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Design of autonomous PV/RO desalination systems – case studies for Egypt and Greece

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ABSTRACT

The aim of the present work is to develop a design and sizing methodology for autonomous reverse osmosis (RO) desalination systems and assessing their feasibility taking into consideration the following parameters: climatic conditions, water demand profile, water salinity, RO capacity (from 1 to 48 m^3/d), energy recovery techniques, photovoltaic (PV) power generation with its battery storage and required accessories such as DC/AC inverters and charge controllers. Based on the design tool calculations, the RO water desalination system, the intake pump, high-pressure pump, network pump and energy saving recovery pump are sized. According to the required daily electrical energy and the meteorological site parameters, the required PV system is designed by sizing the peak power of PV modules, the battery bank capacity in Ah, the required battery charge controllers, as well as the DC/AC inverters. The specific energy consumption (SEC; kWh/m^3) and the specific energy cost (euro/kWh) are obtained for different plant capacities namely 50, 100, 220, 500, 1,000, 1,500 and 2,000 L/h for Egypt (Marsa Matrouh, latitude of 31.35° N, longitude of 27.23° E) and Greece (Milos island, latitude of 37.58° N, longitude of 23.26° E).

Keywords: Reverse osmosis; Water desalination; Energy recovery; System optimization; Cost analysis; Solar irradiation; Photovoltaic generation system; Greece; Egypt

1. Introduction

As water is the essence of life, the main challenge for developing remote and rural areas, where no freshwater is available, is to supply water for human purposes from the locally available water resources such as seawater and brackish water. This can be accomplished by means of onsite water desalination systems, which are considered a better option than transferring freshwater via tanks or long distance pipe lines.

Desalination can be defined as the process that removes or eliminates salts from water through special treatment processes. Reverse osmosis (RO) desalination uses high pressure to 'push' saline water through a semipermeable membrane. The membrane allows water molecules to pass and block salts and other saline water contaminants. Energy is needed to drive the high-pressure pumps and other RO plant pumps, which is most often supplied in the form of electricity. The inlet (feed) water to the RO system is the saline water to be treated, while there are two outputs that are the produced freshwater and the brine [1].

Since often rural or remote areas are far from the electric power grid, desalination using autonomous renewable energy (RE) systems is currently acknowledged as the most promising option for supplying freshwater to these communities. Among the RE technologies, photovoltaics (PVs) are clean and almost maintenance free, simple and reliable and can be coupled with an RO system to produce freshwater close to the demand without the need to transfer either the energy or the treated water. Moreover, a considerable price decrease has been observed in the last years [2], making PV energy more affordable. PV/RO can be used as modular systems in remote areas for different water load profiles [3].

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The layout of a PV/RO system with energy recovery (ER) is presented in Fig. 1 as follows [1]:

- solar system (PV modules, storage battery bank, battery charger controller, DC/AC inverter and system mounting structure),
- pretreatment system (to protect the system membrane and to keep the desalination efficiency high; feedwater must be pretreated to remove large and dissolved solids before entering the system membrane),
- high-pressure pump (feedwater must be pressurized above its osmotic pressure for water molecules to cross the membrane),
- membrane (it is used to separate freshwater from salts and other contaminants using high pressure),
- post-treatment system (freshwater must be treated to neutralize the acidity and eliminate infection via certain additives such as chlorine in order to be suitable for human purposes) and
- ER system (to maximize the system efficiency and reduce production costs, the ER system transfers brine pressure to the feed).

Many investigations have been carried out for PV/RO desalination systems over the world. He et al. [4] analyzed theoretically the operation of a standalone PV/RO system using a mathematical model based on hourly irradiation data, in addition to a case study of an installed PV/RO desalination system in Perth, Australia. Caldera et al. [5] studied hybrid RE water desalination systems powered by PV and wind with batteries as storage. They estimated the production cost of RE desalinated water for the year 2030 and concluded that future world water supply limitations can be overcome in a sustainable and financially competitive way by using RE. Jones et al. [6] presented a simulation model for a desalination system to be used for agricultural purposes in Jordan with variable speed pumps and no battery storage. The simulations were carried out for PV, diesel and grid electricity for different membrane types, more than one configuration of electric inverters and two ER system rates. The study showed the advantages of using PV to drive the desalination plant over grid electricity or diesel.

The economic feasibility of water desalination in remote areas using RE was investigated using mathematical software and experimental data from a pilot plant installed in New Mexico (Alamogordo) by Karimi et al. [7]. Two software models – WinFlows and WATSYS – estimated the energy consumption for RO and electrodialysis desalination systems, respectively, for different water flow rates, salinities and temperatures, while the design of RE system needed to power different desalination systems was carried out by HOMER software. The net present cost (NPC) of the examined RE/RO systems was calculated and the results showed that in regions with high irradiation levels (such as Alamogordo) it is feasible to power both RO and electro-dialysis (ED) desalination configurations with solar energy. PV/RO is preferable to PV/ED for high-salinity water.

For countries with high irradiation levels such as the United Arab Emirates, Helal et al. [8] suggested small PV/RO seawater desalination systems for supplying freshwater to small rural and remote communities that are far from electrical grid and water supply networks. Alghoul et al. [9] explained that using RE in the form of PVs with small-scale water desalination plants in arid and remote locations

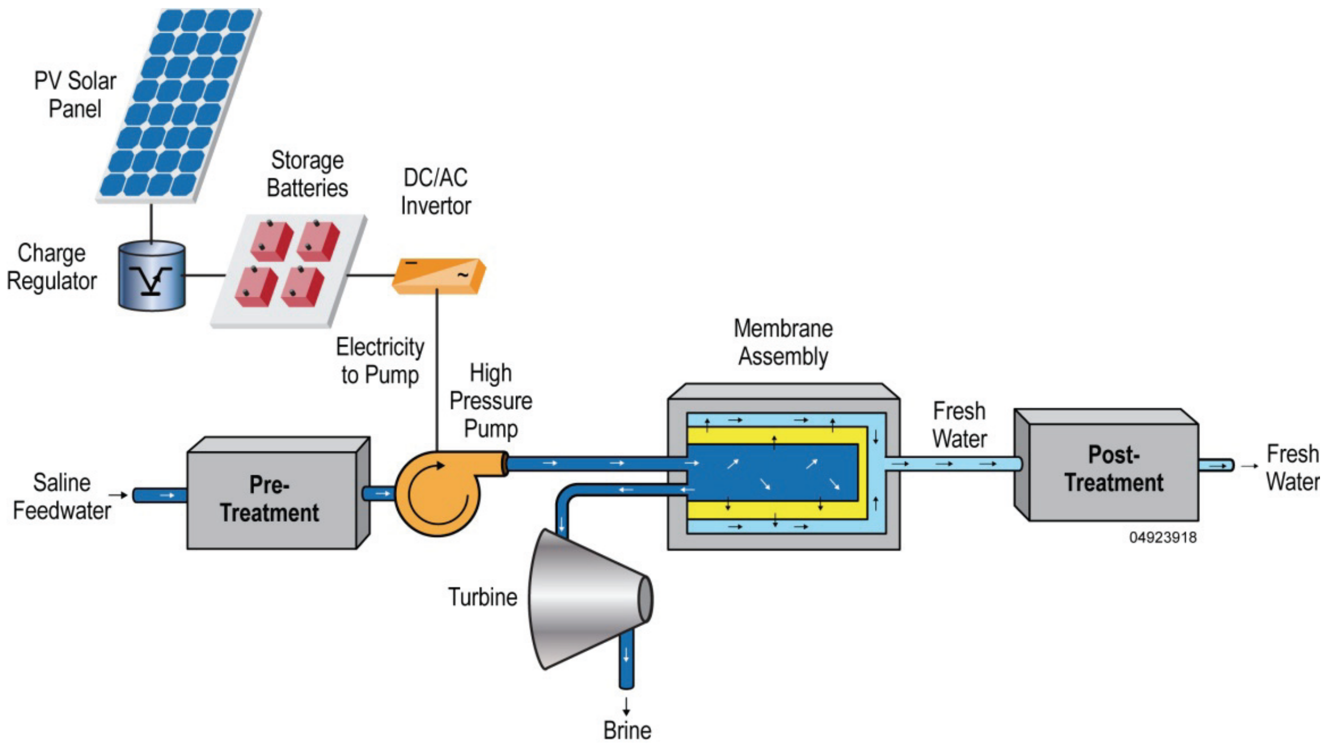

Fig. 1. Layout of a PV/RO system with energy recovery.

can help in the commercial deployment of such systems. They designed a small PV/RO desalination plant with 2 kWp PV power and the required battery storage. The plant was installed and tested for a period of 6 months using feedwater salinity of 2,000 mg/L and permeate water salinity of 50 mg/L, with five membranes.

Ahmad et al. [10] simulated the RO water desalination system powered by PV energy for stationary and solar tracking PV systems (one and two axis). For experimental verification, they built a PV/RO plant in Saudi Arabia (Dhahran city). They concluded that the optimum tilt angle for the PV system was 0.913 times its latitude and freshwater production gains were 43% and 62% for the single-axis and two-axis tracking over the stationary PV system, respectively.

Schallenberg-Rodríguez et al. [11] highlighted the drawback of water desalination plants, which depend on conventional energy sources by referring to the operation of the oldest plant in Europe in Lanzarote (Canary Islands). As the plant capacity was 600,000 m^3/d, it consumed about 12% of the total electrical energy demand for the island. This energy problem can be solved by depending on other RE sources such as solar (PV) or wind. Outzourhit et al. [12] presented two RO water desalination plants constructed in two different places for supplying freshwater for households in the framework of the ADIRA project funded by the MEDA-Water program of the EC. The plants used two PV systems of 4.8 and 3.9 kW, respectively, along with the required battery storage system for a production capacity of 1 m^3/h. Espino et al. [13] presented a solution for drinking water supply in remote communities, where the conventional energy sources are not readily available, by building a small PV/RO desalination plant with a production capacity of 3 m^3/d. The results of the economic analysis showed that using PV/RO plants can help in solving the water scarcity problem in these areas in an economically competitive way in comparison with the traditional energy sources.

Gilau and Small [14] presented an economic analysis of a standalone small PV/RO seawater desalination plant for rural and remote areas. Based on an hourly power production model, they simulated the performance of a 35 m^3/d PV/RO desalination plant in order to calculate the produced freshwater from the plant on an hourly basis. They found out that optimizing the operating parameters (appropriate membrane, booster pump and recovery system) can significantly decrease the energy consumption and consequently the water production cost. Banat et al. [15] installed a small (0.5 m^3/d) autonomous PV/RO desalination unit powered by a 432 Wp PV system in Jordan in the framework of the ADIRA project. The plant used a battery bank for energy storage and ER. Castellano et al. [16] presented an autonomous system driven by a 10.5 kWp PV solar array. The whole system was controlled automatically and 15 m^3/d freshwater was produced from the existing brackish water well through a 50 m^3/d RO desalination unit. Their system was found to be a feasible alternative that allows the meeting of the water needs of the village.

Gkeredaki [17] presented a study of an autonomous PV powered seawater RO system for remote coastal areas in the island of Crete (Greece) in cooperation with the Technical University of Crete. It was found that the SEC ranged from 2.73 to 3.50 kWh/m^3, which can be considered considerably low for RE powered seawater desalination systems. For comparison, typical SEC values found in literature for similar seawater PV/RO systems are about 4–5.5 kWh/m^3 for systems with ER and 6.3–17.9 kWh/m^3 for systems without ER. The results of the sizing approach showed that for 10 panels (230 Wp each) and an average annual water production of 781 m^3 (1.16 m^3/d in winter and 3.12 m^3/d in summer), the average annual water cost is estimated to be around 4.74 €/m^3. It is concluded that the viability of RE desalination systems is very site specific. It can be suggested that PV/RO seawater desalination is promising mainly for remote arid regions with high irradiation levels (where water scarcity is covered with transportation of water and there is no access to the grid) and with no potential for exploiting brackish water resources.

Sassi and Mujtaba [18] simulated the full performance of a PV/RO desalination system using a theoretical model (solution–diffusion) to study the significant factors affecting the PV powered desalination process for optimization purposes. Two alternative ER techniques (pressure exchanger and turbine) were taken into consideration. The results showed that the advantage of using a pressure exchanger recovery system is the reduction of pump costs by 50% in comparison with the turbine ER.

In this work, two autonomous PV/RO seawater/brackish water desalination systems with ER are designed; one for Egypt (Marsa Matrouh, latitude of 31.35° N, longitude of 27.23° E) and one for Greece (Milos island, latitude of 37.58° N, longitude of 23.26° E). The design and sizing process is taking into consideration the local meteorological parameters in terms of solar irradiation at optimally tilted angles and the water demand profiles at both locations. The sizing of the RO desalination unit includes the calculation of the required electrical power needed for each pump (feedwater, RO, freshwater pumps) and hence the total daily required electrical power. The sizing process of the required PV system needed to electrically drive the RO unit includes the sizing of the PV arrays, the capacity of battery bank, the required electronic accessories such as battery charge controllers as well as DC/AC inverters. The design is considered for different plant capacities of 50, 100, 220, 500, 1,000, 1,500 and 2,000 L/h. A cost analysis for the PV/RO systems is also elaborated for each plant capacity in terms of specific energy costs.

2. Theoretical analysis

The theoretical analysis of the PV–RO water desalination system with ER can be divided into three main parts as follows:

- choice of desalination unit capacity,
- calculation of the daily energy consumption profiles of system based on the system configuration and daily hours of system operation and
- sizing of the PV batteries system, i.e., PV capacity (kWp), battery bank capacity (Ah), battery charge controller (A) and DC/AC inverter (kW).

2.1. Desalination unit capacity

The average daily water demand per month as a percentage of the average daily demand in the peak month (L) shows the monthly variation of water demand and is hereafter called the water demand profile. The left axis of Fig. 2 shows the water demand profile in Matrouh and Milos for 1 year. The figure indicates that the required water demand varies significantly within the year, reaching its maximum during the summer months and August in particular. This can be explained due to the touristic character of both Milos and Matrouh cities that attract a large number of tourists during the summer period.

According to the water demand profile and taking a safety factor of 20% for the capacity of the desalination unit in terms of increased water demand, the maximum daily water demand (WD_{max}) in m^3/d can be calculated with Eq. (1).

$$WD_{max} = 1.2 * WD_{Aug} \tag{1}$$

The desalination unit capacity in L/d will be calculated with the assumption that the capacity factor of the unit will be equal to 100% for the month with the highest demand (August), which translates to 24 h of operation (HO).

$$Q = \frac{WD_{max} \times 1000}{HO} \tag{2}$$

The average daily hours of operation per month in Matrouh and Milos are presented in the right axis of Fig. 2. The bars of Fig. 2 have the same shape for both left and right axes, since the monthly average hours of operation per day for Matrouh and Milos are directly calculated from the water demand profiles. For optimum operation of the solar desalination system, the hours of operation must be centered around noon for each day of the year. This will ensure maximum utilization of solar radiation and minimization of energy storage requirements.

2.2. Daily energy consumption profiles

The daily electrical load required in kW is the sum of the required power for each pump in the water desalination system. These pumps are the seawater/brackish water boost pump, the RO high pressure pump and the potable water pump, taking into consideration the recovered energy by the ER system. For each of these pumps, the required electrical power (P_P) in kW can be calculated as follows:

$$P_P = \frac{Q_P \times \rho \times g \times h}{\eta_P \times \eta_m \times 3.6 \times 10^6} \tag{3}$$

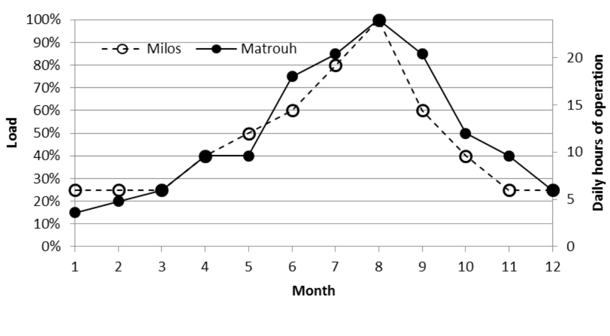

Fig. 2. Average daily water demand and average daily hours of operation.

The net required electrical power for a desalination plant is the difference between the total electrical load required by seawater/brackish water boost (P_{SB}), RO (P_{RO}) and potable water pumps (P_{Po}) and the recovered power (P_{ER}), as follows:

$$P_L = P_{SB} + P_{RO} + P_{Po} - P_{ER} \tag{4}$$

For the recovery system, in calculating the recovery power, the pump capacity can be taken as the difference between the seawater/brackish water boost pump capacity and RO pump capacity, while the recovery efficiency is taken to be 81% [19,20].

The daily electrical energy (E_L) required for the PV–RO desalination plant at a required water capacity with ER system in Wh/d can be calculated as follows:

$$E_L = P_L \times HO \tag{5}$$

In this study, ROSA 9.1 design software was employed for RO system design. Typical seawater composition for Eastern Mediterranean (Table 1) at 20°C was assumed for RO feed and the fact that the produced desalinated water had to be in compliance with WHO guidelines for drinking-water quality was taken into account in system design. Only single pass RO configurations were examined, while RO high-pressure pump overall efficiency was set at 80%. Furthermore, for calculating the required electrical power of seawater and potable water pumps a total head of 10 m and an overall pump efficiency of 80% were assumed in each case. System design was done with the aim to minimize RO energy requirements and the results for certain capacities in the studied range of 50–2,000 L/h are presented in Table 2. For the systems between 220 and 2,000 L/h the SEC, without taking into consideration the ER, is between 4 and 6 kWh/m^3. For the smaller systems of 50 and 100 L/h the energy consumption rises to 12.87 and 7.95 kWh/m^3, respectively.

2.3. PV system design

The design of any PV system mainly depends on the site parameters, especially solar irradiation levels throughout the year. Fig. 3 shows the monthly average daily global irradiation on horizontal and optimally inclined planes in Wh/m^2/d at Matrouh (latitude of 31.35° N, longitude of 27.23° E at 10 m elevation) and Milos (latitude of 37.58° N, longitude of 23.26° E at zero elevation). Since the optimum tilt angle of the autonomous PV system that captures the maximum energy all the year is equal to the site latitude angle ±5° [21], the optimally inclined tilt angles over the horizontal plane are considered 28° and 31° for Matrouh and Milos, respectively. From Fig. 3, it is clear that Egypt has higher daily global irradiation levels

Table 1
Typical seawater composition for Eastern Mediterranean (in mg/L as ion)

TDS	38,496	Mg	1,403.00	CO_3	31.11	Boron	4.28
pH	8.25	Ca	423.00	HCO_3	156.00	CO_2	0.48
Cl	21,200.00	K	463.00	NO_3	2.10		
Na	11,831.47	Sr	8.00	F	1.00		
SO_4	2,950.00	Ba	0.03	SiO_2	3.00		

Table 2
RO system design results with ROSA 9.1

Capacity (L/h)	Recovery (%)	Feed pressure (bar)	Type of element	No. of stages	No. of elements	Permeate TDS (mg/L)	Specific energy[a] (kWh/m^3)	Power (kW)
50	13	48.18	SW30-2540	1	1	339	12.87	0.64
100	22	50.36	SW30-2540	1	2	357	7.95	0.79
220	35	56.97	SW30-2540	1	4	359	5.65	1.24
500	35	53.77	SW30-4040	1	4	223	5.34	2.67
1,000	40	52.34	SW30-4040	2	10	280	4.54	4.54
1,500	30	50.23	SW30HRLE-440i	1	3	149	5.82	8.72
2,000	35	52.20	SW30HRLE-440i	1	4	155	5.18	10.36

[a]Without energy recovery.

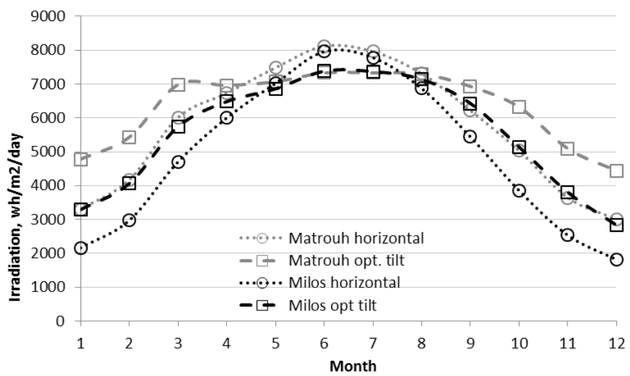

Fig. 3. Monthly average global irradiation on horizontal and optimally inclined planes at Matrouh and Milos.

than Greece, with annual average of 5.76 and 4.93 kW/m^2/d at horizontal surfaces and 6.33 and 5.55 kW/m^2/d at optimally inclined surfaces for Egypt and Greece, respectively. Also, the total yearly values of global irradiation (integral values) at optimum tilt angles at both sites are 2.28 and 1.99 GWh/m^2 for Egypt and Greece, respectively.

The PV system mainly contains the following components:

- the PV array, which generates the electrical power directly from the sun to drive the desalination plant with the required electrical energy, along with the power needed to pump the water to the desalination unit (a 10 m head has been assumed),
- battery bank, which stores electrical energy to drive the plant in case of shortage of solar radiation and night,
- charge controller, which regulates and controls the charging and discharging process of the battery bank,
- DC/AC inverter, which converts the generated DC energy from the PV array directly to AC energy for AC plant operation and
- other system components such as wiring, metal structure for PV and batteries, cables and cabinets needed.

For cost optimization, small systems can be DC operated (without inverter), while larger systems will have to work on AC. For this study a limit equal to 4.4 m^3/d is considered for DC systems, above which the systems are designed as AC. The PV system can be sized according to the required load energy and the daily global irradiation, taking into consideration the efficiencies of all system components and the effect of temperature. The size of the PV system in Wp for the peak load of electrical energy can be calculated as follows [22]:

- For DC system operation:

$$A_{PV} = \frac{E_L}{H \times \eta_{PV} \times T_C \times \eta_C \times \eta_B} \tag{6a}$$

- For AC system operation:

$$A_{PV} = \frac{E_L}{H \times \eta_{PV} \times T_C \times \eta_C \times \eta_{inv} \times \eta_B} \tag{6b}$$

$$P_{PV} = A_{PV} \times H_{SC} \times \eta_{PV} \tag{7}$$

The battery bank in the PV–RO system is used to allow the system operation during night hours as well as to complement the PV produced energy at periods of solar energy shortage. The battery bank can be sized according to the hours of night operation (Nc) during the peak month (August). This is 10 h for both locations, taking into account 14 daylight hours and 24 h of plant operation per day. Furthermore, a safety margin of 2 d is considered to allow for smooth operation during bad weather conditions (cloudy, rainy weather). The size of the battery bank can be calculated as follows [23]:

- For DC operation:

$$B_E = \frac{P_L \times 2 \times N_C}{\mathrm{DOD} \times \eta_C \times \eta_B} \tag{8a}$$

- For AC operation:

$$B_E = \frac{P_L \times 2 \times N_C}{\mathrm{DOD} \times \eta_{inv} \times \eta_B} \tag{8b}$$

The PV system charge controller, which connects the PV array with the battery bank has to be matched to the PV array design in terms of modules in series and in parallel and the corresponding voltage and current. The input current of the charge controller can be calculated as follows:

$$I_{DC} = \frac{P_{PV}}{V_{DC}} \tag{9}$$

The DC/AC inverter converts the DC electrical power produced from the PV system and the power that is drawn from the battery to the required AC electrical power for the desalination plant operation. The DC side input voltage has to match the DC voltage of the battery bank and its power is sized according to the plant AC power rating.

Table 3
Unit cost assumptions for the required PV system and storage batteries

Item	Unit cost
PV	0.7 €/kWp
Batteries	0.2 €/kWh
Charge controller	0.3 €/kW
Inverter	1.5 €/kW
Structure	0.25 €/kW
Cables and electrical cabinet	0.1 €/kW
Installation	5% of the capital cost[a]
Interest rate	6% per year[b]
Operating and maintenance (OM)	100 €/year

[a]The capital cost is the sum of PV, batteries, inverter/charge controller, structure and cables and cabinet costs.
[b]The life time of the PV system, the batteries and the inverter/charge controller can be considered 20, 7 and 15 years, respectively.

3. Techno-economic analysis and discussion

Two PV–RO water desalination systems were studied and analyzed for the two sites (Marsa Matrouh, Egypt, and Milos, Greece) for comparison. Following the technical design of the systems, a techno-economic analysis took place. Table 3 shows the unit cost assumptions for the required PV system and storage batteries.

The water demand profiles for both locations as shown in Fig. 2, as well as the number of hours of operation of the PV–RO plant, have been considered in the analysis. The analysis was carried out for different RO plant capacities of 50, 100, 220, 500, 1,000, 1,500 and 2,000 L/h. For each of these plant capacities, Tables 4 and 5 show the calculated SEC (kWh/m^3), electrical load (kW) (Eqs. (3)–(5)), average daily water demand in peak month (m^3/d) (Fig. 2), annual water demand (m^3/year), size of the PV array (kWp) (Eqs. (6) and (7)), capacity of the storage battery bank (kWh) (Eq. (8)), NPC of the energy producing subsystem (euro) and specific energy cost (€/kWh and €/m^3) for the different plant capacities with ER at Matrouh and Milos. It must be noted that, the plant capacities 50, 100 and 220 L/h are considered to work with DC power,

Table 4
PV–RO system parameters, components and the corresponding costs with energy recovery for Matrouh

PV–RO plant capacity (L/h)	Specific energy consumption with energy recovery (kWh/m^3)	Electrical load (kW)	Water demand in peak month (m^3/d)	Annual water demand (m^3/year)	Size of PV array (kW)	Size of battery bank (kWh)	Net present cost NPC[a] (€)	Specific energy cost (€/kWh)	Specific energy cost (€/m^3)
50	6.09	0.30	1.0	217	1.7	12	7,739	0.29	1.79
100	4.23	0.42	2.0	433	2.3	17	10,277	0.28	1.19
220	3.45	0.76	4.4	953	4.1	30	17,465	0.27	0.92
500	3.25	1.63	10.0	2,165	9.3	58	34,750	0.25	0.80
1,000	2.94	2.94	20.0	4,330	16.9	104	61,833	0.24	0.71
1,500	3.37	5.05	30.0	6,495	29.0	179	105,429	0.24	0.81
2,000	3.17	6.34	40.0	8,660	36.4	224	131,949	0.24	0.76

[a]This cost includes only the energy production subsystem costs.

Table 5
PV–RO system parameters, components and the corresponding costs with energy recovery for Milos

PV–RO plant capacity (L/h)	Specific energy consumption with energy recovery (kWh/m^3)	Electrical load (kW)	Water demand in peak month (m^3/d)	Annual water demand (m^3/year)	Size of PV array (kW)	Size of battery bank (kWh)	Net present cost NPC[a] (€)	Specific energy cost (€/kWh)	Specific energy cost (€/m^3)
50	6.09	0.30	1.0	201	1.7	12	7,767	0.32	1.93
100	4.23	0.42	2.0	403	2.3	17	10,316	0.30	1.28
220	3.45	0.76	4.4	886	4.2	30	17,536	0.29	0.99
500	3.25	1.63	10.0	2,015	9.4	58	34,864	0.27	0.87
1,000	2.94	2.94	20.0	4,029	17.1	104	62,039	0.26	0.77
1,500	3.37	5.05	30.0	6,044	29.3	179	105,783	0.26	0.88
2,000	3.17	6.34	40.0	8,058	36.8	224	132,393	0.26	0.82

[a]This cost includes only the energy production subsystem costs.

while the higher capacities work with AC power for cost optimization. RO plant utilization factors are 49% for Matrouh and 46% for Milos, since for Milos the water demand profile shows higher variability from month to month (Fig. 2), which results in lower utilization factor in non-peak months on average.

Fig. 4 shows the PV array size plotted with the average daily water demand in the peak month for both locations, while Fig. 5 shows the battery bank size. The required battery bank and PV array are almost identical for the two sites, despite the fact that solar conditions are more favorable in Egypt all year around. This is due to the fact that system sizing is based on the peak month for which the same hours of night operation (Nc) have been assumed for both sites, while average solar irradiation at optimal angle (*H*) is slightly different between the two locations (7.30 and 7.22 kWh/m^2/d for Matrouh and Milos, respectively). The figures show that the required PV arrays in kWp as well as the required storage battery bank in kWh directly increase with the plant capacity due to the higher required electrical energy as the plant capacity increases.

The required PV power (kWp) (Eq. (10)) and the storage capacity of the battery bank (kWh) (Eq. (11)) can be calculated by the empirical formulas obtained from the theoretical analysis of the different plants at different water demand rates for both locations based on Eqs. (7), (8a) and (8b) as follows:

$$P_{\text{PV}} = 0.929 \times \text{WD} \tag{10}$$

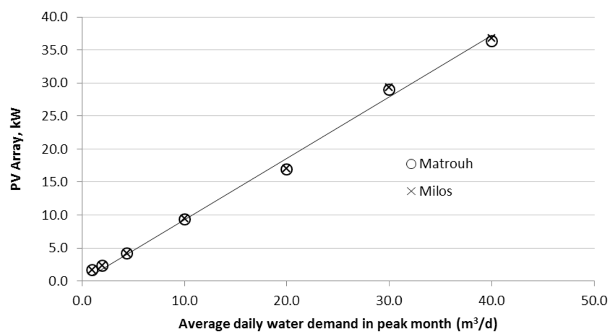

Fig. 4. The PV array size with the average daily water demand in the peak month.

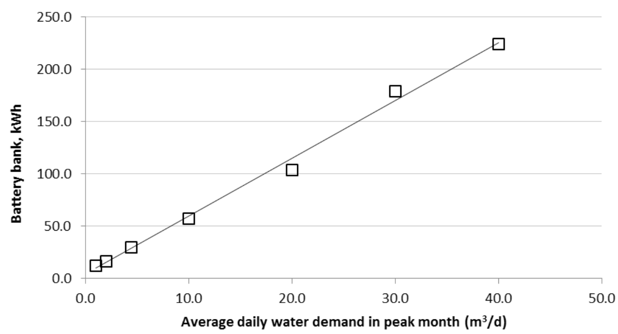

Fig. 5. The battery bank size with the average daily water demand in the peak month.

$$B_E = 5.522 \times \text{WD} + 4.296 \tag{11}$$

The NPC is the sum of all costs of the power system (PV, batteries, inverter and controller, structure, cables and electrical cabinet, installation, interest rate and operating and maintenance) in the 20-year period for which the analysis is made. Since PV power and batteries capacity needed to cover load requirements for each plant capacity are almost the same in Greece and Egypt, the NPC of the power system will also be the same, see Tables 4 and 5. Fig. 6 shows the NPC of the electrical power system with the average daily water demand in the peak month for both locations. According to the cost analysis, the NPC can be calculated from Eq. (12). It is obvious that the proposed Eqs. (10)–(12) can be used to size PV–RO desalination systems and estimate related costs in other locations, apart from Matrouh and Milos, with similar solar irradiation and daylight hours in peak month and similar seawater composition and temperature.

$$\text{NPC} = 3241.3 \times \text{WD} + 3045.9 \tag{12}$$

A good indication of the cost of energy needed for PV–RO water desalination systems can be derived from the index of specific energy cost (€/kWh or €/m^3) especially in case of comparison between energy sources or locations. Figs. 7 and 8 show the DC and AC specific energy cost with the average daily water demand in the peak month for both locations. The index for DC systems decreases with increasing water demand, while for AC systems the index is almost constant

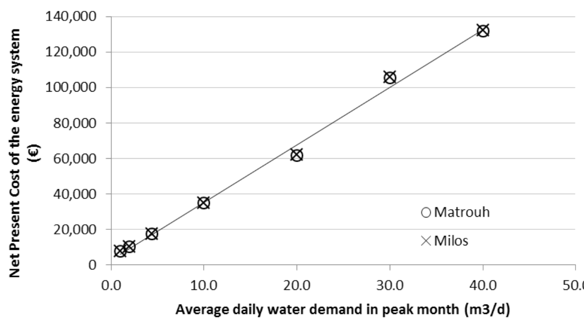

Fig. 6. Net present cost of the electrical energy producing subsystem for Matrouh and Milos.

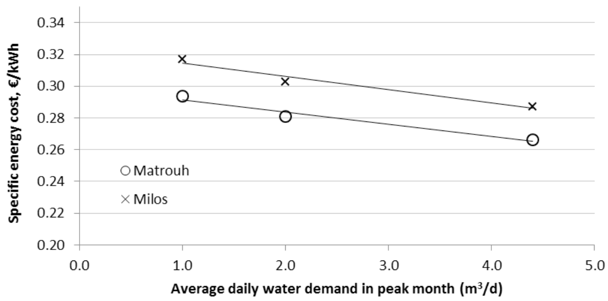

Fig. 7. Specific energy cost in €/kWh in the peak month for DC plants.

for larger plants (Tables 4 and 5). For DC systems the index is 0.27–0.29 and 0.29–0.32 for Egypt and Greece, respectively, while for AC systems it is 0.24 and 0.26, respectively. Energy costs are slightly higher for Milos, due to its different annual water demand profile that results to a lower plant utilization factor.

The empirical formulas for getting the DC and AC index of energy costs for Egypt are given in Eqs. (13) and (14) and for Greece in Eqs. (15) and (16):

$$EC_{DC} = 0.2993 - 0.0078 \times WD \quad (13)$$

$$EC_{AC} = 0.2482 - 0.0002 \times WD \quad (14)$$

$$EC_{DC} = 0.3228 - 0.0083 \times WD \quad (15)$$

$$EC_{AC} = 0.2676 - 0.0002 \times WD \quad (16)$$

where EC_{DC} (€/kWh) and EC_{AC} (€/kWh) are the index of energy costs for the DC and AC systems, respectively.

The specific energy cost expressed in €/m^3 gives the average cost of a unit water volume produced either by DC energy from the small plants or by AC energy from the bigger plants. As shown in Tables 4 and 5 this parameter can accurately be used to compare different plants and sites. Fig. 9 shows this index plotted against the average daily water demand in the peak month for Milos and Matrouh. The specific energy cost sharply decreases with increasing plant capacity for DC plants being two times higher for a plant capacity of 50 L/h

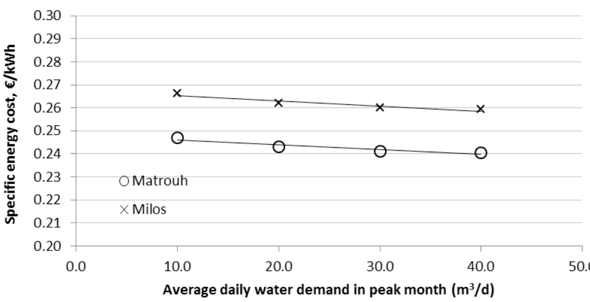

Fig. 8. Specific energy cost in €/kWh in the peak month for AC plants.

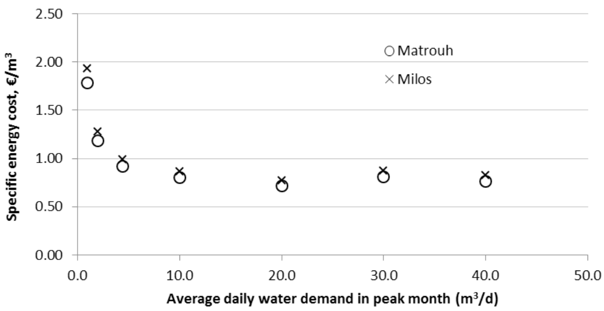

Fig. 9. Specific energy cost in €/m^3 in the peak month.

than for 220 L/h. The index remains almost constant for AC plants in the range of 500–2,000 L/h. Furthermore, in all cases specific energy costs in Matrouh are ~7% lower than those in Milos.

Finally, it has to be noted that the real current water cost both in small Greek islands, as well as in rural areas in the Marsa Matrouh area is much higher. In small islands of the Aegean Sea water is still (2016) transported with water tankers from mainland Greece. The cost for the transportation of water can reach in many cases 12–15 €/m^3. A comparable situation can be observed also in rural areas of the Marsa Matrouh area in Egypt. In remote settlements, where no water network infrastructure exists, the water has to be bought from tankers or water points. Water provided by tankers costs two to three Egyptian pounds for 25 L, which corresponds to water prices of 8–12 €/m^3. Considering this very high real world cost for considerable numbers of population, desalination units powered by RE become a very cost-effective solution.

4. Conclusions

PV–RO water desalination plants using ER systems were designed and studied using a calculation methodology for optimizing these plants. According to water demand and the meteorological conditions of the location, the system can be designed in terms of PV power required, capacity of the battery bank, charge controllers and DC/AC inverters. A cost analysis was made for these types of plants in terms of NPC (€) and specific energy cost (€/kWh or €/m^3). For comparison purposes, two locations were chosen, one in Egypt and one in Greece, each having its own load profile and meteorological conditions. The design was performed for different water desalination plant capacities ranging from 50 to 2,000 L/h. The study concluded that the required PV power and battery storage capacity in Egypt is the same to that in Greece because of the different water need profiles. PV–RO plant utilization factors are 49% for Egypt and 46% for Greece, respectively. Specific energy costs expressed in €/kWh are 0.27–0.29 and 0.29–0.32 for DC systems and 0.24 and 0.26 for AC systems for Egypt and Greece, respectively. Furthermore, the energy producing system is expected to add to the water production a cost of 0.92–1.79 and 0.99–1.93 €/m^3 for DC systems and 0.77 and 0.83 €/m^3 for AC systems for the aforementioned locations, respectively. Empirical formulas for all design parameters are derived from the calculations to issue an accurate calculating methodology for optimizing the design and the cost of installing these plants.

Concluding, it has to be noted that the real current water cost both in small Greek islands, as well as in rural areas in the Marsa Matrouh area is much higher. Considering the very high real world cost for considerable numbers of population, desalination units powered by RE become a very cost-effective solution.

Symbols

A_{PV}	—	PV area, m^2
B_E	—	Battery bank energy, Wh
DOD	—	Battery bank allowable deep of discharge
E_L	—	Peak daily required electrical energy for the PV/RO plant corresponding to month of August, Wh/d

EC_{AC} — Index of AC energy cost, €/kWh
EC_{DC} — Index of DC energy cost, €/kWh
g — Earth gravity, 9.8 m/s^2
H — Daily irradiation at optimally tilted angle in August, Wh/m^2/d
h — Water head, m
HO — Hours of operation, h/d
H_{SC} — Standard solar irradiation, 1,000 W/m^2
I_{DC} — DC current of the PV system, A
L — The average daily water demand per month as a percentage of the average daily demand in the peak month, %
N_C — Hours of night operation in peak month, h
NPC — Net present cost, euro
P_{ER} — Electrical power of energy recovery system, W
P_L — Net required electrical power, W
P_P — Pump electrical power, W
P_{Po} — Electrical power for potable pump, W
P_{PV} — PV power, W
P_{RO} — Electrical power for RO pump, W
P_{SB} — Electrical power for seawater/brackish water boost pump, W
Q — Desalination plant capacity, L/h
Q_p — Pump capacity, m^3/h
T_C — Temperature correction factor of the PV module
V_{DC} — DC voltage of the PV system, V
WD — Daily water demand, m^3/d
ρ — Water density, kg/cm^3
η_B — Battery roundtrip efficiency
η_C — Charge controller efficiency
η_{inv} — Inverter efficiency
η_m — Motor efficiency
η_p — Pump efficiency
η_{PV} — PV efficiency

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