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Solar-driven desalination with reverse osmosis: the state of the art

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ABSTRACT

Solar-driven reverse osmosis desalination can potentially break the dependence of conventional desalination on fossil fuels, reduce operational costs, and improve environmental sustainability. The experience with solar desalination is investigated based on the analysis of 79 experimental and design systems worldwide. Our results show that photovoltaic-powered reverse osmosis is technically mature and — at unit costs as low as 2–3 US\$ m^{-3} — economically cost-competitive with other water supply sources for small-scale systems in remote areas. Under favourable conditions, hybrid systems with additional renewable or conventional power sources perform as good as or better than photovoltaic-powered reverse osmosis. We suggest that in the short-term, solar RO desalination will gain shares in the market of small-scale desalination in remote areas. Concentrating solar power technologies have the highest potential in the medium-term for breakthrough developments in large-scale solar desalination.

Keywords: Concentrating solar power; Photovoltaic; Pressure-driven membranes; Renewable energy; Reverse osmosis; Solar energy; Solar thermal desalination

1. Introduction

Many areas worldwide that suffer from severe water scarcities are increasingly dependent on desalination as a highly reliable, non-conventional source of freshwater. Desalination markets have greatly expanded in recent decades and they are expected to continue expanding in the coming years, particularly in the Mediterranean, Middle East and North African (MENA) regions [1].

Among desalination technologies, reverse osmosis (RO) is rapidly overtaking thermal desalination in terms of market shares [2]. A pressure-driven process that relies on the properties of semi-permeable membranes to separate water from a saline feed, the end result of reverse osmosis comprises the separate flows of freshwater permeate and concentrated brine. System flow rate is proportional to the difference between the applied pressure and the osmotic pressure differential between brine and dilute compartments. Commercially available RO membranes can retain about 98–99.5% of the salt dissolved in the feed water [3] and typical operating pressures range between 10 and 15 bar for brackish water and between 55 and 65 bar for seawater [2]. The amount of freshwater that can be recovered from the feed is limited by membrane fouling and scaling. Overall water recovery rates are typically 45–50% for seawater RO systems, and they can be as high as 90% in brackish water desalination systems [4].

The coupling of reverse osmosis desalination with solar energy is a promising field of development in the desalination sector, with the potential to (i) improve its sustainability by minimizing or completely eliminating the dependence on fossil fuels and (ii) significantly reduce the operational costs of desalination plants. Despite a steady reduction in the energy consumption of pressure-driven membrane processes in recent decades, energy

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consumption is still a major cost component of RO desalination plants, accounting for 40–45% of total costs [5].

This paper provides an extensive assessment of the experience gathered from solar-powered RO desalination. The prospects for commercial penetration and for further development of the principal technological solutions are identified and discussed.

2. The state of the art of solar-driven RO desalination

Since the pioneering studies of solar-powered RO desalination in the late seventies [6], the technical feasibility of this technology has been tested in a relatively large number of experimental units. Most of the research was conducted in countries where the conditions for solar-driven desalination are the most favourable, i.e., intense solar radiation and severe water scarcity exist. These include MENA countries, the southernmost part of Europe and Australia, (Fig. 1) where the yearly average solar irradiance on a horizontal surface is significantly higher than the worldwide average.

Most systems in operation were designed to function autonomously for small-scale desalination plants located in remote areas where freshwater resources are scarce and connection to the local grid power is unavailable. Although several full-scale plants are in operation in Saudi Arabia [7], the US Virgin Islands [8], the Maldives [9], Australia [10], Mexico [11], and Tunisia [12], most of the experimental systems in Fig. 1 are demonstration or prototype units. System capacities range from less than 0.1 m^{3}d^{-1} for prototype units and up to 75.7 m^{3}d^{-1} for full-scale systems. Several design studies investigated the technical and economical feasibilities of medium and large-size desalination units, but to the best of our knowledge, to date, no experimental study of large-scale solar-driven RO desalination plants has been done.

Depending on the type of technology used in the solar sub-unit, three principal technological solutions were investigated for solar-powered RO membrane desalination: (i) photovoltaic-powered reverse osmosis (PV-RO), (ii) solar thermal-powered RO, and (iii) hybrid solar desalination. Hybrid systems comprise combinations of solar power with power from one or more additional source, such as wind, diesel generators, or grid electricity.

2.1. *Photovoltaic-powered RO desalination*

The design option that has been implemented most frequently in solar-driven RO desalination systems is a combination of RO membranes and arrays of photovoltaic (PV) modules. The wide use of the latter is probably because photovoltaics were the first widely commercialized technology for exploiting solar energy. Indeed, at the time of writing, PV panels still dominate the solar technology market, and among the renewable energies, they constitute the fastest growing market.

In PV–RO desalination, the direct current (DC) electrical energy generated in the solar cells by silicon or other semi-conductors is used — directly or after regulation — to power the pumps that generate the pressure required for the feed water to permeate the RO membranes. Despite the many technological improvements of recent years, however, the conversion efficiencies of PV modules remain low, rarely exceeding 15–16% [13]. In addition to such low efficiencies, the retail price for PV modules, which currently stands at 4.70 € and 4.83 US$ per Watt peak (W_p) in the European and US markets, respectively [14], make solar sub-unit cost a key factor in the economic feasibility of PV–RO desalination. The technical and economical feasibilities of PV–RO desalination were tested in a series of studies (Table 1).

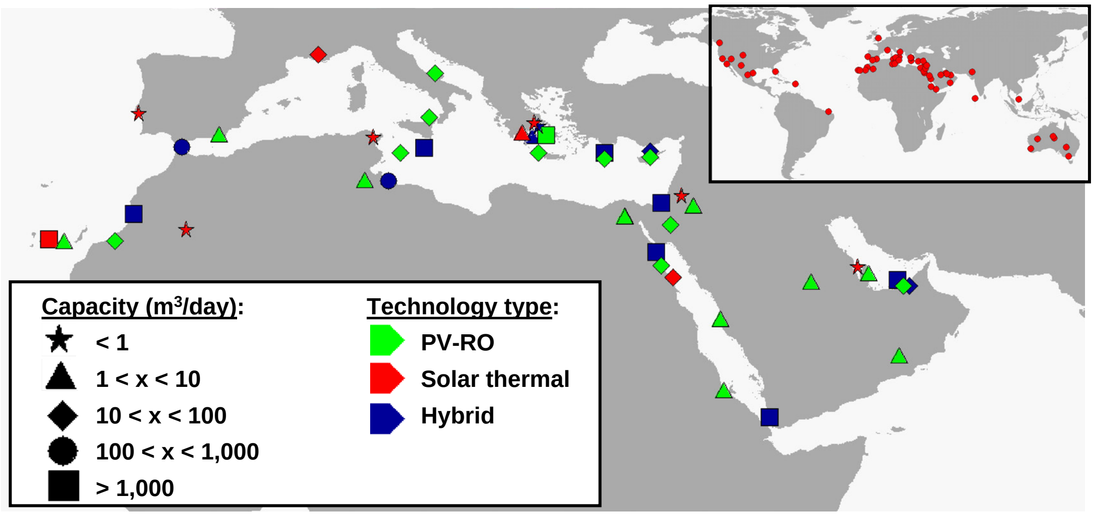

Fig. 1. Solar-driven RO desalination systems: geographical distribution and type in Mediterranean and MENA countries, and worldwide.

Table 1
Overview of PV-powered RO membrane filtration systems

Location and country[a]	Year[b]	Feed TDS, mg L^{-1}	PV capacity, kW$_p$	Battery storage	Pump drive	Production, m^{3}d^{-1}	Cost[c], $\text{US\$ m}^{-3}$	Source
Abu Dhabi, ARE[d]	2008	45,000	11.25	no	AC	20.0[e]	7.3	[15]
Agric. Univ., Athens, GRC	2006	30,000	0.85	no	DC	0.35[e]	9.8	[16]
Aqaba, JOR	2005	4,000	16.8	yes	AC	58.0	9.8	[17]
Baja California Sur, MEX	2005	4,000[f]	25	yes	AC	11.5	9.8	[11,18]
Chania, Crete, GRC[d]	2004	40,000	31.2	yes	AC	12.0[e]	8.3	[19]
Chbeika Centre, MAR[d]	1998	40,000	26.3	yes	AC	12.0[e]	35.9	[20]
Coite-Pedreiras, BRA	2000	1,200	1.1	yes	DC/AC[g]	6.0[e]	12.8	[21]
Concepción del Oro, MEX	1978	3,000	2.5	yes	DC	0.71	12.8	[6,22]
CREST, GBR	2001	32,800	1.54	no	AC	1.45	3.0	[23]
Doha, QAT	1984	35,000	11.2	no	AC	5.7[e]	3.0	[24]
El Hamrawein, EGY	1986	4,400	19.84	yes	AC	53.0	11.6	[25,26]
Fredericksted, VIR	1986	4,400[h]	19.84	yes	AC	75.7	11.6	[8]
Gillen Bore, AUS	1996	1,600	4.16	yes	AC	1.2	11.6	[10]
Giza, EGY	1980	1,600[h]	7.0	yes	AC	6.0[e]	11.6	[27]
Hammam Lif, TUN	2003	2,800	0.59	no	DC	0.05[e]	11.6	[28]
Hassi-Khebi, DZA	1987	3,500	2.59	yes	AC	0.85	10.0	[29]
Heelat Ar Rakah, OMN	1999	1,010	3.25	yes	AC	5.0[e]	6.5	[30]
Denver, ITN, USA	2003	1,600	0.54	no	DC	1.5	6.5	[31]
Java, Cituis West, IDN	1981	1,600[h]	24.5[i]	yes	DC	12.0[e]	6.5	[32]
Jeddah, SAU	1981	42,800	8	yes	DC	3.22	6.5	[33]
Ksar Ghilène, TUN	2005	3,500	10.5	yes	AC	7.0	6.5	[12,34]
Kulhudhuffushi, MDV	2005	2,500	0.3	no	DC	1.0[e]	6.5	[9]
Kuwait, KWT	2005	8,000	0.3	yes	DC	1.0	6.5	[35]
Lampedusa, ITA	1990	8,000[f]	100	yes	AC	40	10.6	[36]
Lipari, ITA	1991	8,000[f]	63	yes	AC	13.7	10.6	[18]
Lisbon, INETI, PRT	2000	2,549	0.1	no	DC	0.02	10.6	[37]
Massawa, ERI[d]	2002	40,000	2.4	no	AC	3.9	10.6	[38,39]
Mesquite, ITN, USA	2003	3,480	0.54	no	DC	1.28	3.6	[31]
Murdoch Univ., AUS	2003	3,480	0.06	no	DC	0.05	3.6	[10]
Nicosia, CYP[d]	2005	3,480[h]	10	yes	AC	50.4[e]	2.3	[18]
NRC, Cairo, EGY[d]	2002	2,000	1.1	yes	AC	1.0[e]	3.7	[40]
Pine Hill, AUS	2008	5,300	0.6	no	DC	1.1	3.7	[41]
Pozo Izquierdo, ESP	2000	35,500	4.8	yes	AC	1.24	9.6	[42,43]
Qatar village, JOR[d]	2000	3,400	32	yes	AC	45.0[e]	9.6	[44]
Sadous, Riyadh, SAU	1994	5,700	10.08	yes	AC	5.7	9.6	[7,45]
San Nicola, Tremiti, ITA	1984	5,700[f]	65	yes	AC/DC[j]	12.0[e]	9.6	[18]
SERIWA, Perth, AUS	1982	5,700[h]	1.2	yes	DC	0.55	9.6	[46]
Solarflow, AUS	1982	5,000	0.12	no	DC	0.4[e]	9.3	[47–49]
Tanote, Thar desert, IND	1986	5,000[h]	0.45	no	DC	1.0[e]	9.3	[24]
Univ. of Almería, ESP	1988	3,360	23.5	yes	DC	8.09	2.5	[50]
Univ. of Amman, JOR	1988	400	0.07	no	DC	0.1	2.5	[51]
Univ. of Athens, GRC[d]	2000	400[f]	1,968	yes	DC	1,000[e]	2.8	[52]
Univ. of Bahrain, BHR	1994	35,000	0.11	yes	DC	0.2	2.8	[53]
Vancouver, CAN	1983	33,000	0.48	no	DC	0.86	9.0	[54]
Various locations, JOR[d]	2007	7,000	1.1	yes	AC	3.6[e]	9.0	[55]
VARI-RO, USA[d]	1999	7,000[f]	1.1	no	AC	3.6	9.0	[56]
Wanoo Roadhouse, AUS	1982	7,000[h]	6	no	AC	3.6	9.0	[24]
White Cliffs, AUS	2003	3,500	0.26	no	DC	0.06	9.0	[57]

Notes: TDS = total dissolved solids; [a]Three-letter ISO 3166 code; [b]Year of commission/design; [c]Actualised cost in USD for year of study. Other currencies were converted with nominal annual average exchange rates from http://www.oanda.com/convert/fxhistory; [d]Design study; [e]Nominal capacity; [f]Seawater feed; [g]DC motor replaced by AC motor after three months operation; [h]Brackish water feed; [i]Fraction of generated power used for purposes other than desalination; [j]AC motor replaced by DC motor after four years operation.

PV–RO technology was implemented for the desalination of both brackish water and seawater (29 and 16 systems in Table 1 respectively). The production flow of experimental units is small, ranging from less than 0.1 m^3d^{-1} [10,28,37,57] to 75.7 m^3d^{-1} [8]. For the systems in Table 1, the ratio between the installed PV capacity and the production flow ranges between 0.1 and 5.5 $m^3d^{-1}kW_p^{-1}$. Although vast experience has been accrued with PV–RO system design since 1978 [6], a standard design approach has thus far not emerged. (Design solutions that either include or omit battery storage, energy inverters, and other features will be discussed in detail later in this section.) Despite the lack of standardization, however, several components are common to all design approaches, and they can be used to create a simplified, general design scheme for PV–RO desalination systems (Fig. 2):

- *Solar sub-unit (PV modules)*. Both mono-crystalline and multi-crystalline silicon modules were used in experimental units. Whether module orientation was fixed or adjustable was recognised as an important factor in determining the electrical power output and thus the overall performance of the desalination plant. While modules with fixed axes are tilted at a constant angle, modules with adjustable axes can be manually repositioned based on seasonal changes, or, if a tracking system with controller and drive motor is installed, the modules can automatically follow the sun's daily path in the sky. Alawaji et al. [7] estimated that utilizing seasonal tilt angle variation increases the yearly average permeate flow of a PV-RO desalination plant in Saudi Arabia from 15 to 17 m^3d^{-1}. For a 0.1 m^3d^{-1} PV-RO testing rig in Jordan, Abdallah et al. [51] measured gains in electrical power output and permeate flow of 25% and 15%, respectively, when a one-axis automatic tracking system was used rather than a fixed tilt plate. Harrison et al. [10] determined that tracking solar arrays produced a 60% higher permeate flow than a fixed array in a small desalinator with a capacity of 0.05 m^3d^{-1}. The high initial investment costs required to install tracking systems, however, have so far limited their use in PV-RO desalination. Maximum power point tracker (MPPT) circuits or similar optimisers [10] are generally installed to maintain system operation at a voltage that achieves maximum power while ensuring efficiency under conditions of low irradiance.
- *Water extraction unit*. The pump(s) that convey the feed water from the seawater intake or groundwater well to the RO pretreatment may be powered either by the arrays of the PV modules of the RO unit [6,7,9,12,17,38], or by other power sources such as wind turbines [30] or conventional grid electricity or a combination of the two [58]. Solar pumps — the solar sub-unit powers the feed pump(s) — were reported to be highly reliable in remote locations and to require limited maintenance, and as such, they have been used frequently [7,9].
- *Pretreatment unit*. Conventional RO pretreatment is generally implemented. The main filter barrier typically has a pore size of 5 μm and is preceded by a coarser filter with pore sizes of 20–25 μm or larger. Active carbon filtration follows for the removal of free chlorine, which can damage the RO membranes. Where bacterial counts in the feed water are high, disinfection by ozonation [31] or chlorination are used to protect the membranes from biofouling. The experience with ultrafiltration (UF) as a pretreatment step was limited to several experimental tests performed in Australia with different kinds of brackish groundwater [41,57]. UF pretreatment involves higher investment costs than conventional pretreatment, but because it removes significant numbers of microorganisms and generally delivers higher quality RO feed, which eliminates the need for membrane disinfection, UF pretreatment may reduce RO membrane cleaning

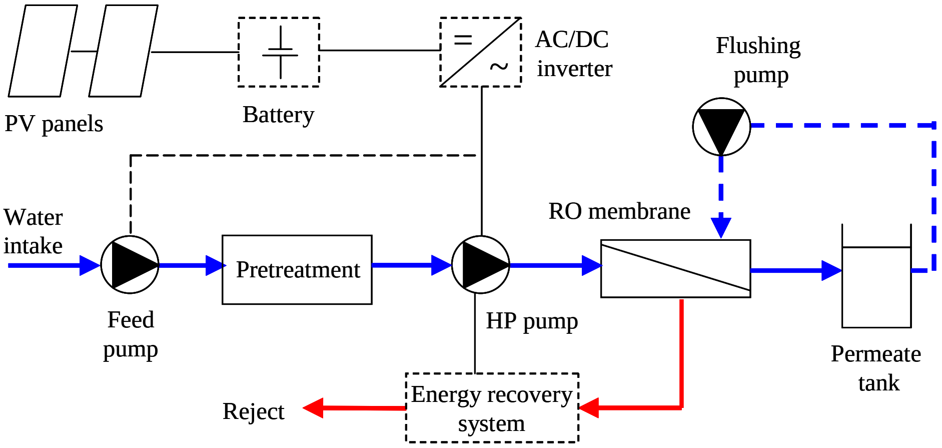

Fig. 2. Simplified general design scheme of a PV–RO desalination plant. Dashed lines identify components and connections that may be absent.

and replacement costs. Chemical pretreatment with antiscalants is frequently implemented to reduce the risk of membrane surface scaling. Alternatively, the plant may be operated at low recovery rates to prolong membrane viability [10,54].

- *High-pressure pump and motor.* As a rule, positive displacement pumps are used because of their higher energy efficiencies — with respect to centrifugal pumps — at low flows. Both rotary positive displacement pumps (e.g., rotary vane [30,31,57] and progressive cavity pumps [41]) and reciprocating pumps (e.g., piston [6,9,10,22,47] and diaphragm pumps [37]) were used. The Clark pump, a reciprocating pump that was specifically developed for energy recovery in small desalination systems and that was used in several PV–RO applications in combination with reciprocating plunger pumps [23,38] and rotary vane pumps [16] for seawater desalination, was shown to significantly reduce energy consumption. For the desalination of brackish water, systems using rotary pumps have the lowest energy consumption. Specific energy consumptions (SEC) as low as 1.4 kWh m^{-3} were reported both for rotary vane pumps (influent TDS = 3,480 mgL^{-1}; Dankoff Solar Slow pump; [31]) and for progressive cavity pumps (influent TDS = 5,300 mgL^{-1}; custom-designed MonoPumps; [41]). SEC values for systems using reciprocating pumps, however, were only available for outdated units (SEC = 6.9 kWh m^{-3}; influent TDS = 3,000 mgL^{-1}; [22]) and small prototypes (SEC = 29.1 kWh m^{-3}; influent TDS = 2,137 mgL^{-1}; [37]). Pump motors are powered with either direct current (DC) or alternating current (AC). In the latter case, since both PV arrays and batteries produce DC, a current inverter is required.
- *Reverse osmosis membranes.* Spiral-wound, thin film composite RO membranes are the standard choice for PV–RO desalination systems. The most common RO configuration is single pass, in which the membranes are organised in series within one or more pressure vessels. Concentrate recirculation was used in some brackish water desalination installations to increase the overall water recovery rate and reduce brine disposal issues [7,10,57]. PV–RO desalination systems are often designed with generous membrane areas since, for a fixed recovery rate, they can operate at lower pressures and thus at higher energy efficiencies [23]. Large membrane areas, however, introduce a trade-off with permeate quality, which decreases as operating pressure increases. Nanofiltration membranes were suggested as a cost-effective alternative to reverse osmosis in brackish water solar desalination [31,57] due to their lower operating pressures and energy requirements, but no study thus far has monitored the continuous operation of a nanofiltration solar desalination plant.

In addition to the basic components of PV–RO desalination plants, a series of other elements may also be present in such systems. These include:

- *AC/DC inverter.* Desalination plants that use AC induction motors for the high pressure pumps require inverters to transform the DC current generated in the PV modules or stored in the batteries. The use of DC motors eliminates the need for inverters but generally involves a higher initial investment. Since DC motors do not experience the energetic losses inherent in inverters, PV–RO desalination plants with DC motors are expected to function at higher energy efficiencies [59,60]. In a study conducted on a 6 m^3d^{-1} brackish water PV–RO desalination system, however, de Carvalho et al. [21] experienced steadier operation and significantly lower energy consumption (3 kWh m^{-3} vs. 4.7 kWh m^{-3}) after replacing a DC motor with an AC induction motor. Systems with DC motors are also more reliable compared to systems with inverters, whose failures are frequently related to the inverter overheating during plant operation [58] or overloading when the motors in systems with more than one pump in the RO unit and no soft-start features are installed [7].
- *Electrical storage.* Batteries can be included in the system either to balance the electrical output of the PV modules during day-time operation or to provide extended operation during night-time and overcast days. Although electrical storage enables steady plant operation and may increase overall productivity, it entails a series of drawbacks: (i) Installation and replacement add significantly to the investment cost of the plant. (ii) Batteries imply additional losses of electricity and reduce system efficiency. (iii) When all auxiliary components such as charge controller and wiring are considered, the inclusion of batteries in the system results in a more complex system. (iv) The absence of careful maintenance typical in remotely located systems may dramatically reduce battery life, particularly for large storage batteries [16,23]. Batteryless PV–RO systems are based on the idea that water storage is often more efficient and cost-effective than energy storage [31]. These systems are operated either at fixed or variable capacity. In the former, all radiation below the threshold value for start-up of the high pressure pump is dropped and the desalination plant works only during peak radiation hours (generally 5–8 h, depending on the local meteorological conditions). Systems operating at variable capacity achieve higher performance and flexibility by including speed control systems on the pumps and electronic power converters [61]. The technical feasibility and short-term operation of variable speed, batteryless PV–RO systems was tested in a series of studies [23,31,41], but long-term performance has not been monitored. RO membrane biofouling can prevent the long-term

operation of such systems. The hot climate typical of the regions where PV-RO systems are implemented promotes biofouling when the plant is not operating. Automatic shut-down devices and membrane cleaning systems are usually installed in such systems so that during periods of low solar radiation, the pump is shut off, thereby reducing the potential for membrane biofouling [20,42]. The recirculation process used for membrane cleaning can be gravity-driven, rely on the high pressure pump, or on a dedicated flushing pump. Timing of membrane flushing is crucial: recirculation should be activated while there is still enough radiation to power the flushing pump, but limiting to a minimum the waste of radiation that could be used for the desalination process. For this purpose, ITN [31] designed an electronic circuit that initiates the shut-down cycle based on the current from a separate, small solar cell. Adjustable delay may be built-in to avoid repeated shut-down cycles that may be induced by passing clouds.

- *Energy recovery device*. With the development of suitable devices for implementation in small-scale units, the use of energy recovery devices in seawater PV–RO desalination is rapidly becoming standard practice. Pelton turbines were used in early systems [29]. More recently devices that are more efficient at low flows were developed, such as Clark pumps [16,38], hydraulic motors [11], energy recovery pumps [47,54], and pressure exchangers [11,19]. Studies comparing different recovery mechanisms applied to the same PV-RO system reached different conclusions [11,38], possibly indicating that the choice of the most efficient energy recovery device is system-specific. Only a limited number of studies [29,47] investigated the use of energy recovery devices in brackish water desalination since low concentrate pressure and high water recovery rates make energy recovery less critical in such systems.

2.1.1. SEC and actualized water cost in PV–RO desalination

Due to the high investment costs for PV modules, energy efficiency is a key requirement for PV-RO desalination, and most of the design solutions highlighted in the previous paragraphs were developed with a clear focus on energy efficiency. Fig. 3 illustrates the SEC of several experimental and design PV–RO desalination systems (see also Table 1).

The SEC in PV–RO desalination is comparable to that of conventional RO desalination, which ranges from roughly less than 1 to 7 kWh m^{-3} for salinities between 1,000 and 45,000 mgL^{-1} [2]. As expected, energy consumption is higher for seawater desalination, in early-model systems [6,33], and for small prototypes [37]. The development of energy recovery devices for small-scale plants played a crucial role in reducing the energy consumption for seawater desalination below 5 kWh m^{-3} (see Fig. 3a). For brackish water, SEC below 2.0 kWh m^{-3} are reported for a relatively large PV–RO plant with battery storage in Egypt [18] and for two batteryless plants with DC motors developed by ITN [31] and the University of Edinburgh [41] and installed in the USA and Australia, respectively.

The actualised costs of several experimental and design PV–RO desalination systems are illustrated in Table 1. The estimates were derived with different assumptions concerning the useful life-time of the plants (ranging from 10 to 30 years [19,54]), the replacement frequency of system components such as batteries, membranes, and pumps, and the applied discount rate (ranging from 0% to 10% [21,40,54]). Due to such differences, direct cost comparisons across systems are not

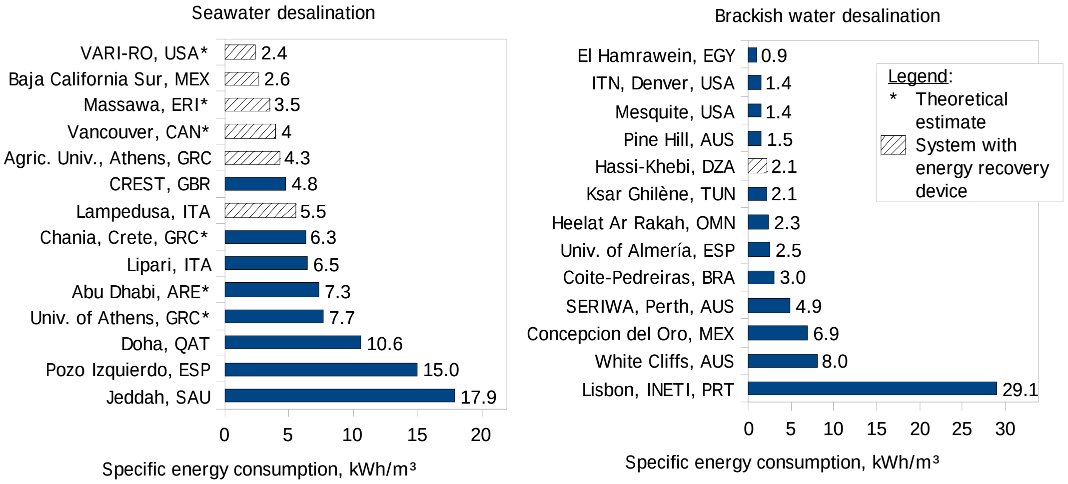

Fig. 3. SEC of several PV–RO desalination plants for (a) seawater and (b) brackish water desalination.

particularly illuminating. Despite a general trend of a decrease in cost over time, particularly after the development of energy recovery devices for small-scale seawater desalination, state-of-the-art PV–RO desalination is not cost-competitive with conventional desalination. Even allowing for the higher costs entailed in building and operating small and medium-size grid-connected RO plants (which range from 1 to 2.5 US\$ m^{-3} [62]), with respect to large desalination plants (which can desalinate seawater for as low as 0.5 US\$ m^{-3} [2]), cost ranges for PV–RO desalination are higher: only the lowest estimates approach those for grid-connected plants and they are mostly theoretical. Only in remote areas that suffer water scarcity and do not have access to grid electricity, the costs of efficient PV–RO plants are competitive with those of alternative water supply solutions, which include water transport by tankers or trucks—whose costs range from about 7.5 to 25 US\$ m^{-3} [19,20,63,64]—rainwater harvesting [20], and, taking surging oil prices into account, RO desalination with autonomous diesel generators [30,652.2. Solar thermal-powered RO desalination

While research on solar RO desalination has thus far focused mainly on power generation by PV modules, there is increased interest in solar thermal technologies. Solar thermal collectors absorb solar radiation as heat that a working fluid (e.g., water, oil, refrigerants) transfers to a thermodynamic steam cycle for the generation of the electrical or mechanical power required by the membrane desalination process. The recent interest in solar thermal technologies is largely tied to the development of concentrating solar power (CSP) technologies, which have the medium-term potential to become a key technology for cost-effective large-scale solar seawater desalination [66]. To date, experience with solar thermal RO desalination has been limited (Table 2).

Early experimental units utilized non-concentrating collectors such as solar ponds and flat plate collectors. Solar ponds are shallow bodies of water, in which the bottom water layers can store thermal energy and reach temperatures as high as 85°C [73]. Mixing between the top and bottom layers of the pond is prevented by a salinity gradient. Experiments on the coupling of solar ponds with RO desalination were conducted in Texas [69,74] and California [69,75]. Flat plate collectors consist of a transparent, flat front plate, an insulating zone, and an absorbing rear plate (with channels in which the heating fluid flows), and they can reach temperatures of up to 90°C [73]. Experimental RO desalination devices with flat-plate collectors were constructed in France [68] and Egypt [68]. None of these early devices achieved commercialization.

Compared to non-concentrating collectors, CSP devices function at both higher working temperatures and higher conversion efficiencies by using reflecting surfaces to focus the incoming solar radiation on a receiver that absorbs the thermal radiation with minimum heat losses and transfers it to the working fluid within the receiver itself. The four mainstream CSP technologies are parabolic troughs, solar power towers, linear Fresnel, and dish Stirling [66].

2.2.1. SEC and actualized water cost in solar thermal RO desalination

Manolakos et al. [63,71] described a system with vacuum tube solar collectors and mechanical coupling between the solar and RO units. The heat absorbed by the collectors evaporates the working fluid (HFC-134a), which subsequently undergoes expansion and generates the mechanical work for running the RO unit pumps. The system operates at low temperatures (70°C) and it has low energy consumption for seawater desalination (2.5 kWh m^{-3}), which is enabled by using a Clark pump energy recovery device. The actualized cost of water for

Table 2
Overview of solar thermal-driven RO desalination systems

System (country)[a]	Year[b]	Feed type	Collector type	Pump drive	Production, $m^3 d^{-1}$	SEC, kWh m^{-3}	Source
Cadarache, FRA	1978	BW	Flat plate	Mechanical	15	0.7	[67]
El Hamrawein, EGY	1981	BW	Flat plate	Mechanical	45	1.0	[68]
El Paso, TX, USA	1981	BW	Solar pond	Mechanical	45	1.0	[69]
Los Baños, CA, USA	1987	BW	Solar pond	Mechanical	45	1.0	[69]
Rankin, TX, USA[c]	1981	BW	Solar tower	Mechanical	45	1.0	[70]
VARI-RO, USA	1999	SW	Dish Stirling	Electrical	0.93[d]	2.4	[56]
VARI-RO, USA	1999	SW	Parabolic trough	Mechanical	0.85[d]	2.1	[56]
VARI-RO, USA	1999	SW	Thermal dish	Mechanical	1.19[d]	2.1	[56]
Univ. of Athens, GRC[c]	2005	SW	Evacuated tube	Mechanical	2.8	2.5	[71]
Univ. de La Laguna, ESP[c]	2007	SW	Parabolic trough	Mechanical	1,346	1.8	[72]

Notes: SEC = specific energy consumption; [a]Three-letter ISO 3166 code; [b]Year of commission/design; [c]Design study; [d] Production flow per m^2 of effective area.

the system is estimated at 15.21 US\$ m^{-3} (10.34 € m^{-3}, excluding land cost) for the local conditions on a Greek island, substantially higher than for batteryless PV–RO desalination (6.58 US\$ m^{-3}, 4.47 € m^{-3}, excluding land cost) [63].

No results from experimental CSP-RO units are reported in the literature, but several studies investigated the feasibility of the concept at a design level. Delgado-Torres et al. [72] provide the preliminary design of a CSP-RO system, using parabolic troughs and mechanical coupling between solar and RO units. Various design alternatives with heat transfer fluid or direct vapour generation, three types of working fluids, and two models of parabolic troughs collectors are investigated. The use of a pressure exchanger to recover energy helps reduce the estimated SEC for seawater desalination to a low value (1.8 kWh m^{-3}). Childs et al. [56] evaluated three systems in which CSP technologies are combined with an innovative integrated pumping and energy recovery system for seawater RO desalination (VARI-RO™). The lowest SEC (2.1 kWh m^{-3}) and highest conversion efficiency (25%) are achieved by a solar dish concentrator-thermal module mechanically coupled to the RO unit.

Studies on CSP–RO desalination suggest that their energy consumption is lower than that of PV–RO systems [69]. None of the studies on autonomous CSP–RO desalination, however, disclosed the economics of the described systems.

2.3. Hybrid solar RO desalination

Hybrid solar RO desalination plants are designed to combine the power output of solar technologies with electrical power from other renewable (e.g., wind) or conventional (e.g., fuel generators and grid electricity) sources. The power generated by the auxiliary source may be used to extend the number of hours of daily operation [15] or as backup to ensure steady operation during periods of low or intermittent solar radiation. Table 3 illustrates some basic characteristics of several hybrid solar RO systems.

Several systems in Table 3 were designed to exploit the complementary aspects of two renewable energy sources, wind and solar radiation, with or without backup from conventional grid power or fuel generators. Experimental units built in Greece [58] and Israel [60] demonstrated the technical feasibility of the concept and the possibility of long-term operation with minimal maintenance. Both systems achieved steady system operation using battery banks. The hybrid system in Maagan Michael, Israel,

Table 3
Overview of hybrid solar RO desalination systems

System (country)[a]	Year[b]	Feed TDS, mg L^{-1}	Solar unit	Additional power supply	Production[c], m^3 d^{-1}	Cost[d], US\$ m^{-3}	Source
Abu Dhabi, ARE[e]	2008	45,000	PV	Fuel	20	7.2	[15]
Abu Dhabi, ARE[e]	2007	45,000	CSP (Fresnel)	Fuel	24,000	7.2	[66]
Agadir, MAR[e]	2007	36,500	CSP (Fresnel)	Fuel	24,240	7.2	[66]
Al Khawkah, YEM[e]	2007	43,000	CSP (Fresnel)	Fuel	24,024	7.2	[66]
Aqaba, JOR[e]	2007	42,000	CSP (Fresnel)	Fuel	24,336	7.2	[66]
Brownsville, TX, USA[e]	1981	6,000	CSP (Parab. trough)	Wind	6,300	7.2	[76,77]
Chania, Crete, GRC[e]	2004	40,000	PV	Wind	12	6.5	[19]
CRES, Lavrio, GRC	2001	37,700	PV	Wind	0.8	31.8	[58]
Curtin Univ., AUS	2001	37,700	PV	Fuel	1	31.8	[78]
Gaza, PSE[e]	2007	38,000	CSP (Fresnel)	Fuel	23,976	31.8	[66]
Hurghada, EGY[e]	2007	43,000	CSP (Fresnel)	Fuel	24,096	31.8	[66]
Maagan Michael, ISR	1997	4,000	PV	Wind and fuel	3	6.8	[60]
Marettimo, ITA	1993	4,000[f]	PV	Fuel	5	6.8	[24]
Nicosia, CYP[e]	2005	4,000[g]	PV	Grid	50.4	0.9	[18]
Ras Ejder, LBY[e]	2005	42,000	PV	Wind and grid	300	0.9	[79]
Saudi Arabia, SAU[e]	1981	5,371	CSP (Parab. trough)	Fuel	28.2	0.9	[80]
St.Lucie, FL, USA	1995	32,000	PV	Fuel	0.6	0.9	[45]
Tarifa, ESP[e]	1987	32,000[f]	PV	Wind	150	0.9	[81]
Valetta, MLT[e]	2007	38,000	CSP (Fresnel)	Fuel	24,024	0.9	[66]
Various locations, GRC[e]	1998	35,000	CSP	Fuel	24,024	0.9	[82]
Yabu, SAU	1998	35,000[f]	CSP (Fresnel)	Wind	24,024	0.9	[73]

Notes: TDS = total dissolved solids; [a]Three-letter ISO 3166 code; [b]Year of commission/design; [c]Nominal capacity; [d]Actualised cost in USD referring to year of study. Other currencies were converted with nominal annual average exchange rates from http://www.oanda.com/convert/fxhistory; [e]Design study; [f]Seawater feed; [g]Brackish water feed.

included a diesel generator for backup, but it was never used during the entire period of system testing.

The combination of solar thermal technologies with grid electricity or fuel generators was investigated in several hybrid systems. Bowman et al. [80] provide an early example of a CSP–RO desalination system, which includes backup from an oil-fired boiler to maintain the vapour pressure necessary for system operation and to ensure functionality in the event of insufficient solar radiation. The system is designed to operate in either all-solar or hybrid solar–oil mode. The AQUA–CSP project [66] investigated the feasibility of combining linear Fresnel CSP systems with RO membranes for large-scale seawater desalination plants (24,000 m^3d^{-1}) in seven locations in the MENA region. Fossil fuel co-firing is provided to allow for steady-state operation under variable solar irradiation levels. The plants are designed to include energy recovery devices. SEC is estimated to range between 4.9 and 5.9 kWh m^{-3}.

2.3.1. Actualized water cost in hybrid solar RO desalination

The costs of hybrid PV–diesel and, where meteorological conditions are favourable, PV–wind RO systems are lower than those of PV–RO desalination. In a study that examined the design of a 12 m^3d^{-1} autonomous desalination unit, Mohamed and Papadakis [19] estimated actualised costs of 7.67 US\$ m^{-3} (5.21 € m^{-3}) for a hybrid PV–wind system and 9.77 US\$ m^{-3} (6.64 € m^{-3}) for a fully PV-powered unit. Kaldellis et al. [64] evaluated the cost of hybrid solar and wind-powered seawater desalination in the Aegean Archipelago in Greece. Assuming a 15 year lifetime, the estimated costs ranged between 1.5 and 4.4 US\$ m^{-3} (1.2 € m^{-3} and 3.5 € m^{-3}) for capacities between 10 and 2,500 m^3d^{-1}. Plant size significantly affected costs, but for any size, the estimated costs were less than those for importing water into the Archipelago. Helal et al. [15] compared the overall performance and cost expectations of three different design configurations for a 20 m^3d^{-1} seawater desalination plant. Under the model assumptions, the hybrid PV–diesel generator configuration resulted in slightly lower costs (7.21 US\$ m^{-3}) than solar-driven (7.34 US\$ m^{-3}) and diesel-driven (7.64 US\$ m^{-3}) systems.

At the present level of technological development, only theoretical cost estimates are available for hybrid RO desalination plants with CSP technologies and fuel backup. Voros et al. [82] estimated that assisting the conventional fossil fuel-based power supply with CSP technologies may lead to a 20% reduction in unit cost of permeate water in RO systems that rely on steam cycles to generate power for the desalination process. Both the AQUA–CSP project [66] and Zejli et al. [83], however, estimated that hybrid CSP–RO would cost more than conventional RO desalination. For plant sizes of 24,000 m^3d^{-1} and 1,200 m^3d^{-1}, the unit cost for seawater desalination was appraised at 2.12–2.54 US\$ m^{-3} (1.55–1.85 € m^{-3}) and 2.58 US\$ m^{-3} (2.73 € m^{-3}), respectively, values that exceed the costs of conventional RO desalination [2].

3. Future prospects for solar RO desalination

In this section, we briefly highlight the main technological advancements that are envisaged in the solar power and RO units and in the integration of the two, all of which may help improve the competitiveness of solar RO desalination in the coming years.

3.1. Solar unit technologies

Although the level of technological development of PV–RO desalination plants has allowed their commercialization [9,49], market penetration has thus far been small, mainly due to the high investment costs for the PV modules. Research in the field of PV modules, however, is developing rapidly, which seems to offer hope that significant cost reductions can be expected in the short-medium term. Promising lines of research are the exploration of the properties of both crystalline and amorphous silicon and of other semi-conductors such as cadmium telluride and copper indium gallium diselenide for application in thin-film cells [2], and the development of concentrating PV systems [84]. The development of CSP technologies, on the other hand, will be crucial in determining whether solar desalination will become attractive for large-scale desalination systems. Previous research has estimated that very large concentrating solar thermal desalination units up to 100,000 m^3d^{-1} have the medium-term potential to achieve a cost of water below 0.55 US\$ m^{-3} (0.40 € m^{-3}) and to become the lowest cost option for desalted water in the MENA region [66].

3.2. RO unit design and operation

Advanced membrane pretreatment by ultrafiltration or nanofiltration can potentially reduce fouling and scaling of the RO membranes and thus decrease energy consumption and overall costs [2]. Nanofiltration membranes may also be applicable in the solar-powered desalination of brackish water due to their lower operating pressures and energy requirements [31,59]. Finally, the development of mechanisms to automatically control the water recovery rate in solar RO desalination systems can help promote the development of energy efficient systems that will require only minimal maintenance [31].

3.3. Solar and RO unit integration

First, to date, the full potential of dual-purpose designs for the co-generation of power and water has not been sufficiently explored. Such designs have a potential to operate at low water generating costs and levelized electricity costs [66]. Second, an operation strategy with the potential to increase both energy efficiency and permeate water production comprises preheating the RO feed by cooling the PV panels or absorbing rejected thermal energy in solar thermal power systems [31,72]. Third, improvements in the durability of batteries may eliminate the current maintenance and replacement issues and make energy storage attractive for long daily operation.

4. Conclusions

This paper investigated the main technological solutions and current developments in the field of solar-powered RO desalination on the basis of the analysis of 79 experimental and design units worldwide. The study prompted the following conclusions:

- PV-powered RO desalination is mature for commercial implementation. Although no standard design approach has been developed, the technical feasibility of different design concepts was demonstrated in a relatively large number of case studies. State-of-the-art, batteryless systems that directly couple the PV modules to variable speed DC pump motors seem to have the highest potential for energy efficient and cost-effective small-scale PV–RO desalination. The long-term performance and reliability of such systems was, however, not sufficiently tested yet.
- CSP–RO desalination is the most promising field of development for medium and large-scale solar desalination. Preliminary design studies suggest that CSP–RO systems may compete in the medium-term with conventional RO desalination and as a result, gain large market shares. There is a need for testing such promising potential in demonstration and full-scale plants.
- The combination of solar power with additional power sources may be beneficial both in small and large-scale desalination. In small-scale systems, PV panels may combine favourably with wind turbines, achieving lower overall costs where the complementary aspects of the two renewable sources can be exploited. In large-scale systems, CSP and fuel co-firing of desalination plants help confer stability on desalination unit operation during the night-time or periods of low irradiation. In both small and large-scale systems, connection to the electrical grid for combined power and water generation will promote stable operation of the system.

State-of-the-art solar RO desalination is cost-competitive with other water supply sources only in context of remote regions (e.g., islands and remote inland areas) where grid electricity is not available and freshwater demand is met by water imports or—taking into account surging oil prices—small-scale fuel-driven desalination plants. In this market, the share of PV–RO and hybrid PV–RO desalination plants is likely to increase in the near future. A penetration of solar RO desalination in other markets seems unlikely in the short-term. The rapid advancements of both CSP and PV solar technologies offer the best hope for the wider implementation of these potentially sustainable water supply technologies in the future.

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