

Photovoltaic-powered Membrane Desalination in Urban and Rural Areas

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Abstract: The integration with renewable energy sources is a key area of development in the desalination sector for its potential to reduce the environmental footprint of the energy-thirsty state-of-the-art technologies and bring sustainable development to remote, arid areas lacking access to inexpensive electric energy. In light of the recent market trends, which indicate a rapid gain in market shares by membrane technologies at the expense of thermal processes, this study critically evaluates the research and field experience with coupling photovoltaic power and membrane desalination, with a focus on reverse osmosis, nanofiltration and electrodialysis processes. The results suggest that photovoltaic-powered membrane desalination is technologically well developed and mature for gaining larger shares in the desalination market where the conditions are favorable, i.e., for small and medium-scale applications in remote regions. Two case-study examples are presented discussing the feasibility of solar desalination for the production of drinking water in an urban area in Jordan and of irrigation water in a remote rural community in Israel.

Key words: Electrodialysis, membrane desalination, nanofiltration, photovoltaic, renewable energy, reverse osmosis, solar energy.

Global demand for freshwater increased in the past century at a rate that is double the rate of population growth. Water scarcity has become a pressing limitation for the development of many areas worldwide and increasing demands from economic activities and growing populations, as well as changing precipitation patterns due to climate change have raised fears of an imminent severe global water crisis (UNESCO, 2003). Offsetting freshwater shortages requires the integration of different policy and management interventions aimed at reallocating resources, preventing waste or augmenting the available supplies. Among supply-side solutions, the last few decades witnessed a growing interest in the exploitation of unconventional water supply sources such as saltwater desalination, reclamation of treated wastewater, exploitation of marginal quality groundwater aquifers, and rainwater harvesting (Gleick, 2000).

Desalination of seawater and brackish water plays an increasingly important role as a clean and highly reliable source of freshwater for many communities worldwide. Since seawater desalination with modern technologies in large land-based plants became economically feasible for the production of drinking water in the 1950s,

the cumulative capacity of desalination worldwide has steadily increased (Fig 1).

Although desalination has not met the overly optimistic expectations of those analysts who in the 1960s and 1970s held it as the ultimate and within reach solution to world's water problems, several countries, particularly in Middle East and North Africa region (MENA) nowadays heavily depend on desalination for the supply of freshwater to households, industries and agriculture (Global Water Intelligence, 2004). Countries such as Israel and Australia are experiencing a boom in investments in large-scale seawater desalination plants to make their water supplies increasingly independent from rainfall patterns (Dreizin *et al.*, 2008). The expectations for the coming years are for a doubling of the global capacity in 2015 with respect to the levels of 2005 and for a massive increase in capacity in particular in Mediterranean countries, where a 300% increase in demand between 2005 and 2015 is expected (Global Water Intelligence, 2004).

Desalination technologies can be broadly classified into two categories: thermal processes and membrane processes. The former ones include technologies such as multi-effect distillation (MED), multi-flash distillation (MSF) and mechanical vapor compression (MVC), which involve the evaporation

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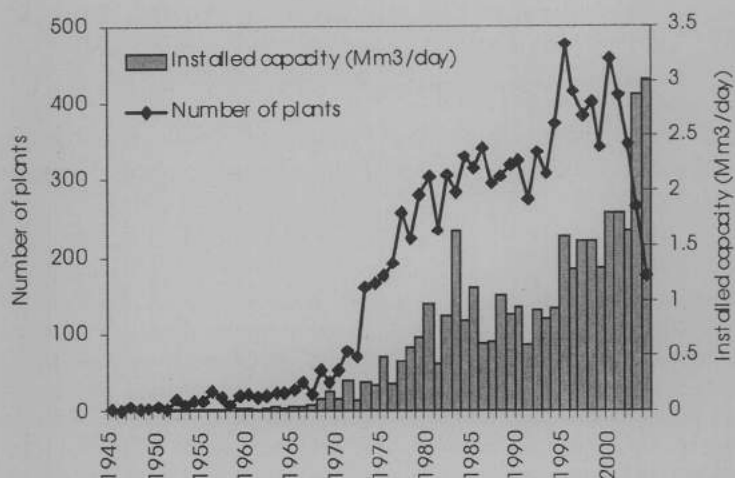


Fig. 1. Desalination capacity and number of plants installed yearly between 1945 and 2004 (source: Gleick, 2000).

of the feed water through the transfer of heat from an external source and the collection of the condensed vapor. Such processes deliver a very high quality permeate and were the first desalination technologies to be implemented commercially on a large scale (Al-Shammiri and Safar, 1999). They remain the primary technology in terms of desalination capacity as they dominate the largest desalination market in the Gulf area (Global Water Intelligence, 2004). Membrane processes rely on the filtration properties of polymeric membranes to achieve saltwater desalination. Since reverse osmosis (RO) technology was first made practical for seawater desalination (Loeb and Sourirajan, 1963), membrane desalination and RO in particular have known substantial reductions in the cost and energy consumption and are currently the technologies of choice in most regions outside the Middle East (Greenlee *et al.*, 2009). In 2001, 51% of new installed desalination capacity used RO desalination, and in 2003, RO desalination accounted for 75% of new production capacity (Greenlee *et al.*, 2009). Membrane processes are expected to continue to take market shares from thermal desalination in the next couple of years (Global Water Intelligence, 2004).

The three principal membrane desalination processes are RO, nanofiltration (NF) and electrodialysis (ED). Both RO and NF are pressure-driven membrane processes in which water passes through a semi-permeable membrane under the driving force of an externally applied pressure while dissolved solids are rejected and remain on the feed water side, eventually concentrating into a brine solution. System flow

rate is proportional to the difference between the applied hydrostatic pressure and the osmotic pressure differential between brine and dilute compartments. The end product comprises two separate flows of freshwater permeate and concentrated brine with a recovery rate ranging between 35% and 85% depending on feed salinity. Commercially available RO membranes can retain about 98-99.5% of the salt dissolved in the feed water (Wilf, 2004) and typical operating pressures range between 10 and 15 bars for brackish water and between 55 and 65 bars for seawater (Fritzmann *et al.*, 2007). 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 (Wilf and Klinko, 2001).

NF processes are characterized by intermediate properties between RO and ultra filtration. Like RO, NF membranes offer a high retention of multivalent ions and organic compounds with molecular weight above 300 Da, but are operated at a lower pressure, allow for a higher water flux, and are less prone to fouling (Pontié *et al.*, 2008; Eriksson *et al.*, 2005). NF membranes show, however, a lower retention of monovalent ions compared to RO (Pontié *et al.*, 2008). It has been estimated that 10% of the brackish water desalination market in 2004 was dedicated to NF membranes (Rovel, 2004). Seawater desalination by multi-pass NF filtration was shown to be technically feasible, but has thus far not proved competitive with RO processes in commercial

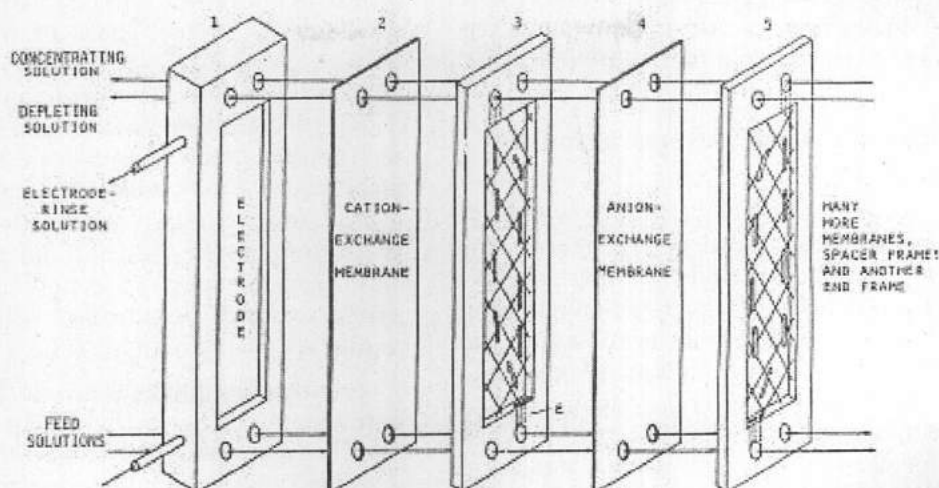


Fig. 2. Main components of a conventional electro dialysis stack.

applications (Pontie *et al.*, 2003; Gouellec *et al.*, 2006).

Unlike pressure-driven membranes, ED relies on an external electric field and the properties of ion-selective membranes to drive the passage of ionic species – rather than water – from an increasingly diluted solution to an increasingly concentrated one. The principle of ED is shown in Fig. 2. In a conventional ED stack, cation- and anion-exchange membranes are alternated forming an array of individual parallel cells between two electrodes (Strathmann, 2004). Each cell consists of a cation-exchange membrane, a dilute compartment, an anion-exchange membrane, and a concentrate compartment. Under the external driving force, the positively (negatively) charged ions migrate towards the cathode (anode), permeating the cation-(anion-) exchange membranes, but being retained by the anion-(cation-) exchange ones. Salinity builds up in the concentrate compartments and decrease in the dilute ones. Although ED was invented before RO, it is currently much less widely used and almost exclusively for brackish water desalination (Strathmann, 2004). In this application ED competes with RO and NF, having the advantages of lower tendency to membrane fouling and scaling, higher recovery rates, and stable operation under a wider range of feed water temperature but the disadvantage of higher investment and operation costs (Strathmann, 2004).

Although membrane desalination is less energy intensive than thermal desalination (Fritzmann *et*

al., 2007), energy consumption is a primary concern in all types of desalination. Despite steady improvements triggered by the introduction of energy recovery technologies and the development of low energy RO elements (Busch and Mickols, 2004; Stover, 2007), energy consumption is still a major cost component of desalination plants, accounting for 40–50% of the total plant costs for seawater RO desalination (Greenlee *et al.*, 2009; Betts, 2004). Moreover, the externalities involved in the use of fossil fuels to produce the energy required by desalination cast doubts on the long-term environmental sustainability of conventional technologies and call for innovative solutions based on renewable energy sources.

Solar technologies are particularly promising among renewable energies for application to desalination, given that the highest supply of energy coincides with the summer period when also demand is highest. Previous research has focused extensively on solar desalination (Papapetrou *et al.*, 2010; Chaibi, 2000; García-Rodríguez, 2003; 2007). This paper provides a comprehensive assessment of the experience gathered with solar desalination with pressure-driven membranes and ED. The prospects for commercial penetration and further technological development are identified and discussed with a focus on the production of drinking water in urban areas and irrigation water in arid rural areas. Then we discuss the potential of hybrid systems exploiting the complementary aspects of solar power and one or more additional power sources (e.g., wind, diesel generators or grid electricity). Two case-studies

of photovoltaic-powered membrane desalination are presented, the first in an urban setting in Aqaba, Jordan, and the second in a rural agricultural area of Israel.

Photovoltaic-powered Reverse Osmosis and Nanofiltration

The technical feasibility of solar-powered RO desalination has been tested in a relatively large number of experimental units, starting from the pioneering experiments with photovoltaic-powered reverse osmosis (PVRO) in the late 1970s (Petersen *et al.*, 1979; 1981). The number of photovoltaic-powered nanofiltration (PVNF) systems is much smaller and limited to the desalination of brackish water in inland locations of Australia and Israel (Richards *et al.*, 2008; Richards and Schäfer, 2003; Schaefer *et al.*, 2007; Ghermandi and Messalem, 2009). Figure 3 gives an overview of the geographical distribution and typical size of pressure-driven solar desalination systems.

Research on PVRO and PVNF has focused on regions where the availability of solar radiation is highest and where severe water scarcity issues exist, notably in MENA countries, Australia, and the southernmost part of Europe. 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 (Alawaji, 1995), the US Virgin Islands (Headley, 1997), the Maldives (Kanzari, 2005), Australia (Harrison *et al.*, 1996),

Mexico (Kunczynski, 2003), and Tunisia (Castellano and Ramirez, 2005), most of the experimental systems in Fig. 3 are demonstration or prototype units. System capacities range from less than 0.1 m³ day⁻¹ for prototype units to 75.7 m³ day⁻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, no experimental study of large-scale solar-driven pressure-driven desalination plants has been conducted.

Among solar-powered membrane desalination technologies, PVRO is the design option that has been implemented most frequently, possibly due to the fact that photovoltaics were the first widely commercialized technology for exploiting solar energy and still dominate the solar technology market. In PVRO 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. The technical and economical feasibilities of PVRO desalination were tested in a series of experimental and design studies as illustrated in Table 1.

PVRO 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 m³ day⁻¹ (Richards and Schäfer, 2003; Harrison *et al.*, 1996; Bouguecha *et al.*, 2005; Joyce, 2001) to 75.7 m³ day⁻¹ (Headley,

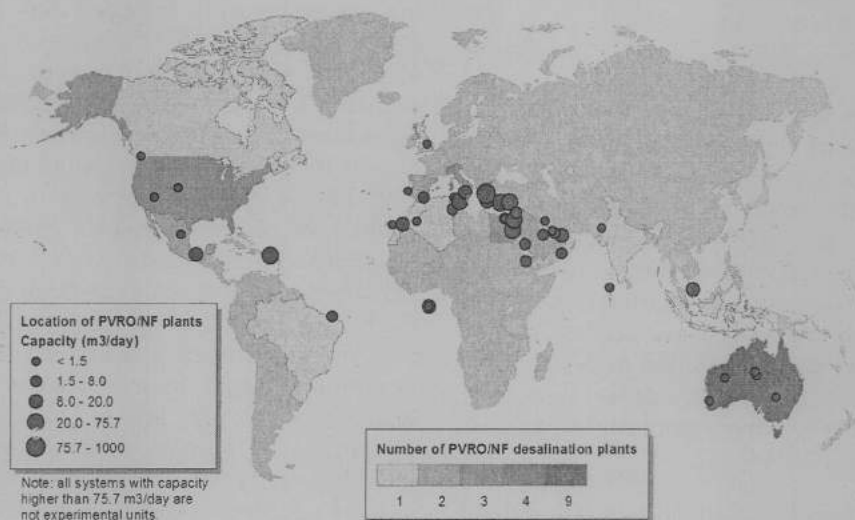


Fig. 3. Size and distribution of solar-driven RO and NF desalination systems.

Table 1. Overview of PVRO 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 day ⁻¹	Cost ^c US\$ m ⁻³	Source
Abu Dhabi, ARE ^d	2008	45,000	11.25	no	AC	20.0 ^e	7.3	Helal <i>et al.</i> , 2008
Agric. Univ., Athens, GRC	2006	30,000	0.85	no	DC	0.35 ^e	9.8	Mohamed <i>et al.</i> , 2008
Aqaba, JOR	2005	4,000	16.8	yes	AC	58.0		Touryan <i>et al.</i> , 2006
Baja California Sur, MEX	–	– ^f	25	yes	–	11.5	–	Kunczynski, 2003; ADU-RES, 2005
Chania, Crete, GRC ^d	2004	40,000	31.2	yes	AC	12.0 ^e	8.3	Mohamed and Papadakis, 2004
Chbeika Centre, MAR ^d	1998	40,000	26.3	yes	AC	12.0 ^e	35.9	Tzen <i>et al.</i> , 1998
Coite-Pedreiras, BRA	2000	1,200	1.1	yes	DC/AC ^g	6.0 ^e	12.8	de Carvalho <i>et al.</i> , 2004
Concepción del Oro, MEX	1978	3,000	2.5	yes	DC	0.71		Petersen <i>et al.</i> , 1979; 1981
CREST, GBR	2001	32,800	1.54	no	AC	1.45	3.0	Thomson, 2003
Doha, QAT	1984	35,000	11.2	–	–	5.7 ^e	–	Anonamous, 1998
El Hamrawein, EGY	1986	4,400	19.84	yes	–	53.0	11.6	Maurel, 1991
Fredericksted, VIR	–	– ^h	–	–	–	75.7	–	Headley, 1997
Gillen Bore, AUS	1996	1,600	4.16	–	–	1.2	–	Harrison <i>et al.</i> , 1996
Giza, EGY	1980	– ^h	7.0	–	–	6.0 ^e	–	Rayan <i>et al.</i> , 2004
Hammam Lif, TUN	2003	2,800	0.59	no	DC	0.05 ^e	–	Bouguecha <i>et al.</i> , 2005
Hassi-Khebi, DZA	1987	3,500	2.59	yes	AC	0.85	10.0	Kehal, 1991
Heelat Ar Rakah, OMN	1999	1,010	3.25	yes	AC	5.0 ^e	6.5	Al Malki <i>et al.</i> , 1998
Denver, ITN, USA	2003	1,600	0.54	no	DC	1.5	–	Cheah, 2004
Java, Cituis West, IDN	1981	– ^h	24.5 ⁱ	yes	–	12.0 ^e	–	Effendi, 1988
Jeddah, SAU	1981	42,800	8	yes	DC	3.22	–	Boesch, 1982
Ksar Ghilène, TUN	2005	3,500	10.5	yes	AC	7.0	–	Castellano and Ramirez 2005; Penate, 2008
Kulhudhuffushi, MDV	2005	2,500	0.3	no	DC	1.0 ^e	–	Kanzari, 2005
Kuwait, KWT	–	8,000	–	yes	–	–	–	El-Kady and El-Shibini, 2001
Lampedusa, ITA	1990	– ^f	100	yes	AC	40	10.6	Sardi and Beer, 1996
Lipari, ITA	1991	– ^f	63	yes	AC	13.7	–	ADU-RES, 2005
Lisbon, INETI, PRT	2000	2,549	0.1	no	DC	0.02	–	Joye, 2001
Massawa, ERI ^d	2002	40,000	2.4	no	AC	3.9	–	Thomson and Infield, 2003; Thomson <i>et al.</i> , 2001
Mesquite, ITN, USA	2003	3,480	0.54	no	DC	1.28	3.6	Cheah, 2004
Murdoch Univ., AUS	–	–	0.06	–	–	0.05	–	Harrison <i>et al.</i> , 1996
Nicosia, CYP ^d	2005	– ^h	10	yes	AC	50.4 ^e	2.3	ADU-RES, 2005
NRC, Cairo, EGY ^d	2002	2,000	1.1	yes	AC	1.0 ^e	3.7	Ahmad and Schmid, 2002
Pine Hill, AUS	2008	5,300	0.6	no	DC	1.1	–	Richards, 2008
Pozo Izquierdo, ESP	2000	35,500	4.8	yes	AC	1.24	9.6	Herold and Neskakis, 2001; Herold <i>et al.</i> , 1998

Table 1. *contd....*

Location and country ^a	Year ^b	Feed TDS, mg L ⁻¹	PV capacity, kW _p	Battery storage	Pump drive	Production, m ³ day ⁻¹	Cost ^c US\$ m ⁻³	Source
Pozo Izquierdo, ESP	2000	35,500	4.8	yes	AC	1.24	9.6	Herold and Neskakis, 2001; Herold <i>et al.</i> , 1998
Solarflow, AUS		5,000	0.12	no	DC	0.4 ^e	9.3	Mathew <i>et al.</i> , 2001; Maslin <i>et al.</i> , 2003; Dallas <i>et al.</i> , 2009
Tanote, Thar desert, IND	1986	— ^h	0.45	—	—	1.0 ^e	—	Anonymous, 1998
Qatar village, JOR ^d	—	3,400	32	yes	—	45.0 ^e	—	Gocht, 1998
Sadous, Riyadh, SAU	1994	5,700	10.08	yes	AC	5.7	—	Alawaji <i>et al.</i> , 1995; Thomas, 1997
San Nicola, Tremiti, ITA	1984	— ^f	65	yes	AC/DC ^j	12.0 ^e	—	ADU-RES, 2005
SERIWA, Perth, AUS	1982	— ^h	1.2	yes	DC	0.55	—	James, 1983
Univ. of Almería, ESP	1988	3,360	23.5	yes	DC	8.0	92.5	Peral <i>et al.</i> , 2001
Univ. of Amman, JOR		400	0.07	no	DC	0.1	—	Abdallah <i>et al.</i> , 2005
Univ. of Athens, GRC ^d	2000	— ^f	1,968	yes	—	1,000 ^e	2.8	Voivontas <i>et al.</i> , 2001
Univ. of Bahrain, BHR	1994	35,000	0.11	yes	DC	0.2	—	Al-Qahtani, 1996
Vancouver, CAN	1983	33,000	0.48	no	DC	0.86	9.0	Keefer <i>et al.</i> , 1985
Various locations, JOR ^d	2007	7,000	1.1	yes	AC	3.6 ^e	—	Hrayshat, 2008
VARI-RO, USA ^d	1999	— ^f		no	AC			Childs <i>et al.</i> , 1999
Wanoo Roadhouse, AUS	1982	— ^h	6					Anonymous, 1998
White Cliffs, AUS	2003	3,500	0.26	no	DC	0.06		Richards and Schäfer, 2003)

Notes: TDS = Total Dissolved Solids; ^a Three-letter ISO 3166 code; ^b Year of commission/design; ^c Actualised cost in US\$ 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.

1997). The ratio between the installed PV capacity and the production flow ranges between 0.1 and 5.5 m³ day⁻¹ kW_p⁻¹.

The experimental investigation of the combination of PV modules and NF membranes has been thus far limited to a series of studies conducted in remote inland locations of Australia (Richards *et al.*, 2008; Richards and Schäfer, 2003; Schaefer *et al.*, 2007). The investigated systems were small demonstration units, capable of producing a freshwater flow rate of 0.05–1.50 m³ day⁻¹ and equipped with 0.255–0.600 kW_p PV modules. The studies compare the performance of the desalination systems when interchangeably equipped with either NF or RO membranes and without energy storage.

Although design approaches for PVRO and PVNF systems may differ significantly across the investigated systems, such as for instance in the

use of battery storage and DC/AC inverters, all design approaches share a number of common features. A general design scheme is given in Fig. 4 and is discussed in more detail in the following sections.

Design of the solar sub-unit

All the investigated solar desalination units make use of silicon PV modules, either mono-crystalline or multi-crystalline. The possibility to adjust module orientation is recognized 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

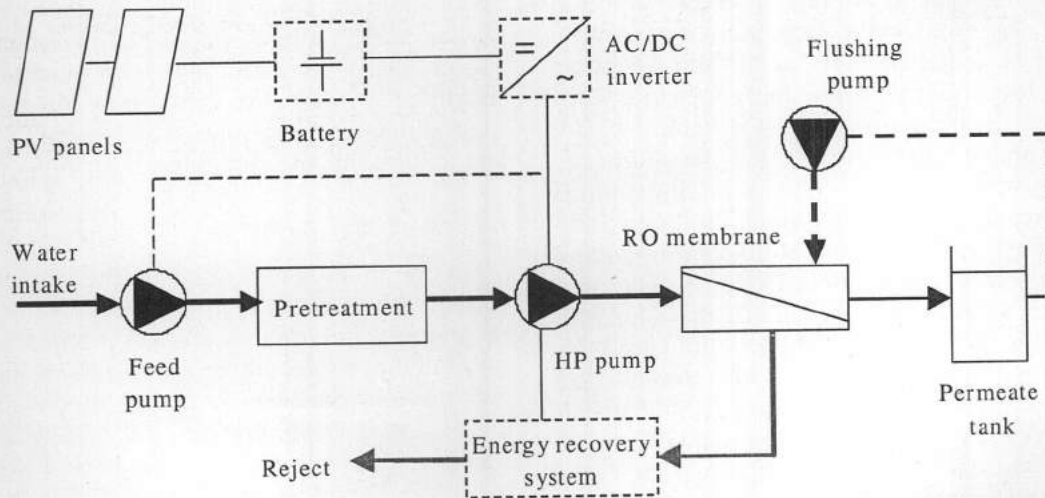


Fig. 4. Simplified design scheme of a PVRO and PVNF desalination plant.

can automatically follow the sun's daily path in the sky. Alawaji *et al.* (1995) estimated that utilizing seasonal tilt angle variation increases the yearly average permeate flow of a PVRO desalination plant in Saudi Arabia from 15 to 17 m³ day⁻¹. For a 0.1 m³ day⁻¹ PVRO testing rig in Jordan, Abdallah *et al.* (2005) 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.* (1996) 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 m³ day⁻¹. The high initial investment costs required to install tracking systems, however, have so far limited their use in PVRO desalination. Maximum power point tracker (MPPT) circuits or similar optimizers (Harrison *et al.*, 1996) are generally installed to maintain system operation at a voltage that achieves maximum power while ensuring efficiency under conditions of low irradiance.

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, PVRO desalination plants with DC motors are expected to function at higher energy efficiencies (Schaefer, 2007; Weiner *et al.*, 2001). In a study conducted on a 6 m³ day⁻¹ brackish water PVRO desalination system,

however, de Carvalho *et al.*, 2004 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 more reliable compared to systems with inverters, whose failures are frequently related to the inverter overheating during plant operation (Tzen *et al.*, 2008) or overloading when the motors in systems with more than one pump in the RO unit and no soft-start features are installed (Alawaji *et al.*, 1995).

Electrical storage in 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 (Mohamed *et al.*, 2008; Thomson, 2003). Batteryless PVRO systems are based on the idea that water storage is often more efficient and cost-effective than energy storage (Cheah, 2004). 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 hours per day, 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 (Burgess, 2003). The technical feasibility and short-term operation of variable speed, batteryless PVRO systems was tested in a series of studies (Richards, 2008; Thomson, 2003; Cheah, 2004), 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 PVRO 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 (Tzen *et al.*, 1998). Herold and Neskakis, 2001. 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 (Cheah, 2004) 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.

With the development of suitable devices for implementation in small-scale units, the use of energy recovery devices in seawater PVRO desalination is rapidly becoming standard practice. Pelton turbines were used in early systems (Kehal, 1991). More recently devices that are more efficient at low flows were developed, such as Clark pumps (Mohamed *et al.*, 2008; Thomson and Infield, 2003), hydraulic motors (Kunczynski, 2005), energy recovery pumps (Mathew *et al.*, 2001; Keefer *et al.*, 1985), and pressure exchangers (Kunczynski, 2003; Mohamed and Papadakis, 2004). Studies comparing different recovery mechanisms applied to the same PVRO system reached different conclusions (Kunczynski, 2005; Thomson and Infield, 2003), possibly indicating that the choice of the most efficient energy recovery device is

system-specific. Only a limited number of studies (Kehal, 1991; Mathew *et al.*, 2001) 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.

Design of the membrane sub-unit

In the investigated systems, the pump(s) that convey the feed water from the seawater intake or groundwater well to the RO pretreatment are generally powered either by the same array of PV modules that are connected to the RO unit (Alawaji *et al.*, 1995; Kanzari, 2005; Castellano and Ramirez, 2005; Touryan *et al.*, 2005; Petersen *et al.*, 1979; Thomson and Infield, 2003). In other cases, wind turbines (Al Malki *et al.*, 1998), conventional grid electricity, or a combination of the two (Tzen *et al.*, 2008) are implemented. Where implemented, solar pumps were reported to be highly reliable in remote locations and to require limited maintenance (Kanzari, 2005; Alawaji *et al.*, 1995).

Conventional RO pretreatment is generally implemented in PVRO units. 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 (Cheah, 2004) 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 (Richards *et al.*, 2008; Richards and Schäfer, 2003). UF pretreatment involves higher investment costs than conventional pretreatment, but because it removes significant numbers of microorganisms and generally delivers higher quality RO feed, it may reduce RO membrane cleaning 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 (Harrison *et al.*, 1996; Keefer *et al.*, 1985).

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 (Richards and Schäfer, 2003; Al Malki

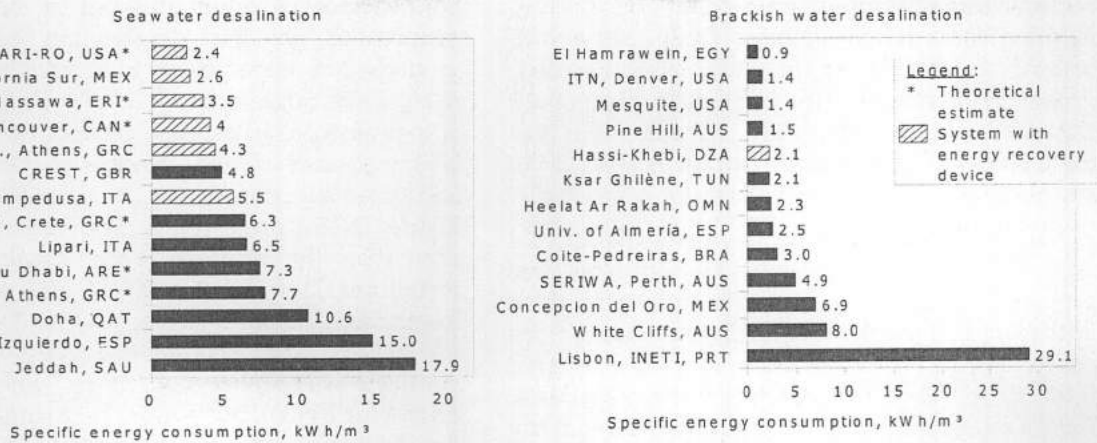


Fig. 5. SEC of PVRO plants for seawater (left) and brackish water desalination (right).

et al., 1998; Cheah, 2004) and progressive cavity pumps (Richards *et al.*, 2008) and reciprocating pumps (e.g., piston (Petersen *et al.*, 1981; Kanzari, 2005; Harrison *et al.*, 1996; Petersen *et al.*, 1979; Mathew *et al.*, 2001) and diaphragm pumps (Joyce *et al.*, 2001) 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 PVRO applications in combination with reciprocating plunger pumps (Thomson, 2003; Thomson and Infield, 2003) and rotary vane pumps (Mohamed *et al.*, 2008) 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 mg L⁻¹; Dankoff Solar Slow pump; (Cheah, 2004) and for progressive cavity pumps (influent TDS = 5,300 mg L⁻¹; custom-designed MonoPumps; (Richards *et al.*, 2008). SEC values for systems using reciprocating pumps, however, were only available for outdated units (SEC = 6.9 kWh m⁻³; influent TDS = 3,000 mg L⁻¹; (Petersen *et al.*, 1981) and small prototypes (SEC = 29.1 kWh m⁻³; influent TDS = 2,137 mg L⁻¹; Joyce *et al.*, 2001). 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.

Spiral-wound, thin film composite RO membranes are the standard choice for PVRO desalination systems. The most common RO configuration is single pass, in which the membranes are organized 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 (Richards and Schäfer, 2003; Alawaji *et al.*, 1995; Harrison *et al.*, 1996). PVRO 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 (Thomson, 2003). Large membrane areas, however, introduce a trade-off with permeate quality, which decreases as operating pressure increases.

Specific energy consumption and actualized water cost

Since the cost for PV modules is generally acknowledged as the key factor in determining the economic feasibility of PVRO desalination, energy efficiency is a key requirement for PVRO desalination and most of the design solutions highlighted in the previous paragraphs were developed with a clear focus on energy efficiency. Figure 5 illustrates the SEC of several experimental and design PVRO desalination systems (see also Table 1).

The SEC in PVRO 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 mg L⁻¹ (Fritzmman *et al.*, 2007). As expected, energy consumption is higher for seawater desalination, in early-model systems (Petersen *et al.*, 1979; Boesch, 1982), and for small prototype units (Joyce *et al.*, 2001). 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. 5 left).

For brackish water, SEC below 2.0 kWh m⁻³ are reported for a relatively large PVRO plant with battery storage in Egypt (ADU-RES Research Project, 2005) and for two batteryless plants with DC motors developed by ITN (Cheah, 2004) and the University of Edinburgh (Richards *et al.*, 2008) and installed in the USA and Australia, respectively.

The actualized costs of several experimental and design PVRO desalination systems are presented in Table 1. The estimates were given in the original studies with different assumptions concerning the useful life-time of the plants (ranging from 10 to 30 years (Mohamed and Papadakis, 2004; Keefer *et al.*, 1985), the replacement frequency of system components such as batteries, membranes, and pumps, and the applied discount rate (ranging from 0% to 10% (de Carvalho *et al.*, 2004; Ahmad and Schmid, 2002; Keefer *et al.*, 1985) and therefore a direct cost comparison across systems is not possible. A general trend towards a decrease in cost over time, particularly after the development of energy recovery devices for small-scale seawater desalination is, however recognizable.

At the state of the art, PVRO desalination is, in general, 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 (Hafez and El-Manharawy, 2003), with respect to large desalination plants (which can desalinate seawater for as low as 0.5 US\$ m⁻³ (Fritzmam *et al.*, 2007), cost ranges for PVRO 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 PVRO 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 (Mohamed and Papadakis, 2004; Tzen *et al.*, 1998; Manolakos *et al.*, 2008; Kaldellis *et al.*, 2004) – rainwater harvesting (Tzen *et al.*, 1998), and taking surging fossil fuel prices into account, RO desalination with autonomous diesel generators (Al Malki *et al.*, 1998; Fiorenza *et al.*, 2003).

NF membranes were suggested as a cost-effective alternative to RO in brackish water solar desalination due to their lower operating pressures and energy requirements (Ghermandi and Messalem, 2009; Cheah, 2004). The comparative

performance of different types of NF and RO membranes in the desalination of brackish groundwater were tested in Australia (Richards *et al.*, 2008; Schaefer *et al.*, 2007). The tested unit is a prototype, batteryless device, which installs UF membranes as pretreatment step. Under similar solar irradiance conditions, the NF membrane Dow Filmtec NF90 produced a 54% higher permeate flow than the brackish water desalination RO membrane Dow Filmtec BW30 and with a 60% lower SEC (1.5 kWh m⁻³ for NF90; 2.4 kWh m⁻³ for BW30). The electroconductivity of the NF permeate was higher (0.42 dS m⁻¹ for NF90; 0.17 dS m⁻¹ for BW30), but within the Australian norms for drinking water. Such results encourage the use of NF membranes for solar-powered brackish water desalination, but need confirmation in a wider range of applications and for a longer period of operation.

Photovoltaic-powered Electrodialysis

Coupling of ED desalination with PV solar energy (PVED) was first explored in the late 1970s (Kvajic, 1981; Savchenko *et al.*, 1978), at about the same time of the first PVRO experimental units. An overview of PVED installations is given in Table 2.

The two largest PVED systems thus far in operation were both built in Japan. The largest was constructed in a remote area near Fukue city, Japan, and tested for a 2-year period (Ishimaru, 1994). It was designed to desalinate brackish water (TDS = 1,500 ppm) and produce 200 m³ day⁻¹ of drinking water. It equipped a 65 kW_p PV array and 1,200 amp-hour battery storage allowing for 10 hours autonomy. The system worked consistently at a SEC of 0.6–1.0 kWh m⁻³, exceeding design expectations. Kuroda *et al.* (1987) report of a PVED system in Oshima island, which was in operation since 1986 with a 250 cell pairs ED stack and a 25 kW_p array of PV modules. This is the only experimental PVED unit that desalinates seawater. It copes with fluctuations in the PV output by using a two-stage desalination approach. When large power outputs are available, the feed water is partially desalinated and stored in a tank. When small outputs are available, the partially desalinated water is retrieved and the desalination process is completed. The system is reported to have produced 10 m³ day⁻¹ of quality drinking water (TDS = 400 ppm).

Adiga *et al.* 1987 describe a PVED brackish water desalination plant installed in Panote, India.

Table 2. Overview of PVED membrane desalination units

Location and country ^a	Year ^b	Feed TDS, mg L ⁻¹	PV capacity, kW _p	Pro-duction, m ³ day ⁻¹	Cost ^c , US\$ m ⁻³	Source
Tanote, IND	1986	5,000	0.45	1.0	–	Adiga <i>et al.</i> , 1987
La Luz, NM, USA	1979	– ^d	5	15	1.85	Lundstrom, 1983; Lundstrom, 1979
University of Bahrain, BHR	2002	3,300	0.13	0.57	–	AlMadani, 2003
Fukue, JPN	1994	1,500	65	200	–	Ishimaru, 1994)
Oshima, JPN	1986	– ^e	25	10	–	Kuroda <i>et al.</i> , 1987
Spencer Valley, NM, USA	1992	885	2.3	2.7	16	Lichtwardt and Remmers, 1996; Lichtwardt and Williams, 2000
University of Alicante, ESP	2006	3,938	0.15	1.2	0.37 ^f	Ortiz <i>et al.</i> , 2008
University of Alicante, ESP	2004	2,000	0.15	2.1		Ortiz <i>et al.</i> , 2006; 2007

Notes: TDS = Total Dissolved Solids; ^a Three-letter ISO 3166 code; ^b Year of commission/design; ^c Actualised cost in US\$ for year of study. Other currencies were converted with nominal annual average exchange rates from <http://www.oanda.com/convert/fxhistory>; ^d Brackish water feed; ^e Seawater feed; ^f Theoretical estimate based on a larger system with 15 m³/day capacity.

The system was built in 1986 and installs a PV array of 0.45 kW_p. It desalinated brackish water with a 5,000 mg L⁻¹ TDS concentration to produce about 1 m³ day⁻¹ of permeate with an energy consumption of 5 kWh m⁻³.

A small commercial ED system consisting of 24 cell pairs and powered with a 0.132 kW_p PV array was tested at the University of Bahrain in 2002 (AlMadani, 2003). The unit was used to desalinate both brackish groundwater (TDS = 3,300 ppm) and a sodium chloride solution with concentration ranging between 1,000 ppm and 5,000 ppm and temperature between 10°C and 40°C. The system provided a 95% salt rejection for the brackish water and rejection ranging between 35% and 99% for the solution, the dilute flow ranging between 0.19 m³ day⁻¹ and 1.14 m³ day⁻¹.

An experimental unit using PV-powered electrodialysis reversal (EDR) was tested in Spencer Valley, New Mexico (Lichtwardt and Remmers, 1996; Lichtwardt and Williams, 2000). In EDR, the direction of ion flow within the ED stack is periodically reversed by reversing the polarity of the applied electric current. Three fixed arrays with a capacity of 2.3 kW_p provide energy to the EDR unit, while a second array of PV modules is installed to power the feed pump. The system has been in operation for more than 7,000 hours and has produced more than 340 m³ of drinking water at a rate of 2.8 m³ day⁻¹. Al-Karaghoul *et al.* (2010) report a cost of 16 US\$ m⁻³ for this system.

Several experiments on a batteryless PVED demonstration unit were run at the University of Alicante in Spain (Ortiz *et al.*, 2006; 2007; 2008). The system was used for the desalination of different types of brackish waters with TDS concentrations ranging from 2,000 ppm to 5,011 ppm. The system was run for short periods of time during peak radiation hours for several days in 2004 and 2006. The SEC of the system was measured between 0.92 kWh m⁻³ and 1.69 kWh m⁻³ for the desalination of the feed to meet drinking quality standards. The economic estimates simulated for a full-scale system producing 15 m³ day⁻¹ of desalinated water are very promising, indicating that drinking water quality can be achieved at a cost ranging between 0.25 US\$ m⁻³ and 0.47 US\$ m⁻³ depending on feed water salinity.

The experimental experience gathered with PVED in the investigated systems shows that this technological solution is technically feasible and stable long-term operation has been demonstrated for systems with battery storage. Batteryless devices seem to offer the best opportunities in terms of economic viability, especially for brackish water desalination, but demonstration of the long-term operation of such systems is still lacking from the literature.

Hybrid Solar Membrane Desalination

Hybrid solar membrane 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 (Helal *et al.*, 2008) 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 (Tzen *et al.*, 2008) and Israel (Weiner *et al.*, 2001) 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, included a diesel generator for backup, but it was never used during the entire period of system testing.

The costs of hybrid PV-diesel and, where meteorological conditions are favorable, PV-wind RO systems are lower than those of PVRO desalination. In a study that examined the design of a 12 m³ day⁻¹ autonomous desalination unit, Mohamed and Papadakis (2004) estimated actualized costs of 7.67 US\$ m⁻³ for a hybrid PV-wind system and 9.77 US\$ m⁻³ for a fully

PV-powered unit. Kaldellis *et al.* (2004) 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 capacities between 10 and 2,500 m³ day⁻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.* (2008) compared the overall performance and cost expectations of three different design configurations for a 20 m³ day⁻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.

PV-powered Desalination in Urban and Rural Areas: Two Case-studies

PVRO for potable water production in the city of Aqaba, Jordan

Within the framework of the technological scientific cooperation between Midwest Research Institute - National Renewable Energy Laboratory (NREL) Division in Colorado, USA, and the National Energy Research Center (NERC) in Amman, Jordan, a PVRO brackish water facility has been installed within the campus of Aqaba International Industrial Estate (AIIE) to meet its demand of potable water, which is estimated at 8000 m³ year⁻¹. The RO facility was financed by

Table 3. Overview of hybrid PVRO 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	Helal <i>et al.</i> , 2008
Chania, Crete, GRC ^e	2004	40,000	PV	Wind	12	6.5	Mohamed and Papadakis, 2004
CRES, Lavrio, GRC	2001	37,700	PV	Wind	0.8	31.8	Tzen <i>et al.</i> , 2008
Curtin Univ., AUS	–	–	PV	Fuel	1	–	Al-Alawi, 2007
Maagan Michael, ISR	1997	4,000	PV	Wind & fuel	3	6.8	Weiner <i>et al.</i> , 2001
Marettimo, ITA	1993	– ^f	PV	Fuel	5	–	European Commission, 1998
Nicosia, CYP ^e	2005	– ^g	PV	Grid	50.4	0.9	ADU-Res, 2005
Ras Ejder, LBY ^e	2005	42,000	PV	Wind & grid	300	–	Kershman <i>et al.</i> , 2005
St.Lucie, FL, USA	1995	32,000	PV	Fuel	0.6	–	Thomas, 1997
Tarifa, ESP ^e	1987	– ^f	PV	Wind	150	–	Gonzalez <i>et al.</i> , 1987

Notes: TDS = Total Dissolved Solids; ^a Three-letter ISO 3166 code; ^b Year of commission/design; ^c Nominal capacity; ^d Actualised cost in US\$ 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.

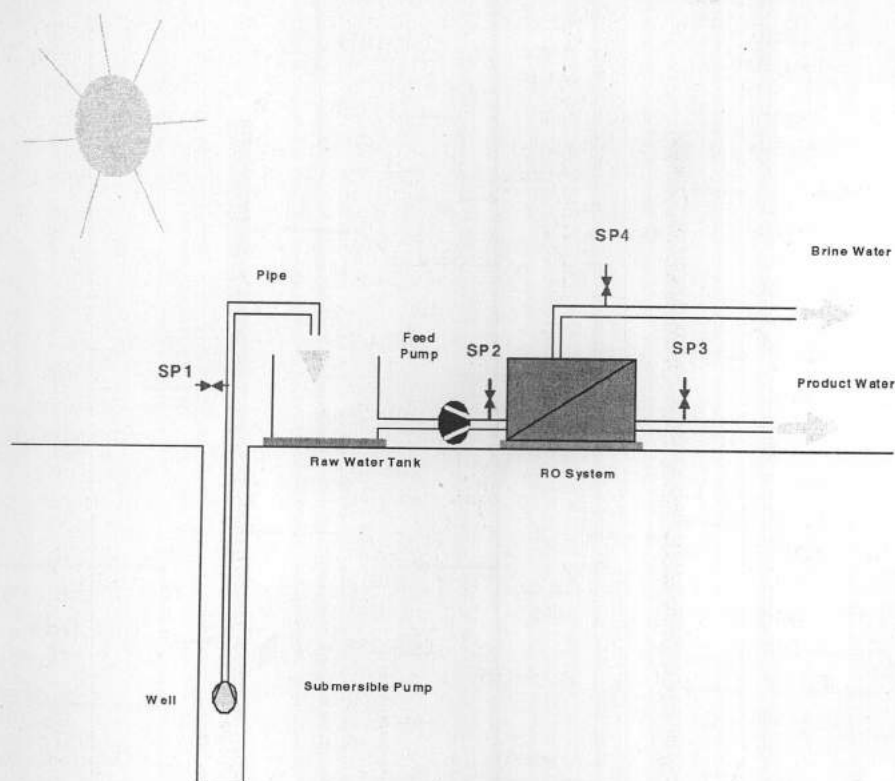


Fig. 6. Design concept of the PVRO facility installed at Aqaba, Jordan.

a United States Agency for International Development (USAID) grant through the project named "Solar Powered Desalination and Pumping Unit for Brackish Water in Jordan". Also, the AIIE was financed by a USAID grant.

The RO facility is located within the Aqaba Special Economic Zone Authority. The plot of land on which it was constructed and installed was rented by PBI Aqaba Industrial Estate LLP (PBI Aqaba) – a subsidiary of Parsons Brinckerhoff International (PBI), a leading US civil engineering company, and SUTA Construction, a substantial Turkish land development company – which has a 30 year concession to plan, finance, develop, market and operate the AIIE. A plot of 2000 m² land was allocated for the infrastructure and installation of the RO facility. The design concept of the PVRO plant is shown in Fig. 6.

A 100 m deep well was drilled by the Water Authority of Jordan (WAJ) in the chosen site to extract brackish water over the life of the project. Raw water is extracted at a rate of 14 m³ h⁻¹ from a static water level of 73.15 m. The chemical composition and quality of the brackish water is given in Table 4. After extraction, the water is conveyed to a raw water storage tank (35 m³) made of glass fiber reinforced plastic (GRP).

Table 4. Brackish water quality extracted at Aqaba, Jordan

Parameter, unit	Value
pH	6.57
Electroconductivity, dS m ⁻¹	5.31
Ca, ppm	575
Na, ppm	453
K, ppm	12
SO ₄ , ppm	157
HCO ₃ , ppm	519
NO ₃ , ppm	12
Cl, ppm	1699
Mg, ppm	49

The site for the construction of the PVRO system was selected for its high potential of solar energy, the annual daily average of solar radiation on a horizontal surface reaching 5.5 kWh m⁻² day⁻¹. PVRO arrays with a total capacity of 16.8 kW_p were installed on two parallel concrete foundations (27 m long). The PV unit consists of 140 silicon mono-crystalline PV panels each rated at 120 W_p (Kyocera KC-120-1). A battery bank with a total storage capacity of 73.44 kWh is installed, which consists of 24 sealed lead acid batteries each rated

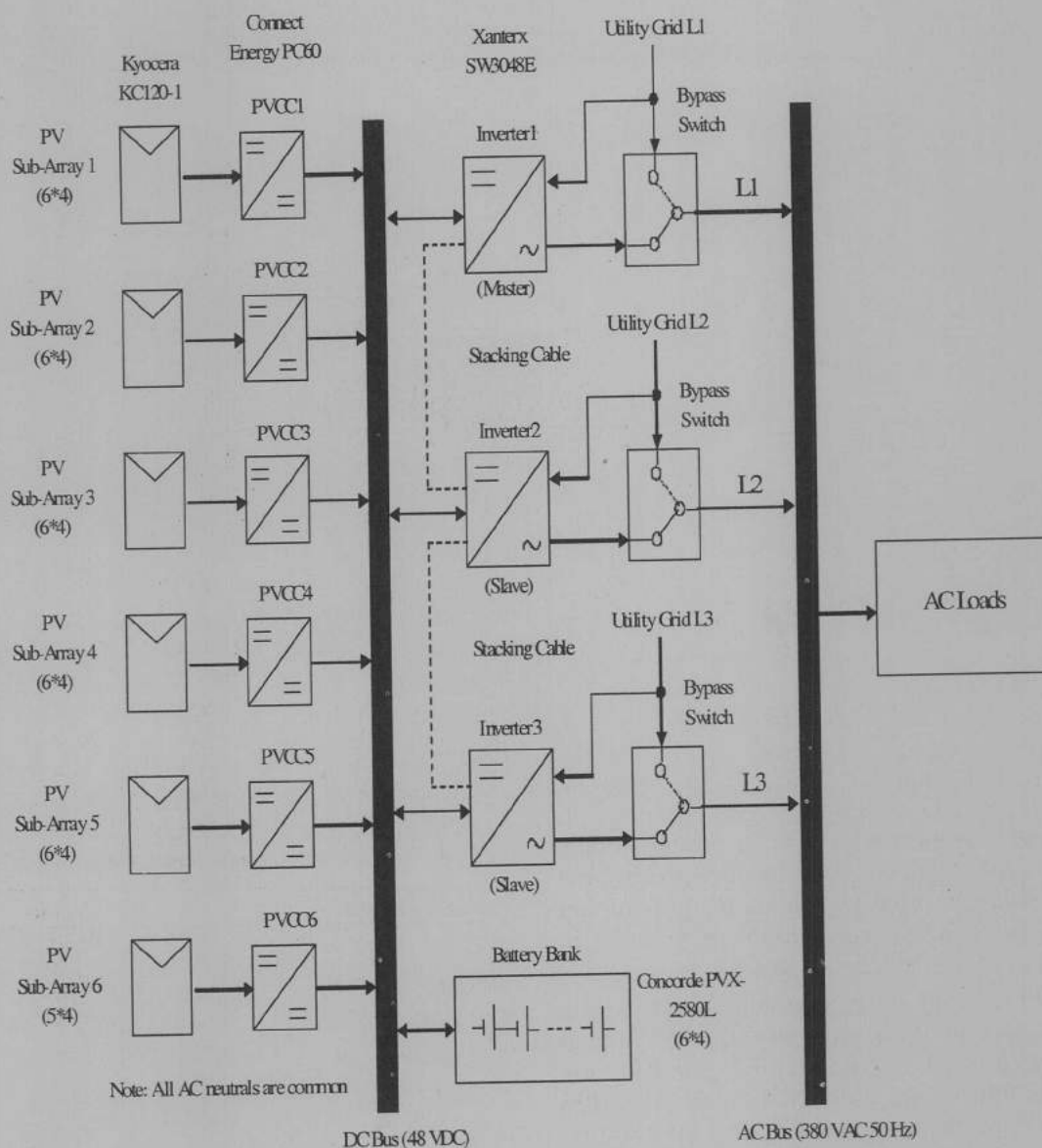


Fig. 7. Electrical system configuration at the PVRO facility in Aqaba, Jordan.

at 12V/255Ah (Concorde PVX-2580L). The system includes six charge controllers and four pure sine-wave inverters/chargers, each rated at 220V, 50 Hz and 3.3 kVA (Xantrex SW3048E). In addition to the installed solar power supply system, a utility grid connection was obtained by PBI Aqaba to electrify the lighting and the air conditioning systems within the facility. Electricity from the utility grid is also used to operate the RO facility up to 24 hours/day according to the water demand of the AII. Schematics of the electrical system configuration are given in Fig. 7.

A control system was specifically designed and built by NERC for automation of the station. The

control system operates in two phases, alternating filling of the raw water tank via the submersible pump and RO operation via the high pressure pump until a preset minimum level is reached in the raw water tank and the cycle is restarted.

The basic system components of the desalination unit are cartridge filter pre-treatment, high-pressure pump, pressure vessels, RO membranes, automatic permeate flush system and control system. The configuration of the RO membranes is in three stages. The first two stages consist of three pressure vessels with two membrane elements per vessel, while the third stage consists of two pressure vessels only. The installed membranes are Hydranautics

Table 5. Groundwater quality in Hatzeva, Israel

Parameter, unit	Value	Parameter, unit	Value
Alkalinity as CaCO ₃ , ppm	170	CO ₃ , ppm	n.d.
Electroconductivity, dS m ⁻¹	2.42	HCO ₃ , ppm	208
pH	7.63	K, ppm	12.5
TDS, ppm	1,577	Mg, ppm	82.5
TSS, ppm	2	Na, ppm	225
Turbidity, NTU	0.16	NH ₄ -N, ppm	<0.3
B, ppm	0.34	NO ₃ , ppm	9.6
Ba, ppm	0.194	SO ₄ , ppm	505
Ca, ppm	150	Sr, ppm	5.52
Cl, ppm	359	Zn, ppm	0.15

Note: EC = electroconductivity; TDS = total dissolved solids; TSS = total suspended solids; n.d. = not detected.

CPA2-4040 modules, which were designed to operate at a pressure of 13.1 bar to treat a feed water flow equal to 5.68 m³ h⁻¹.

The desalinated water produced at the PVRO facility is pumped to the main water reservoir of the AIIE (2,900 m³) wherein mixed with the water of the WAJ and sold to AIIE customers. The concentrate, backwash outlet and drain of the solution tank are connected via hoses to a brine water evaporation pond (600 m²), coated with a special liner to prevent infiltration of the brine to the groundwater aquifer.

The infrastructure for the facility was completed in August, 2005. The PVRO facility was installed and operated in September, 2005. The facility has performed according to its rated specifications producing 3.4 m³ h⁻¹ of freshwater, with a recovery rate of 60%, a permeate salinity equal to 70 ppm of TDS, and an energy consumption of 3.6 kWh m⁻³. PV-produced electricity covered 47% of the total electricity required for the operation of the desalination plant (84 kWh day⁻¹ out of 180 kWh day⁻¹). According to the amount and the quality of the permeate water being produced by the RO facility, PBI Aqaba may depend completely on the RO facility to meet the demand of potable water at the AIIE.

PVNF for agricultural irrigation in the Arava Valley of Israel

Irrigation with brackish water from marginal-quality aquifers is largely practiced in rural areas of the Middle East and India (Qadir *et al.*, 2007), but the potential of the technique is limited by a series of drawbacks: (i) High salinity levels cause osmotic imbalances and reduce water uptake and transpiration, which results in lower yields than are obtainable with freshwater irrigation

(Sadeh and Ravina, 2000). (ii) The choice of crops is limited by each crop's specific salinity tolerance, a fact that often translates into support for the production of staple crops at the expense of other, horticultural crops that would fetch higher returns (World Bank, 2004). (iii) Even when appropriate irrigation management strategies are implemented, salt accumulates in the root zone unless large volumes of water, in excess of plant requirements, are used to leach salts, thus limiting the potential for damage to plants and soil structure. Such large water requirements may ultimately make irrigation with brackish water highly unsustainable (Ben-Gal *et al.*, 2008).

The Arava valley of Israel is an example of the potential for highly profitable agriculture in a region of extreme water scarcity. Despite the extremely hot climatic conditions and an average annual precipitation of only 32 mm, the valley is home to the most intensive and profitable agricultural activities in Israel (Portnov and Safriel, 2004). Mild winter seasons provide a comparative advantage for the seasonal production of high-value export crops such as bio-organic vegetables (e.g., peppers and melons) and flowers. About 60% of Israeli vegetable exports are produced in the Arava. To compensate for the adverse climate, farmers have developed efficient agricultural techniques that make intensive use of greenhouses, cooling systems, and water-efficient drip irrigation techniques (Gadiel, 2008). The local agricultural activities rely exclusively on marginal quality groundwater extracted from the local aquifers. Brackish water irrigation is widely practiced.

The potential of PV-powered membrane desalination as a more water-efficient and viable alternative to brackish water irrigation in the Arava was explored in the frame of the CSPD-COMISJO

Table 6. Design operation and permeate quality with NF and RO membranes in Hatzeva, Israel

	BW30-4040 (RO)	NF90-4040 (NF)
Total active area, m ²	14.49	15.24
Operating pressure, bar	9.04	5.00
Feed blending, m ³ /hour	0.12	0.09
Specific energy costs, kWh/m ³	1.01	0.65
Permeate TDS, ppm	562	656
Permeate Ca, ppm	51	50
Permeate Mg, ppm	28	28
Permeate SO ₄ , ppm	172	159

project for the agricultural community of Hatzeva (Ghermandi and Messalem, 2009; Alawneh *et al.*, 2008). Local wells supply is characterized by moderately saline water, which is routinely used for irrigation. A characteristic water quality is presented in Table 5.

In the frame of the study, a pilot PV-powered desalination plant was designed for the production of 5 m³ day⁻¹ of freshwater and the irrigation of 500 m² of agricultural plots (Ghermandi and Messalem, 2009). The power supply of the pilot plant is designed according to a hybrid configuration that allows for the high pressure pump and the other auxiliary systems to be powered with energy either from the PV modules or from the electric grid. The installation of a minimum size of 2.1 kW_p for the PV arrays and a bank of batteries (4 × 420 Ah) is envisaged to allow for smooth operation over 15-20 hours day⁻¹ with solar energy only. Flexibility of operation is provided by the installation of a helical rotor, positive displacement pump (Grundfos SQFlex 1.2-2) equipped with a built-in inverter, which allows for operation both with DC power supply from the battery or AC power supply from the electric grid.

Two alternative design configurations were considered, involving RO and NF membranes. In the case of PV-powered desalination for agriculture, NF desalination has several advantages compared to RO. First, NF operates at lower pressures and correspondingly lower energy requirements, translating into a smaller PV area and consequently in economic savings. Second, NF permeate contains a higher concentration of ions that are essential to plant growth such as calcium, magnesium and sulphate (Yermiyahu *et al.*, 2007). Table 6 compares the differences in operating pressure, power consumption, and effluent quality that can be obtained with respectively NF and RO membranes,

respectively Dow Filmtec NF90-4040 and BW30-4040. The calculations in Table 6 rely on the design tool software ROSA (Reverse Osmosis System Analysis, www.dow.com/liquidseps/design/rosa.htm) and include blending of the membrane permeate with a fraction of the feed water in order to achieve a final product that complies with the water quality standards recommended for agricultural use by Yermiyahu *et al.* (2007) (i.e., 32-48 ppm of calcium, 12-18 ppm of magnesium, and 30 ppm or higher of sulphate). Apart from the type of membranes, the two design configurations are identical for what concerns number of membranes (one pressure vessel with two membranes), overall water recovery rate (80%), recycle flow (0.50 m³ hour⁻¹) and feed water flow and quality.

Table 6 shows that the selected NF membranes operate at a 45% lower pressure than reverse osmosis membranes (5.00 bar versus 9.04 bar). The difference in operating pressure translates into significantly lower specific energy costs for the NF membranes relative to the RO membranes (0.65 kWh m⁻³ versus 1.01 kWh m⁻³, i.e., 36% lower power consumption). The slight increase in the overall salinity of the irrigation water in the PVNF desalination plant configuration compared to PVRO (656 ppm versus 562 ppm) is not expected to result in any substantial reduction of crop yield due to salinity intolerance (Ghermandi and Messalem, 2009).

With respect to the current practice of brackish water irrigation, it is estimated that irrigation with desalinated water would facilitate a 45% reduction in the current water irrigation volume in the case of bell pepper – the most commonly cultivated crop in the Arava – while simultaneously resulting in a crop yields increase. Taking into account the water recovery rate of the desalination plant and assuming that the brine cannot be used for any

further irrigation use, such a reduction in irrigation volume corresponds to a savings in the quantity of abstracted groundwater of 34%.

Theoretical economic estimates show that the pilot units can produce irrigation water at a cost of 2.6 US\$ m⁻³ relying purely on solar power and that costs are reduced to less than 1.5 US m⁻³ in the case of grid operation. Even without accounting for economies of scale in full-scale units, such costs may make the system competitive in remote locations without inexpensive access to grid electricity and, possibly, in more accessible areas for the production of salt-sensitive crops with high commercial value. Such preliminary estimates and the overall economic viability of the system are currently under evaluation in an experimental unit built in Hatzeva according to the described design configuration.

Synthesis and Conclusions

Although important lessons in the design of PV-powered membrane desalination systems have been learnt since the first experimental units were built in the late 1970s, solar desalination has not prominently entered the desalination markets, although some PVRO units started to be commercialized in recent years (Dallas *et al.*, 2009). The results of this study suggest that a penetration of solar membrane desalination in the market of small-scale desalination seems likely in the future, although we do not expect that these technologies will occupy a very large share of the desalination market any time soon. In particular, state-of-the-art PVRO desalination is cost-competitive with other

water supply sources in the 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 small-scale fuel-driven desalination plants. Such view seems to be confirmed by several studies that evaluated the technical feasibility and economic viability of solar membrane desalination in arid regions of India (Abraham and Luthra, 2011), Tunisia (Houcine, 1999), the Arabian Gulf region (Al-Mutaz and Al-Ahmed, 1989), Brazil (Silveira Jucá, 2005), and other countries. PV-powered membrane desalination is particularly suited for small systems to be operated in remote areas since the implemented desalination technologies are modular, easy to install, compact in size and simple to operate. Similarly, PV modules are modular, do not contain any moving part, have a long lifetime and involve low maintenance (Richards and Schäfer, 2010).

The best hope for a wide implementation of PV-powered desalination lies in the rapid advancements of solar technologies such as concentrating solar power (Alawneh *et al.*, 2008) and the recent trends towards a reduction in the cost for PV modules, whose retail price has dropped respectively by 29% and 36% in the US and European market between November 2007 and January 2011 (see Fig. 8). If the industry will succeed in driving PV module prices down to 1.5-2.0 US\$ per watt over the next decade, one can expect that the commercial interest in PV-powered desalination will increase considerably.

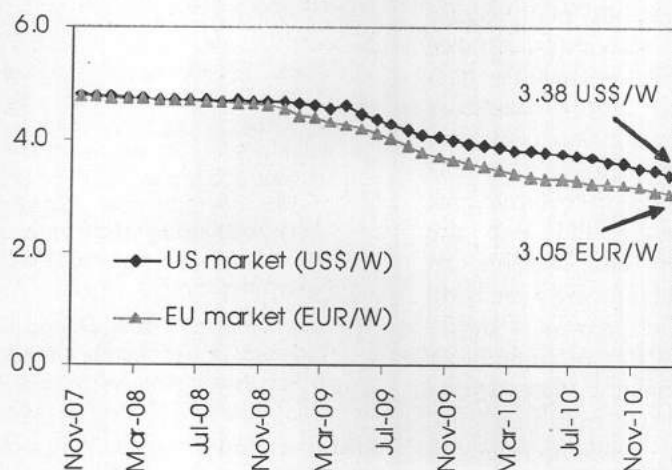


Fig. 8. Retail price per watt peak for 125 watts or higher modules (source: Solarbuzz, <http://www.solarbuzz.com/Moduleprices.htm>)

Several studies have pointed out to the potential for cogeneration of water and energy (Rheinländer and Geyer, 2009; Bayod-Rújula and Martínez-Gracia, 2009 and on hybrid processes that combine two or more desalination technologies (Maurel, 1991; Voivontas *et al.*, 2001; Delyannis and Belessiotis, 1995; Delyannis, 1987) or two or more energy sources. Although our analysis shows that there is a potential for cost reduction when the complementary aspects of two renewable energy sources can be exploited, the increase in complexity for the maintenance of these systems is a concern that should be kept in mind when the systems are to be installed in remote areas (García-Rodríguez, 2007). Grid electricity backup, where available, may allow for continuous operation also during low irradiation periods and significantly reduce the actualized cost of the desalinated water.

Despite the relatively large number of pilot and demonstration units built over the last decades, in particular PVRO units, a standard design approach has thus far not emerged as revealed, for instance, by the different technical solutions adopted in the use of battery storage and DC/AC energy inverters. While the combination of PV panels and ED is straightforward since both technologies operate on DC, there seems to be a potential for DC-powered PVRO units due to the increase in system efficiency. Richards and Schäfer (2010) estimated 5-10% energy loss in conversion from DC to AC.

Battery storage may increase the overall productivity of solar desalination plants and enable steady operation, but involves a 20-25% reduction in efficiency, higher investment and maintenance costs, and potentially issues with their disposal in remote areas. Recent studies with batteryless PVRO/PVNF (Richards *et al.*, 2008; Schaefer *et al.*, 2007) and PVED (Ortiz *et al.*, 2006; 2008) have shown that these systems are technically feasible and are able to tolerate fluctuations in solar radiance availability. It has been suggested that the fluctuating water supply from these systems can be matched with the water demand by oversizing them and providing water storage as a buffer for days with minimal freshwater production. A key issue here is to ensure that the water stored in the permeate tank remains free from biological contamination, which can be problematic in hot climates.

Although the recent trends both for pressure-driven PV and PVED desalination are towards batteryless systems operated with DC

power, such technologies are still under development and there is a need for confirmation of the preliminary encouraging results in the long-term operation of full-scale units.

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