficult to predict the performance of the same unit in a similar seawater desalination process. Jacobson et al. [71] provides a data comparison of the same MDC unit operated with either NaCl solution or synthetic seawater and finds superior results for NaCl.

One study found that MDCs are useful for decreasing the salt concentration of feed water with salinity around that of seawater. An essential issue would be their long-term performance, but this is extremely difficult to assess due to the scarcity of reports in the literature and the fact that they are all at the lab scale. A relevant experimental work in this regard was conducted by Meng et al. [45]. They describe an advanced MDC with a test campaign of 300 days. Luo et al. [72] studied performance evolution over 8 months. Moreover, Ragab et al. [39,40] report a thorough analysis of working conditions.

Regarding the coupling of wastewater treatments and water desalination within the same unit, Kim et al. [73] discuss product water safety considering the potential crossover of contaminants existing in the wastewater through the electrodialysis membranes. Requirements regarding membrane pore sizes and the molecular weight of contaminants are provided by the authors. Viruses and bacteria are not able to cross the membrane barrier. Lastly, as complementary information, Wilberforce et al. [74] review the exploitation of wastewater by electrochemical systems.

2. Assessment of Potential Advances in Reverse Osmosis (RO) Desalination for Improving Small-Capacity REDES

The best opportunities for improving RO desalination when developing REDES rely on two research topics:

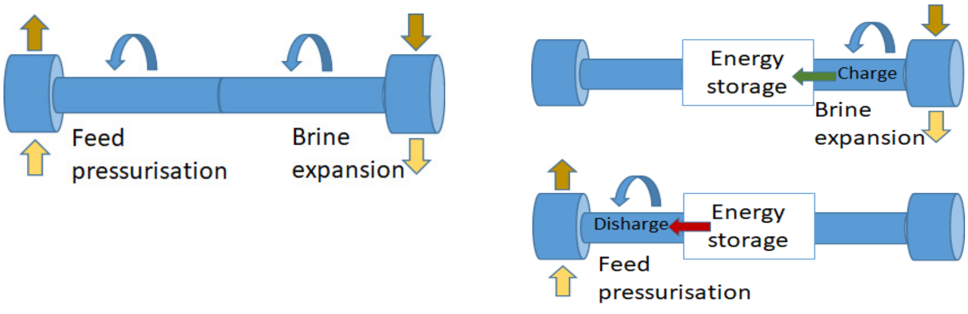
- Innovative configurations to decrease the energy consumption and investment costs of the RO desalination subsystem.
- The exploitation of power production from salinity gradients to decrease the energy consumption of the RO process.

They are discussed in subsequent subsections.

2.1. Opportunities of Innovative RO Configurations

In addition to the success of CCD in brackish water desalination, seawater desalination systems with higher energy efficiency could be made reliable via the development of dedicated energy recovery devices that allow for higher reductions in energy consumption, as described by [16].

The current technology of energy recovery devices simultaneously carries out the brine expansion and the feedwater (seawater) pressurization. Moreover, they normally operate continuously. Nevertheless, energy recovery devices should operate discontinuously in CCD systems, and processes of brine expansion and feedwater pressurization are not simultaneous. Therefore, theoretical and experimental research activities are needed. For instance, it might be feasible to couple the turbocharger concept with an energy storage device as Figure 4 describes. In a conventional turbocharger, the brine expansion generates the rotation of a central axis with which the feedwater pressurization process is coupled. Alternatively, this might be performed by means of two axes. Brine expansion produces rotation that charges a conventional battery or a flywheel whereas the energy stored is delivered for driving the seawater pressurization whenever necessary. This concept would be an innovative application of conventional flywheels, which have been used in several RE-driven RO desalination methods over the past twenty years [1].



(**a**) (**b**)

Figure 4. Conceptual diagrams of: (**a**) a conventional turbocharger and (**b**) a possible energy recovery device with discontinuous operation for SWRO desalination with a CCD configuration.

An experimental study of RO desalination operated in batches with energy recovery was carried out by Lee et al. [75]. Nevertheless, the proposed system is less energy efficient than CCD since the recycling input is placed before the main pump. After the main pump, a turbocharger enables energy recovery from the concentrate flow.

2.2. Innovative Layouts of RO Systems for Variable Power Inputs

Conventional configurations of REDES plants can be improved to fit the variable RE power output. Implemented SWRO designs with variable power outputs mainly consist of several SWRO trains operated in parallel and gradual-capacity systems. An exemplary plant was installed at the Instituto Tecnológico de Canarias (ITC) (Gran Canaria island, Spain) and comprised eight SWRO plants working in parallel [1]. In those days, no energy recovery devices were installed but it should be noted that the model RO Kinetic® has specific features for RE-driven SWRO to improve the plant operation at variable working conditions. Indeed, as described in [76], the shutdown of a unit installed in parallel with several RO Kinetic® systems does not cause a cascade shutdown of the rest of the units.

Moreover, a more cost-efficient candidate design consists of designing three trains with membrane racks of 40%, 40%, and 20% of plant capacity, respectively, as proposed by Peñate et al. [77], referred to as a gradual capacity plant. Finally, other options correspond to implementing an adequate control system to allow variable working conditions within the membrane series [78] and to combine variable working conditions with a gradual capacity as reported in [79], proposing a gradual capacity plant with three SWRO trains of 25%, 25%, and 50% of the plant capacity.

Some authors recommend the development of innovative concepts based on a non-conventional SWRO configuration as follows. Rosales-Asensio et al. [80] proposed two layouts with two high-pressure pumps in parallel and two-stage SWRO desalination to reduce water costs in wind-driven desalination in comparison to a conventional configuration. Their proposal represents the unconventional use of two stages. The conventional two stages concept with an interstage pump achieves significant energy savings with high energy recovery since the first stage operates at a relatively low pressure in comparison to the second stage. Thus, only the concentrate flow of the first stage is pumped up to the high working pressure of the second stage. However, the most energy efficient devices for energy recovery cannot be installed since pressure exchangers require not only similar flow rates of feed and concentrate but also similar low and high pressures. Energy recovery devices based on turbochargers do not exhibit said restrictions but achieve lower energy efficiency. Therefore, with usual recovery rates of 40–50%, two stages are not recommended since a negligible energy saving is achieved as plant complexity increases. On the contrary, it is worth noting that these authors designed two plant configurations with significant advantages:

- Their first diagram presents two SWRO stages with no interstage pump. Both stages consist of pressure vessels with six membrane elements in series but the number of pressure vessels in the second stage is lower to allow for a suitable feed flow. This configuration does not exhibit any technical problems concerning the pressure exchanger operation and the conventional booster pump is placed at its feed-pressurized outlet.
- Their second diagram proposes the installation of a booster pump between the two stages, thus adjusting the inlet high pressure of the pressure exchanger.

Although the analysis of the part load operation of these innovative configurations was outside the scope of this study [80], future experimental assessments should obtain successful results concerning the fitting of power curves of output and consumption.

Other feasible options should be explored. To this end, the performance of a conventional pressure vessel with seven membrane elements with variable working conditions is assessed. Reliable working conditions are preliminarily analyzed in the following tables under Mediterranean conditions, namely 40,686 ppm and a temperature range of 21–28 °C [81]. The results were obtained by using the software Q+ by LG [82] with no design warnings, which normally corresponds to:

- Excessive permeate flow (flux above recommendations of the manufacturer). This occurs at the first element of the membrane series and results in a high risk of membrane damage attributable to fouling effects.
- A low feed flow at the tail of the series of the membrane elements contributing to the scaling risk.

In addition, European standards of product quality, a TDS below 500 ppm, and a maximum Boron content of 1 ppm, among other standards, must be complied with—otherwise the simulation results are discarded. Input parameters set in all simulations carried out with LG Q+ are the following: fouling factor, 0.86; overall performance of the high-pressure pump, 0.90; energy recovery device based on pressure exchanger (isobaric chamber) with high pressure differential pressure, 0.6 bar along with negligible volumetric mixing and leakage.

The results of power consumption with variable feed flow at constant pressure are depicted in Tables 1–3 for a single pressure vessel with seven membrane elements. The columns give the feed pressure and flow rate (p_F, q_F), the permeate flow rate (q_P), the recovery rate (r—ratio of product flow rate to that of the feed), the permeate TDS and boron content (TDS_P and $Boron_P$), the specific energy consumption (SEC), the feed temperature (T), the power consumption (Pw), the percentage of Pw of the maximum Pw, and the percentage of q_F of the maximum q_F considered.

Table 1. Working conditions of a single pressure vessel with seven LG SW 440 SR membrane elements operated at a constant pressure under Mediterranean conditions at an unfavorable temperature.

p_F. bar	q_F. m^3/h	q_P. m^3/h	r	TDS_P. ppm	$Boron_P$. ppm	SEC. kWh/m^3	T. °C	Pw. kW	% Pw	% q_F
63.5	6.0	2.95	49.0	258	1.00	2.05	28	6.05	73.07	66.7
63.5	7.5	3.50	46.7	207	0.87	2.07	28	7.25	87.54	83.3
63.5	8.5	3.81	44.8	184	0.80	2.08	28	7.92	95.75	94.4
63.5	9.0	3.96	44.0	175	0.77	2.09	28	8.28	100.00	100

Table 2. Working conditions of a single pressure vessel combining two membrane models (1 LG SW 440 SR and 6 LG SW 440 GR) operated at a constant pressure under Mediterranean conditions at an unfavorable temperature.

p_F. bar	q_F. m^3/h	q_P. m^3/h	r	TDS_P. ppm	$Boron_P$. ppm	SEC. kWh/m^3	T. °C	Pw. kW	% Pw	% q_F
60.3	6.0	2.85	47.4	239	0.98	1.95	23	5.56	71.4	66.7
60.3	7.5	3.43	45.7	255	0.99	1.96	28	6.72	86.4	83.3
60.3	8.5	3.77	44.4	226	0.92	1.98	28	7.46	95.9	94.4
60.3	9.0	3.93	43.7	214	0.89	1.98	28	7.78	100.0	100

Table 3. Working conditions of a single pressure vessel combining two membrane models (2 LG SW 440 SR and 5 LG SW 440 R) operated at a constant pressure under Mediterranean conditions at an unfavorable temperature.

p_F. bar	q_F. m^3/h	q_P. m^3/h	r	TDS_P. ppm	$Boron_P$. ppm	SEC. kWh/m^3	T. °C	Pw. kW	% Pw	% q_F
59.9	6.0	2.86	47.6	239	0.99	1.94	21	5.55	70.4	66.7
59.9	7.5	3.45	46.0	255	1.00	1.95	26	6.73	85.4	83.3
59.9	8.5	3.84	45.2	252	0.99	1.96	28	7.53	95.5	94.4
59.9	9.0	4.00	44.4	239	0.96	1.97	28	7.88	100.0	100

Table 1 corresponds to the lowest water permeability of the RO membranes manufactured by LG, the LG SW 440 SR element. Table 2 combines one of the abovementioned elements with six elements with higher water permeability. Finally, Table 3 shows the results of two LG SW 440 SR elements with five elements with higher permeability (LG SW 440 Rs). It is worth noting that a single pressure vessel can operate at a constant pressure over a wide range of feed flows and power consumptions while complying with the European product quality regulations. Since product quality decreases with temperature, the top temperatures achievable while complying with product regulations are given if 28 °C leads to insufficient quality. Membrane elements with the lowest water permeability, LG SW 440 SR, is able to operate over the whole range of temperatures and feed flows with a gauge pressure of 63.5 bar. On the contrary, LG SW 440 GR and LG SW 440 R must be combined with other elements of lower permeability within the membrane series in order to comply with the product quality requirements. A study of design recommendations combining different models of membrane elements within the same pressure vessel is thoroughly described in [83] and considers three other relevant membrane brands, namely Filmtec, Toray, and Hydranautics. Since the membrane elements of different manufacturers can be sorted into groups with the same range of permeabilities of water and salts as described in [83], similar results are expected for other membrane brands. The well-known behavior of RO membrane elements is shown in Tables 1–3 as follows. Considering the same temperature, SEC and product quality decrease as water permeability increases. Moreover, product quality decreases with feed temperature. Additionally, working pressure decreases with water permeability at a given recovery rate.

As a complementary analysis, to give an example of the behavior of a single pressure vessel operated at constant feed flow and variable feed pressure, Table 4 shows a set of results at 28 °C regardless of the product quality along with the results at the maximum temperature required for the compliance of permeate quality requirements. A maximum temperature of 22 °C is needed for suitable product quality at a 25% recovery rate, 25 °C at 30%, and 27 °C at 35%. Under Mediterranean conditions, membrane elements with higher permeabilities are not recommended to be operated at variable pressures. Table 4 proves that up to 22 °C of feed temperature the operation of a SWRO system may be reliable within a range of power consumption of 44–100% at a constant feed flow of 8.5 m^3/h with an adequate selection of membrane permeability.

Table 4. Working conditions of a single pressure vessel with seven LG SW 440 SR membrane elements operated at a constant feed flow under Mediterranean conditions at an unfavorable temperature.

p_F. bar	q_F. m^3/h	q_P. m^3/h	r	TDS_P. ppm	$Boron_P$. ppm	SEC. kWh/m^3	T. °C	Pw. kW	% Pw	% p_F
45.6	8.5	2.13	25.0	261	1.21	1.59	28	3.39	42.9	71.7
46.8	8.5	2.13	25.0	186	0.98	1.63	22	3.47	44.0	73.6
49.4	8.5	2.55	30.0	229	1.10	1.67	28	4.26	54.0	77.7
50.2	8.5	2.55	30.0	194	0.99	1.70	25	4.34	54.9	78.9
53.6	8.5	2.98	35.0	208	1.02	1.78	28	5.30	67.2	84.3
54.0	8.5	2.98	35.0	196	0.99	1.79	27	5.33	67.6	84.9
58.4	8.5	3.40	40.0	193	0.97	1.91	28	6.49	82.3	91.8
63.6	8.5	3.83	45.0	184	0.93	2.06	28	7.89	100.0	100.0

The quantitative results given in Tables 1–4 are more favorable than those of other plant locations with higher seawater salinity and/or temperatures. In those cases, only membranes with a low water permeability will be recommended for operation under variable conditions. On the contrary, results corresponding to lower feed salinity and/or temperatures will be better than the reported results. Therefore. membrane elements with higher water permeability can be used to decrease the SEC with an adequate permeate quality.

As an overall assessment, given the ability of SWRO membrane racks to part load operation, dedicated designs of the SWRO train for applications to REDES should be conceptually developed and experimentally assessed. Feed pressurization by means of two pumps in a series or in parallel connection should be compared to conventional pumps with variable frequency drivers. In addition, other concepts recommended by the authors are presented in Figures 5 and 6. Figure 5 shows a possible layout in which valves installed at specific pressure vessels of the SWRO membrane rack allow for its operation with said pressure vessels on or off depending on the power output of the RE system and the selection of the working point of the pressure vessels. the Corresponding design of the high-pressure pumping system will be carried out on a case by case basis depending on the plant's location and a comparative cost assessment of the candidate configurations. One or two pumps with adequate operation profiles should be selected. An array of RO Kinetics® as energy recovery devices is recommended to be coupled with the SWRO membrane rack. One or several units of the array will be disconnected according to the part load operation of the membrane rack.

Additionally, Figure 6 describes two high pressure pumps (HPP) in parallel pumping the feed to a common collector that drives several membrane racks that can be connected or disconnected as a function of the number of HPPs in operation. Each of the membrane racks will be coupled to their energy recovery devices.

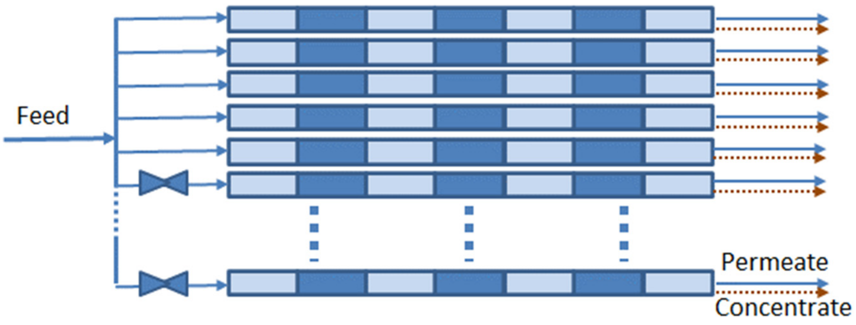
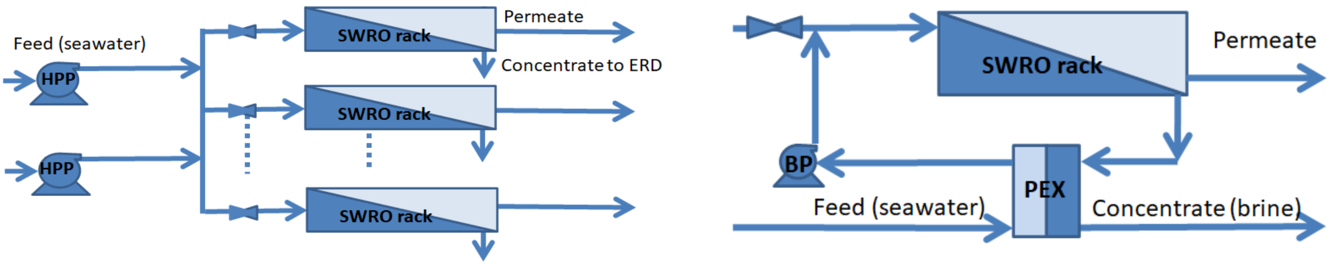


Figure 5. Innovative concept of gradual capacity SWRO rack consisting of the disconnection of specific pressure vessels to allow for adequate feed flow at operating pressure vessels.



(**a**) (**b**)

Figure 6. (**a**) Conceptual diagram of two high pressure pumps (HPP) that can be connected or disconnected or coupled in parallel for driving a variable number of membrane racks in operation. Energy recovery devices (ERD) should be installed. (**b**) Conceptual diagram of a SWRO rack when selecting Pressure EXchangers (PEX) as the ERD. The unit PEX means an array of PEXs coupled in parallel.

2.3. Assessment of SeaWater Reverse Osmosis (SWRO) Coupled to Salinity Gradient Systems

Regarding energy production from saline gradients, its application in SWRO desalination should consider the availability of an additional stream of:

- Treated wastewater. If treated wastewater is available, to allow for human consumption it requires two passes through specific membranes such as PRO, forward osmosis (FO), and RO membranes, among others. Since the osmotic pressure of treated wastewater is low, to treat this flow by means of a two-pass RO system is the best option compared with coupling RO to FO, PRO, or RED. Two passes consist of adding a second RO desalination system for further treatment of the product flow (permeate). Note that RO is a mature technology, unlike FO and PRO. Moreover, the permeability of RO membranes for wastewater treatment is quite high, so the membrane area economy should be superior. Therefore, using PRO/RO or RED/RO coupling is expected to exhibit higher capital and operating expenses.
- Treated industrial wastewater. If treated industrial wastewater or industrial wastewater with low osmotic pressure is available, the human consumption after additional treatment is normally not allowed. Thus, energy from gradients of osmotic pressure can be exploited as follows:
  - PRO. In this case, the coupling of SWRO/PRO processes may be advisable if PRO membranes withstand reasonable pressure values. Power can be generated in a PRO system by using the brine outlet of the desalination plant. Configurations such as that depicted in Figure 2b could be used, but system capital costs would limit commercial development.
  - RED. In principle, the coupling of RED and SWRO makes sense. The RED system can be placed at the brine outlet of the desalination plant without modifying

the SWRO system's configuration. Figure 7 depicts a conceptual diagram of coupling RED and RO systems. The electricity produced by the RED system decreases the total energy consumption of the RO/RED desalination system as a whole.

- Seawater. The combination of SWRO and PRO processes with an additional seawater flow and the brine outlet of a desalination plant is feasible. The specific energy consumption of desalination is reduced, but there is also an increase in capital cost attributable to the PRO system. In addition, the seawater flow needed requires the oversizing of the intake infrastructure and pumps. Therefore, PRO technology should be significantly improved before achieving the benefits of such a coupling. For instance, the configuration in Figure 2b would be feasible with adequate operating pressure.

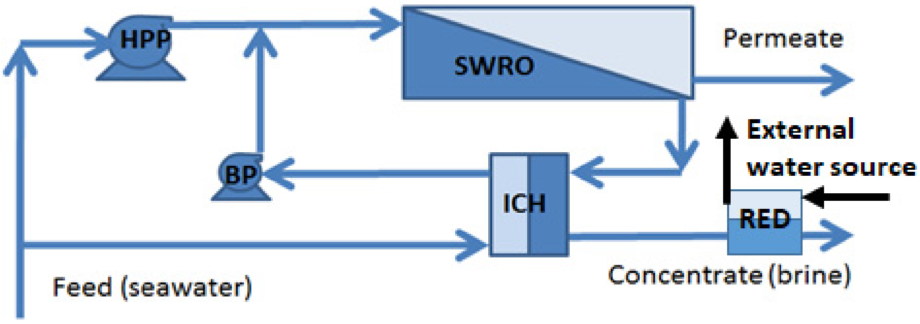


Figure 7. Conceptual diagram of coupling SWRO and RED systems. HPP: high pressure pump. BP: booster pump. ICH: energy recovery device based on isobaric chamber. SWRO: membrane elements of seawater reverse osmosis.

As an overall assessment of PRO, RED, and FO coupled with SWRO, some issues should be highlighted:

- Once discarded, the use of wastewater treated using PRO/SWRO and RED/SWRO systems exhibits important drawbacks as follows. Capital expenses would dramatically increase if an additional seawater flow were used in the PRO or RED systems. Additionally, the energy savings attributable to the installation of the PRO or RED processes may be not higher than the pumping consumption of the seawater intake. Moreover, the use of brine in RED systems and long-term operation should be thoroughly assessed before considering this application. Finally, the option of availability of treated industrial wastewater is limited to very specific cases.
- Power production by PRO or RED corresponds to an additional energy recovery device in a SWRO desalination plant as follows (see Figure 2b). The brine flow exits the RO membrane modules with high pressure and concentration. Conventional energy recovery devices (turbochargers and isobaric chambers) allow for the conversion of the energy associated with the pressure. Furthermore, the dilution of brine with PRO using a secondary flow with lower salinity would allow for the conversion of the energy associated with the salinity gradient. The brine should circulate through a conventional energy recovery device prior the PRO system in order to set an adequate pressure. After passing the PRO system, the low-pressure brine stream with increased flow is expanded to a second conventional energy recovery device. Therefore, the energy saving in comparison to a conventional SWRO plant corresponds to the hydraulic energy associated with the water flow transferred within the PRO device. The benefits in operational expenses should compensate for the significant increase in configuration complexity and capital expenses. Alternatively, a better option would be a RED process connected to the brine blowdown of a conventional SWRO plant due to the simplicity of plant configuration. In addition, SWRO/RED allows us to exploit industrial wastewater (Figure 5).

- Finally, the coupling of FO and RO in seawater desalination plants is not currently an option. This is due to the fact that the draw solution must have higher osmotic pressure than the seawater-brine flow that circulates at the opposite side of the FO system. Therefore, the desalination of the draw solution by semipermeable membranes consumes more energy than seawater desalination.

3. Opportunities with Microbial Desalination Cells (MDCs)

MDCs, when fully developed, could provide a secure and effective method of obtaining freshwater with extremely low energy consumption. Additionally, unlike conventional renewable energies, MDCs operate continuously, thus avoiding oversizing the desalination unit for a given freshwater demand.

The market prospects of MDCs mainly depend on developing upscaling capacity, increasing productivity, and decreasing product costs by generating valuable byproducts, as follows:

- Upscaling. Savla et al. [84] and Salehmin et al. [85] provide a general description of the opportunities of upscaling, whereas Liu et al. [86] focus on configurations. Thus, the upscaling barrier to market development will likely be overcome in the near future.
- Enhanced electrogenic activity by means of genetic engineering. According to Zahid et al. [87] and Gujjala et al. [32], genetic manipulation will result in enhanced MDC performance, thus improving technology prospects.
- Solar PhotoVoltaic (PV) energy as external energy source. The use of solar PV energy as an external energy source could significantly contribute to developing reliable small-capacity systems for brackish water desalination. This may be feasible and reliable according to the experimental assessment conducted by Zhang and He [56] where they applied an external voltage with excellent results for increasing the rate of salt removal. Moreover, the enhanced salt removal might be high enough to produce fresh water from seawater without the requirement of an additional desalination process to treat the MDC product.
- Generation of multiple products. Not only should the desalination process that takes place within MDCs be improved but the wastewater treatment process should also be improved in order to generate two products with economic value: treated wastewater and fresh water. This is technically feasible but further development is needed. To this end, the aforementioned study by Zhang and He [56] concerning a post-aerobic process is remarkable. In addition, Liu et al. [88] showed that the recovery of ammonia and phosphorus among other components from wastewater can be performed with dedicated designs of MDCs. Finally, Meena et al. [89] reviewed recovery from wastewater treatments.

To summarize, in the near future the market prospects of MDC technology are limited to desalination applications at the smallest capacity. Once this commercial phase has been developed, the challenge will be increasing the capacity of the commercial systems.

4. Future Prospects of Innovative REDES for Small Capacity Systems

Within the last decade, REDES technology development has been mainly focused on ocean-drive desalination. Recent papers review this coupling [90–92]. The first SWRO desalination system powered by wave energy was commercialized in 1985 by ISTI Delaware at 6 m^3/d. The DELBOUY system was developed at the University of Delware (USA) [93]. Additionally, mechanic vapor compression driven by wave energy was developed around the same time [94,95]. Nevertheless, currently RO is the only seawater desalination technology that should be considered due to its superior energy efficiency. Indeed, the main REDES developments in the last decade consist of SWRO desalination powered by tidal currents [96,97] and wave energy [98]. The applicability of tidal current-driven SWRO desalination is limited to specific plant locations; however, the predictability of this energy resource is a key feature. It is worth noting that tidal currents can power a SWRO system for 75% of the year in a favorable plant location according to [96]. This cannot be achieved by either solar or wind energies. Concerning wave energy, fifteen designs are described in [91], and among them singular systems can be found. Firstly, an impulse turbine produces electricity from the compression and decompression process of an air column, thus driving a RO water production of 10 m^3/day as reported in a pilot system in India [91,92]. Moreover, Ma et al. [99] proposed a boat that combines tidal current energy and SWRO desalination to supply electricity and fresh water.

Desalination is not the only RO treatments that can use ocean energy. Wastewater treatments and industrial applications can significantly contribute to the commercial development of ocean-driven desalination technologies [100].

Direct coupling between the tidal current turbine and the desalination system is currently under development [101]. On the other hand, different wave energy converters have been directly connected to SWRO plants [91,92,102]. For instance, Ling et al. [103] reported experimental results concerning the novel integrated design of a tidal current turbine and a hydraulic pump coupled by means of a gearbox, referred to as a supercharger. A different concept implemented by Resolute Marine relies on direct pressurization of pre-treated seawater by a wave energy converter [102].

Considering solar technologies, from the point of view of the authors SWRO desalination systems coupled with micro gas turbines (MGT) powered by point focusing solar collectors could be a reliable solar desalination technology in the near future. However, no pilot system has been implemented thus far. A prototype of Solar MGT (SMGT) was installed at the Research Centre ENEA (Italy) within the framework of a project referred to as OMSoP [103], funded by the European Commission. Outstanding assessments have been published [104,105]. It should be emphasized that exhaust gasses of the SMGT exit at around 250–300 °C, thus allowing us to exploit waste heat by means of a phase change process. In addition, SMGTs can be driven by biofuels as energy backup, thus avoiding the oversizing of the desalination system. Furthermore, the concept is scalable within a wide range of power outputs by means of installing heliostats to focus the solar irradiance on a solar tower. Depending on the power output, the gas turbine or only the solar receiver is placed on top of the tower.

For the sake of the comparison of quite different solar desalination technologies, the Figure 8 shows a rough estimation of the solar energy required in kWh to obtain 1 m^3 of freshwater. Only the main energy consumption is assessed. The solar energy technologies considered are solar photovoltaic (PV), stationary solar collectors (SSC), parabolic trough collectors (PTC), dish concentrators, and heliostats. Two thermo-mechanical conversions are studied, organic Rankine cycles (ORC) and micro gas turbines (MGT). Regarding desalination technologies, SWRO desalination with 2.2 kWh/m^3 of main energy consumption is assumed. Additionally, the main thermal energy consumption of phase change technologies is frequently reported in terms of the performance ratio (PR), defined as the ratio of 2300 kJ/kg to the specific thermal energy consumption. The PR has a very similar value to that of another parameter normally used, the GOR. The PR values given in [106,107] are assumed for the phase change technologies considered, namely humidification-dehumidification (HDH), multi-effect distillation (MED), MED with thermal vapor compression (MED-TVC), and membrane distillation (MD). To sum up, solar seawater desalination based on phase change desalination exhibits fewer opportunities to compete with solar SWRO desalination.

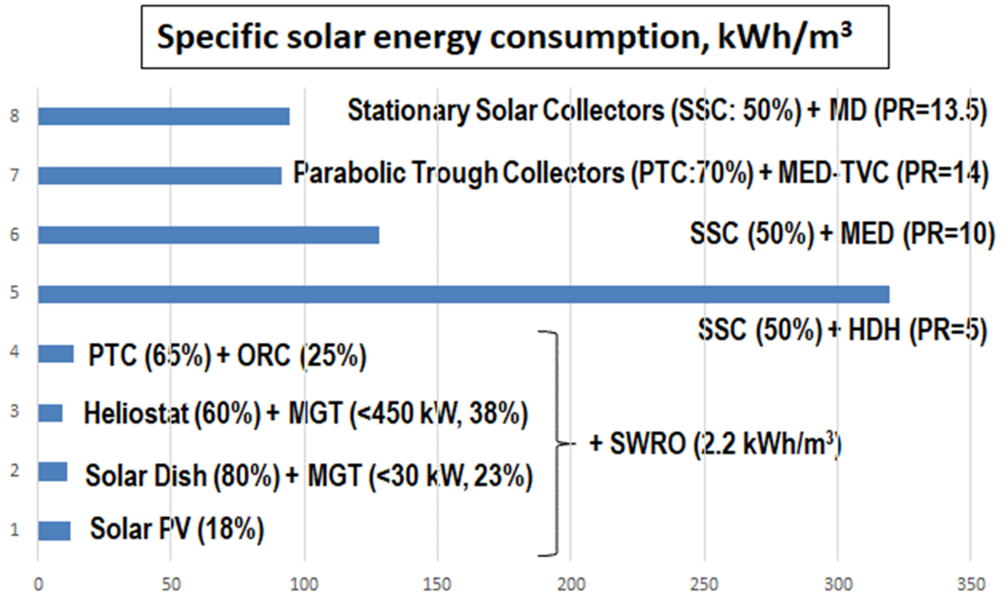


Figure 8. Comparison of solar desalination based on reverse osmosis and phase change desalination technologies. The estimation of the energy efficiency of solar energy technologies are given in brackets along with that of power cycles. The performance ratios of seawater distillation are reported in [106,107].

4.1. Outstanding REDES Technologies

From the literature review, two technologies exhibit the best commercial prospects. They are both applicable to freshwater production from around 3.5 m^3/h and scalable to an unlimited capacity.

The high temperature of the heat power rejected from the solar MGTs and the possibility of operating with biofuel energy backup are singular features that could make this technology superior to PV-driven desalination systems in many scenarios. In isolated rural communities in particular, the sustainable production of both electricity and thermal power means an opportunity to generate productive activities. An exemplary case is a rural isolated community with socioeconomic development based on agriculture activities. In addition to electricity and water production, a heat supply is required in many simple manufacturing activities. Moreover, phase change processes could be useful to treat the concentrate outlet of conventional RO desalination. The recovery of salts with economic value could be one of the objectives of brine evaporation. Concerning applications in seawater desalination, at capacity ranges of around 5–10 m^3/h, solar MGT should exhibit similar or greater efficiency than PV systems. Nevertheless, corrosion and difficulties with the concentration of beam radiation in coastal areas should be considered in comparative assessments. On the contrary, applications in brackish water desalination may result in opportunities for developing the zero liquid discharge (ZLD) concept along with exploiting a sustainable energy source.

Moreover, an assessment of the literature on ocean energy points out that the proposed design by the company Resolute Marine Ltd. is remarkable and innovative. This company has designed a wave energy-powered SWRO with direct coupling (Figure 9). One of its most innovative features is that the wave energy converter powers the RO desalination by directly pressurizing the sea water flow. Thus, the function of the high-pressure pump is performed by the wave energy converter. Nonetheless, for duplicity and safety reasons the high-pressure pump is installed. Figure 9 schematically shows the main units of the proposed system. On the left side—offshore—the wave energy converter increases the pressure of the sea water after being pre-treated. Then, pressurized seawater bypasses the high-pressure pump and enters a conventional RO membrane system, which is located onshore. Depending on the profile of the seawater flow and pressure at the wave energy converter output at a given location, along with the seawater conditions of salinity and temperature, the design of the SWRO membrane rack could be selected when considering operations outside of its nominal conditions. Dedicated designs will maximize annual freshwater production. A key concept could be the advanced gradual capacity rack design (as described in Figure 5). Additionally, other concepts described in Section 2.2 may be useful.

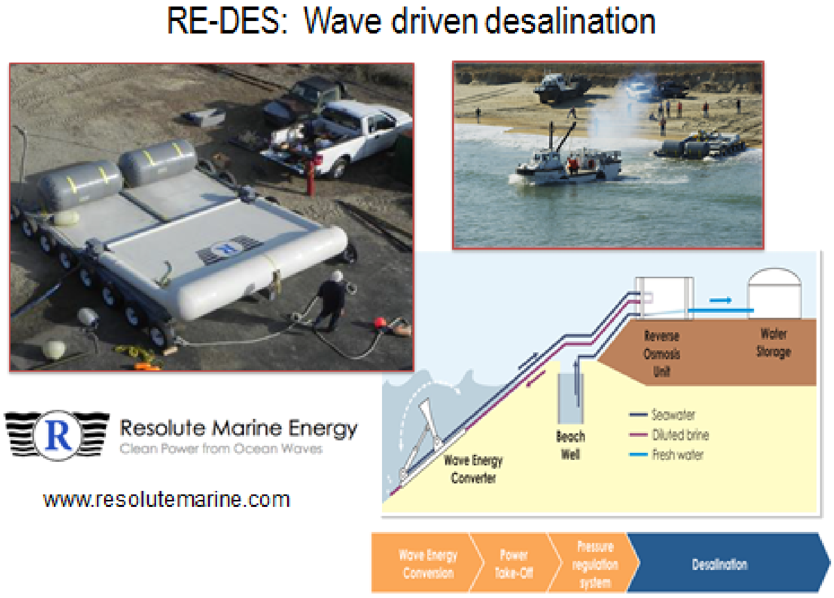


Figure 9. Pictures of Wave$_2$O^{TM} at Cabo Verde (courtesy of Resolute Marine) and system layout of the Wave$_2$O^{TM} desalination system [102].

The activities of Resolute Marine when fully developed will result in a commercial product with the only competing technology of wind-powered RO. Indeed, solar PV-driven desalination cannot compete with wind- and marine-powered systems since the energy storage is neither efficient nor cost-effective. This limits the extension of the operating time. Regarding wave-driven RO, the modular nature of both the RO and the marine subsystem may minimize the technical risk of commercializing this technology by means of installations with increased capacities.

4.2. Assessment of Hybrid Energy Systems

RO desalination driven by solar PV/wind systems is the most mature hybrid technology developed in the past century [103] that has benefited from advances in system control.

In off-grid plants, the simultaneous energy generation results in surplus energy, thus increasing the specific cost of the energy consumed. Energy generation by means of wind and wave overlaps, whereas other RE combinations exhibit complementarity. However, an exemplary case of simultaneous energy production with inherent benefit is a hybrid solar thermal/PV system for driving MD desalination, since the thermal and auxiliary energy demands are simultaneous.

Recently, hybrid energy systems based on the coupling of ocean energy systems have been conceptually or experimentally developed [108,109]. Additionally, the trihybrid combination of ocean/solar/wind energies proposed by Stuyfzand and Kappelhof [110] achieves its best prospects at medium to large desalination capacity since simplicity and unattended operation are more important at a small scale.

Hybrid systems based on ocean energies at a small scale, under 1.000 m^3/d of nominal desalination capacity, are not recommended. Ocean energy could supply the auxiliary electricity consumption of a desalination plant, which is mainly attributable to seawater intake pumping. Nevertheless, the oversizing of the main RE system would be better than implementing a hybrid energy system considering that feedwater can be easily stored to supply the discontinuous operation of the desalination unit. Indeed, part of the surplus energy can be used for the pumping systems of seawater intake and product distribution.

4.3. Enhanced Desalination Processes to Promote REDES

Improvements in the energy efficiency of the RO desalination subsystem will increase the market prospects of REDES by decreasing the nominal RE power installed per m^3/h of freshwater production. Specifically, the main recommendations for brackish water desalination are implementing CCD configurations. In relation to seawater desalination, the main R&D needs are the development of reliable configurations based on CCD and other efficient layouts. Additionally, it is worth noting the potential of producing reliable SWRO configurations that improve the ability of RO desalination plants to fit variable power production profiles. Optimized designs of feed water pumping and the development of gradual capacity RO membrane racks will significantly improve REDES systems, giving greater annual water production, lower oversizing of the RE system for a given annual production, and lower plant stoppages. As a result, product cost may notably decrease but experimental assessments are essential before drawing conclusions in this regard. Additionally, the coupling of RED and SWRO have interesting market prospects in the case of the availability of industrial wastewater.

Moreover, the singular features of MDCs could be useful in RE-driven RO desalination plants and in the generation of multiple products as follows:

- RO desalination powered by REs. When fully developed, MDCs coupled with SWRO plants may play an important role in decreasing the main energy consumption of seawater desalination. Two solutions may be commercialized—seawater pretreatment and permeate posttreatment. With regard to permeate posttreatment, Tables 1–4 show that the operation of SWRO desalination plants out of their nominal conditions can result in permeate production with insufficient quality for human consumption under specific conditions. MDCs can be a key option to treat a small portion of the daily water production that may require further treatment.
- Water desalination for generating multiple products. The production of fresh water and the processing of wastewater by MDCs could promote economic activities that involve producing multiple products with economic value.

4.4. Assessment of Energy Storage

The relevance of developing cost-effective energy storage should be noted. The best trade-off between cost and energy efficiency should be experimentally identified under the specific operating features of REDES plants. It is worth noting that ocean energy systems allow for energy storage that is suitable for solar PV and wind systems with dedicated designs. Manchester et al. [111] report on the use of capacitators, vanadium redox flow batteries, and flywheels in tidal current plants. An interesting paper related to compressed air [112] analysis for tidal stream turbines and energy storage systems referred to as ocean compressed air energy storage (OCAES) reported a cycle efficiency of 60.6%. Similar concepts at a smaller scale use spheres, pressure tanks, and balloons [113]. They are applicable to small capacity systems driven by ocean energy plants. In addition, ocean energy can benefit from using seawater as an energy storage medium as follows. A 25–30 m deep basin built along the dyke of a tidal range plant comprising a reversible pump-turbine, valves, and a generator is an innovative energy storage that has been proposed [114]. Additionally, a reversible pump-turbine is used in a method called underwater pumped hydro energy storage (UPHES) [115]. The application of these methods, along with conventional and advanced concepts on pumping storage [113,116], to wave and tidal current plants at a small scale should be studied. On the other hand, hydrogen [114] and hybrid energy storage systems [115] proposed in the literature are not recommended for small capacity systems.

4.5. Portable REDES Systems

A key issue in relation to small-scale REDES is the concept of portable systems for standalone water production. The Canary Islands Institute of Technology (ITC) has remarkable expertise in developing portable systems based on RO desalination systems powered by either wind or solar PV energies. In recent years, a low-cost system referred to as DESOL+ has been developed (Figure 10).

Figure 10. DESSOL+ desalination system (courtesy of the ITC).

Concerning competing technologies, RO desalination is not the only technology that has market opportunities for developing portable systems. PV-driven ED when applied to brackish water (BW) desalination might be superior to PV-BWRO desalination in specific cases. In addition, the Spanish company SOLATOM [117] has designed and built a portable linear Fresnel concentrator for heat supply (Figure 11). This would be able to drive the following systems:

- Membrane distillation (MD) systems. They should be installed by the sea to avoid high auxiliary consumption due to the required seawater flow for cooling.
- Hybrid RO/MD desalination systems that could be powered by hybrid PV/thermal energy systems. The role of the MD process could involve the brine concentration, along with improving the permeate quality of the SWRO system if necessary.

Scenarios with agriculture activities in which solar heat is temporarily used could be useful for the design of portable solar MD systems.

Concerning MDCs for small capacity systems, the production of fresh water and treated wastewater from seawater and wastewater in the same device would be of major interest. Moreover, solar PV energy could drive auxiliaries and increase MDC productivity in off-grid systems, which could have market opportunities regardless of the capital cost. Portable systems could be an interesting commercial option since there are no competing technologies. However, Section 3 highlighted the main research topics that need to be explored for the development of desalination systems using MDCs.

Finally, dedicated boats for SWRO desalination powered by tidal current turbines could be a key concept for small islands and rural communities in remote coastal locations. Although exploitable tidal current solutions are limited to specific regions, they should be developed due to the convenient transportation that they provide and the fact that they do not require onsite installation, unlike commercial systems based on wind/RO and PV/RO.

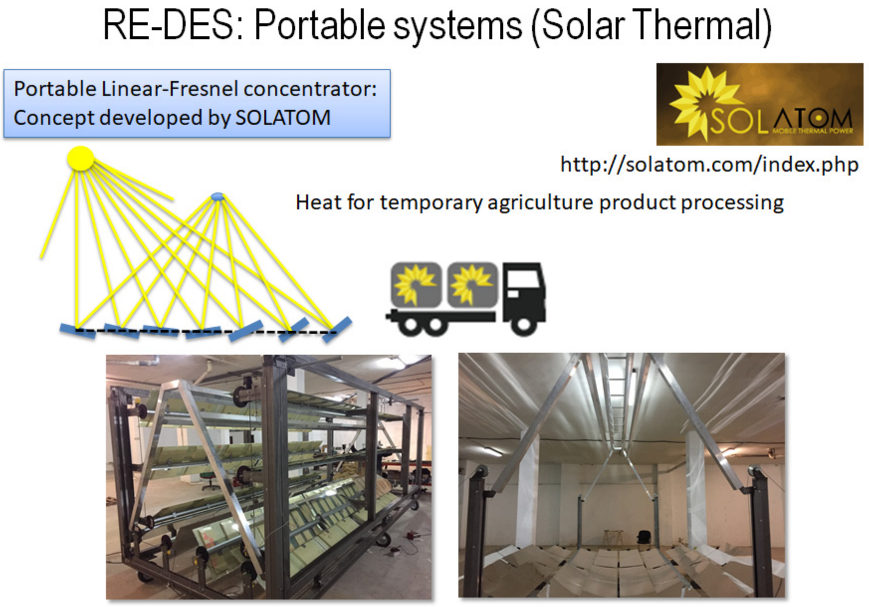


Figure 11. Concept of portable solar heat (courtesy of SOLATOM).

5. Conclusions

The new trends and future prospects for small capacity systems of REDES have been reviewed and assessed. The main conclusions are as follows:

Any technological advance in RO desalination will foster the commercial development of RE-powered systems. To this end, the key recommendations from the point of view of the authors include:

- The development of the CCD concept with dedicated energy recovery devices for SWRO and other innovative configurations of the membrane rack.
- The experimental validation of innovative layouts that enable the enhancement of the fitting of power curves of RE production and RO consumption, namely unconventional pumping system designs, gradual capacity RO racks, and the use of two stages to increase the feed flow at the tail of the series of membrane elements.
- The experimental assessment of coupling the RED process with the brine blowdown of the conventional SWRO plant if industrial wastewater with low contaminant concentration is available.

In addition, the RE-driven RO technologies under development with the best commercial prospects at a small capacity include:

- SMGT/RO with biofuel backup and concentrate treatment for brackish water desalination. This technology is also applicable to industrial wastewater treatments.
- Wave energy converters/SWRO with dedicated design for energy storage systems.
- Portable systems consisting of a SWRO desalination system coupled with a tidal current turbine.

Despite not consuming main energy, MDCs will not replace any of the commercial technologies in the near future. Nevertheless, when fully developed, MDCs could be coupled with RO desalination plants for either feed pretreatment or permeate posttreatment. Moreover, it is worth noting the ability of MDCs to simultaneously carry out desalination and wastewater treatment. Research on the design of portable desalination units based on MDCs is recommended, along with coupling these designs with solar (PV) energy.

Finally, linear Fresnel concentrators coupled with MD systems for portable systems should be thoroughly analyzed in order to assess the product costs before coming to a conclusion on their future prospects.

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