Techno-economic analysis of stand-alone solar desalination at variable load conditions

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Abstract

The operation of large-scale reverse osmosis units in combination with different solar power plants, both, Concentrating Solar Power (CSP) and Photovoltaics (PV) has been evaluated under variable load conditions. In the case of the Reverse Osmosis (RO) unit, configurations with and without an energy recovery device have been considered. In the case of the CSP plant, a thermal storage system with several capacities (8-14 h) covers the periods with low solar radiation and no storage has been taken into account for the PV plant due to the prohibitively high cost of batteries at large scale. The analysis has been done for a specific location in Algeria, considering different scenarios to adapt the operation of the RO unit at partial load in order to assure a stable operation. The dynamic performance of the RO unit is presented for each scenario, together with an economic analysis.

Keywords: reverse osmosis, partial load operation, CSP, PV, gradual capacity, economic analysis

1. Introduction

The development of industrial and agricultural activities together with the increasing population has led to the massive exploitation and contamination of water resources, leading to an alarming shortage of fresh water. Middle East and North Africa (MENA) is one of the regions suffering more and more from serious problems of freshwater availability [1]. Such water scarcity drives to use technologies like seawater desalination that can alleviate this problem [2]. Algeria is one of the countries in MENA region that has included seawater desalination. The strategy of Algeria until 2030 is to have 1 billion m^3/ year of water produced by seawater desalination [3]. The exploitation of renewable energy sources (solar or wind) to produce electricity and fresh water is commonly considered as a very promising way to reduce the pollution and the environmental impact. Algeria has this great solar potential and the climatic conditions are favorable for the implantation of solar plants. Therefore, it seems logical that solar desalination will be one of the solutions to obtain freshwater in many regions of the country.

There are several works in the scientific literature about the combination of RO plants with Photovoltaics (PV) or wind energy ([4], [5], [6], [7], [8]) and with CSP ([9], [10], [11]), which give promising economic results when it is compared with the operation of Reverse Osmosis (RO) driven by fossil energy (0.8 €/m^3 in the case of CSP-RO and between 0.59 €/m^3-2.81 €/m^3 for PV-RO). However, some of them have been done for a design point or don't consider the operation of the desalination plant under intermittent power due to the nature of the source of energy. There are only few works in the literature that consider the intermittent power source. Wenyu Lai *et al.* [12] presented the different solutions and strategies used to adapt the wind power fluctuation to a RO desalination process. Three types of strategies were applied; the first is the storage technology to maintain the energy supply constant. The second is the hybridization to smooth out the wind fluctuation and intermittence. The third strategy, called self-adjusting RO unit, consisted in adapting the operation with the variable energy input as follows: firstly, adjusting the operating conditions of the RO unit within a safe operational window (SOW), secondly, adjusting the RO using the gradual capacity strategy. Ntavou *et al.* [13] presented an experimental evaluation of a small-scale multi-skid RO unit (an RO unit composed of several RO sub-units) with a capacity of 2.1 m^3/day that operate with fluctuating power, considering different seawater temperatures. The authors proved the flexibility of the use of the multi-skid RO unit configuration, especially when the power input derives from a fluctuating renewable energy source.

This paper covers the research gaps in the literature presenting a techno-economic comparison between two stand-alone solar desalination systems (i.e. the RO plants operate only with the electricity provided from the solar plants) at variable load conditions: a 50,000 m^3/day RO plant directly powered by a CSP plant with central receiver tower technology, and the same RO plant directly driven by the electricity produced by a PV plant without batteries. In the first case, different thermal storage capacities have been investigated. Two options have been studied for the RO plant: an RO plant without energy recovery device (ERD) and an RO with two types of ERD (a Pelton wheel turbine (WTR) and a pressure exchanger (PEX)). The study has been performed for a specific location in Algeria: TENES, one of the Algerian coastal regions at the Mediterranean area. On one hand, it has been considered that the CSP plant is located 60 km far from the coast to avoid corrosion problems in the mirrors and the possible reduction in the Direct Normal Irradiation (DNI) and, on the other hand, the PV plant has been located at 5 km far from the coast also to avoid corrosion in the solar panels. In the two solar desalination systems analyzed, the RO plant will be located at 2.5 km from the shore. The study has been performed for a specific location in Algeria: TENES, one of the Algerian coastal regions at the Mediterranean area. In both cases (CSP or PV plants), the RO unit will operate according to the available power coming from the solar plant, adapting its operation following the most suitable strategies developed to assure acceptable fresh water production without affecting the membrane.

2. Methodology

Figures 1 and 2 show the layout of the systems studied. The first one consists of an RO unit connected to a central receiver tower CSP plant (CSP-RO), and the second one of an RO unit connected to a solar photovoltaic plant (PV-RO). In both cases, the power plants have been designed to produce the electric power needed for the RO plant to produce 50,000 m^3/day of freshwater at nominal conditions. The electricity losses in the transmission lines from the solar plants to desalination unit, caused by the Joule effect, have been also determined in both systems. Therefore, the net power to be provided to the RO plant represents the power produced by the solar plant minus the load losses in the transmission lines to the RO unit.

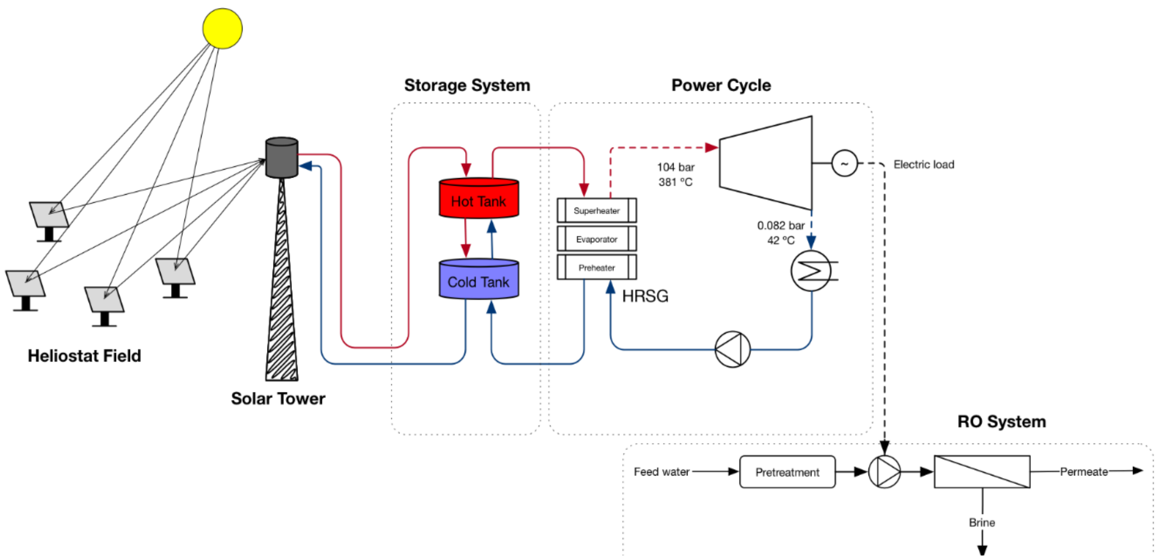


Fig. 1. Flow diagram of the system consisting of an RO unit connected to a central receiver CSP plant

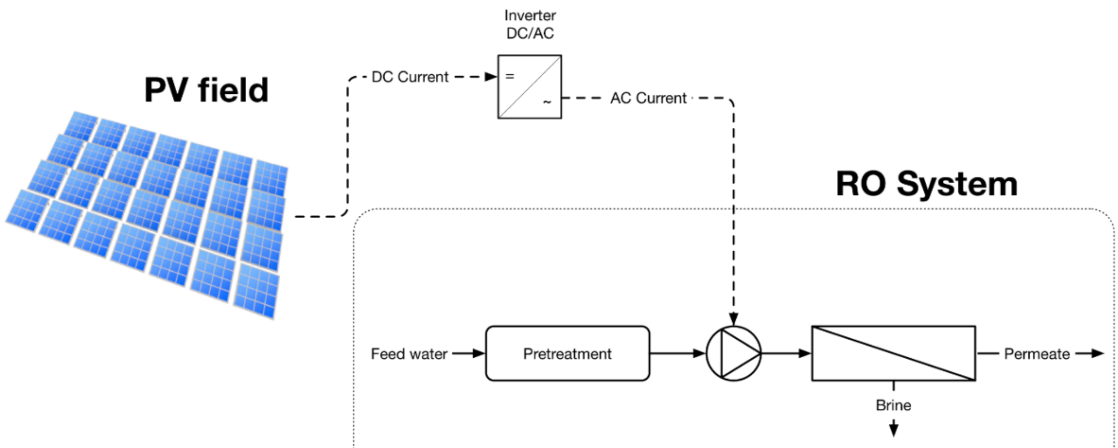


Fig. 2. Flow diagram of an RO unit connected to a PV plant

2.1. Description of the systems

The RO system is a single stage unit with a nominal capacity of 50,000 m^3/day. Three different RO systems have been considered (Figure 3), all of them with a single stage: the first one is the basic RO unit without recovery system (see Figure 3a), and the second and third ones consider an energy recovery device (ERD): Pelton wheel turbine with generator (WTR), and a pressure exchanger (PEX) (see Figures 3b and 3c, respectively). Regarding the solar power technologies, in the case of the CSP plant, solar tower technology has been selected due to its potential compared to parabolic trough technology [17] (more efficient, more favorable land area per energy output, lower operating and maintenance expenses, lower upfront investment, among others). It is composed of a heliostat solar field that collects the solar energy; each heliostat tracks the sun and reflects the direct solar radiation to the receiver placed on top of the tower. In the receiver, the heat transfer fluid (molten salt) is heated by the energy reflected by the mirrors. The thermal storage system is based on molten salts and consists of two tanks: the hot tank (with a temperature of 570 ºC for the molten salt) and the cold tank (with a temperature of 290 ºC). The power block is a superheated simple Rankine cycle with the maximum temperature selected to ensure proper operation under low DNI. In the case of the PV system, it consists of photovoltaic modules and inverters to convert the direct current (DC) generated by the PV modules to the alternating current (AC).

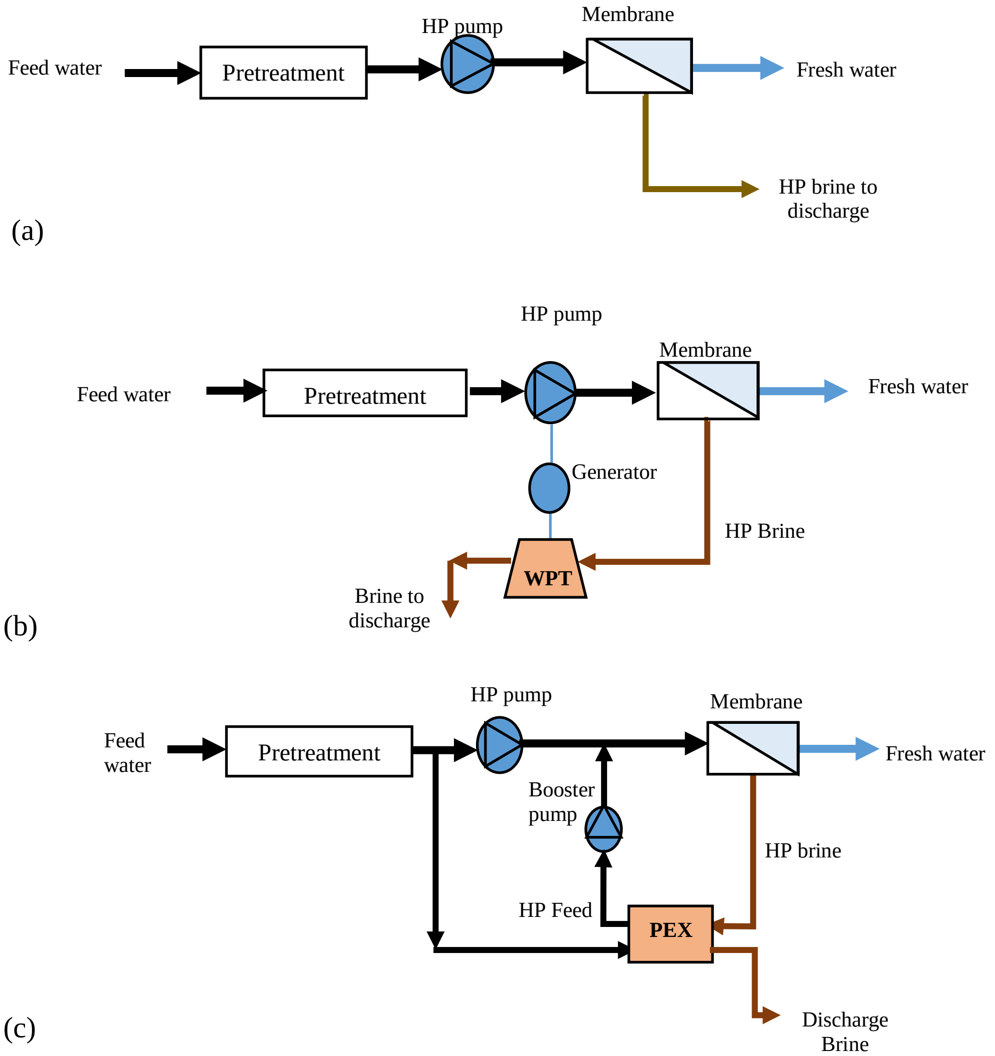


Fig. 3. RO configurations: (a) basic concept without ERD (b) with ERD based on Pelton wheel turbine, (c) with ERD based on pressure exchangers.

2.2. Modeling and design of the systems

The RO unit has been modeled using the equations outlined in [9], [14], [15], [16], [17], which have been implemented in Engineering Equation Solver (EES) software environment. The model allows both the design of the RO plant and the simulation of its operation. The design of the RO plant has been firstly carried out in order to determine the power required and then to size the corresponding solar plants. The required power (in kW) for the high-pressure pump that pumps the seawater against the RO modules is determined using the feed density (ρ_f) and the pump efficiency (η_p), by the following equation:

$$HPP = \frac{1000 \cdot M_d \cdot \Delta P}{3600 \cdot \rho_f \cdot \eta_p} \tag{1}$$

And the specific power consumption (in kWh/m^3) is calculated as follows:

$$SPC = \frac{HPP}{M_d} \tag{2}$$

An optimum design of the RO plant in terms of the number of elements, number of pressure vessels, Recovery Ratio (RR) and Specific Power Consumption (SPC) has been obtained in order to also optimize the size of the solar field, and therefore to minimize the costs. For this purpose, a parametric analysis has been performed, wherein the number of pressure vessels and the number of elements were varied from 500 to 700, and between 7 and 8 elements per vessel, respectively. The membrane selected has been SW30HR-380 whose characteristics can be found in Dow datasheet [18]. The best design has been obtained comparing the results obtained against those ones obtained by ROSA7.2 software and according to the following criteria: the one with the minimum error once compared with the results from ROSA7.2 and that one with the maximum RR and the minimum SPC, taking into account the maximum acceptable pressure (69 bar for SW30HR-380 [18]). In the case of the RO unit with ERD, the efficiency of the turbine and generator have been fixed at 85% and 95%, respectively ([19],[20]). The efficiency of the pressure exchanger has been considered as 98% [21]. On the other hand, the power needed by the intake pump has been calculated based on the pumping pressure (4 bar [22]) to the pretreatment compartment and on the feed flow. Moreover, the SPC required by the pumps used in the pretreatment processes has been determined, resulting in 0.416 kWh/m^3 of feed water [21]. Finally, it has been assumed a feed salt concentration for the Algerian coastal equal to 37000 mg/L [23], a fouling factor of 0.85 [24] and a fixed average feed water temperature of 20 ºC [23]. Once the optimum design of the RO plant has been obtained, the solar fields' areas have been determined. In the case of the CSP plant, it has been determined using the software System Advisor Model (SAM [15]). Different thermal storage capacities have been considered in the present study: 0, 8, 10, 12 and 14 hours in order to evaluate their influence in the freshwater production of the RO unit. Also, it has been established that the CSP plant is located at 60 km far from the sea (Tenes coast in Algeria), in a region of El-Attaf (Wilaya de Ain Defla). For the refrigeration of the power block, an evaporative cooling system has been selected, based on the results obtained in previous works published in the literature [25]. It is considered that the required water used for the refrigeration system can be pumped from an already existing dam in the selected location. The SPC of the cooling system has been assigned as 0.0329 MW_e/MW_e [25] [26], and the specific water consumption as 3 m^3/MW_e. On the other hand, the time-dependent operation of the CSP plant is obtained by a time-step model developed by the authors (using the design parameters as inputs) and implemented within TRNSYS 17.01 software environment. In the case of the PV plant, SAM has been also used, for the design and to predict the instantaneous power produced. In this case, it has been considered that the PV plant is located at 5 km from the Tenes coast in which the RO unit is located. The input meteorological data for both solar plants have been obtained by Meteonorm 7 software.

3. Operating strategies

In order to adapt the operation of the RO unit to the power intermittence and fluctuation from the solar power plants, different operational strategies have been considered. Two scenarios are proposed: scenario 1, in which the RO plant will operate as a whole unit; and scenario 2, in which the RO plant is composed of 10 identical sub-units with a nominal capacity of 5000 m^3/day each one. This last scenario is also called gradual capacity. A detailed description of the different strategies followed for each scenario is presented hereinafter.

3.1. Scenario 1 (whole unit)

Within this scenario, the minimum power (P_{min}) required by the whole RO plant to produce fresh water with a concentration of salts of 500 mg/l (acceptable quality of fresh water [27]) is firstly defined. This value of P_{min} represents the minimum one for the RO plant to operate with the total number of pressure vessels established in the design. Two strategies are considered within this scenario:

(1) when the power produced by the solar plant results higher than P_{min}, it is established that the operation of the RO unit must be within a safe range, called self-operation window (SOW). In this range, the performance of the RO unit varies according to the power availability. The variation of the power will be between P_{min} and the power corresponding to the maximum pressure supported by the membrane (69 bar for SW30HR-380).

(2) when the power produced by the solar plants results lower than P_{min}, some pressure vessels are switched off in order to assure a quality of 500 mg/l in the fresh water produced. In this case, the fresh water production will change according to the number of the active pressure vessels, but the pressure (determined to obtain a quality of 500 mg/L) and the SPC do not change with the power availability.

3.2.Scenario 2 (gradual capacity)

In this scenario, the sub-units always operate under full load with constant performance and they will be switched on/off according to the power availability. The number of pressure vessels per sub-unit is equal to 1/10 the number of pressure vessels of the whole RO unit (design point). The fresh water produced by each sub-unit is 5000 m^3/day.

4. Economic analysis

The economic analysis consists in the calculation of the levelized water cost (LWC), which is defined as the ratio between the total annual capital cost (that includes the annual capital cost of the RO unit (ACC_{RO}) and the annual capital cost of the solar power plant ($ACC_{power\ plant}$)) and the annual fresh water production ($M_{d-annual}$):

$$LWC = \frac{ACC_{RO} + ACC_{power\ plant}}{M_{d-annual}} \tag{3}$$

The costs of the energy recovery systems have not been accounted due to the lack of information in the literature. The calculations of the annual capital cost for the RO unit and the solar power plant (both PV and CSP plant) are outlined in [9], [24], [28], [29], [30], [31], [30]. It is needed to specific the calculation of the pump cost used in the RO unit ($C_{HP\ pump}$). It is based on the correlations described by Malek *et al*. [28], that are divided into three categories as a function of the feed flow rate used in each case (M_f). The corresponding equation will be used for the cases of the whole RO unit and the RO composed of sub-units, depending on the resulting feed flow rate needed by the RO unit (M_{f_RO}). The required pumps to pump the M_{f_RO} are assessed in each case from the value of the RR obtained by the design optimization. With the RR, the M_{f_RO} is found and the number of pumps needed to pump this feed flow is determined by dividing M_{f_RO} between the corresponding value of M_f. In the cases in which the result is not an entire value, more than one category will be used to pump the whole feed flow rate.

Category (A): $M_f = 450\ \mathrm{m^3/h}$ (where M_f is the feed flow)

$$C_{HP\ pump} = 393000 + 10710\ \mathrm{P}_f \tag{4}$$

where P_f is the feed pressure at the inlet of the RO plant (in bar).

Category (B): $200\ \mathrm{m^3/h} < M_f < 450\ \mathrm{m^3/h}$

$$C_{HP\ pump} = 81 \cdot \left(\mathrm{P}_f \cdot M_f\right)^{0.96} \tag{5}$$

Category (C): $M_f < 200\ \mathrm{m^3/h}$

$$C_{HP\ pump} = 52 \cdot \left(\mathrm{P}_f \cdot M_f\right) \tag{6}$$

5. Results and discussion

5.1. Design of the RO unit and CSP/PV plants

Table 1 shows the results obtained from the parametric analysis and its comparison with respect the results obtained with ROSA software. As mentioned before, the optimum design is a balance between the minimum error percentage (the relative error of the model with respect to the result obtained by the software ROSA7.2), the maximum RR (taking into account an aceptable membrane pressure of 69 bar) and a reasonable value of the SPC.

Table 1

Results obtained from the parametric analysis and comparison with the results obtained by ROSA7.2

	7 elements				8 elements			
Number of pressure vessels	550	600	650	700	550	600	650	700
Maximum allowable RR (%) by EES	39.12	41.55	43.54	45.19	7.40	44.75	46.41	47.81
Applied pressure EES (bar)	68.87	68.35	68.31	68.73	68.71	68.66	68.40	68.51
Applied pressure ROSA (bar)	64.86	63.87	63.7	63.36	63.92	63.46	63.10	63.10
Applied pressure error (%)	6.18	7	2.40	8.40	7.40	8.40	8.30	8.57
Permeate concentration EES (g/l)	0.169	0.188	0.204	0.223	0.198	0.218	0.239	0.259
Permeate concentration ROSA (g/l)	0.179	0.199	0.221	0.245	0.212	0.237	0.263	0.290
Permeate concentration error (%)	5.40	5.91	7.23	8.22	5.93	8.22	9.18	10.46
SPC (kWh/m^3) EES	5.97	5.64	5.37	5.15	5.46	5.22	5.03	4.88
SPC (kWh/m^3) ROSA	5.81	5.44	5.15	4.92	5.25	4.98	4.79	4.64
SPC error (%)	2.77	3.6	4.75	4.96	4.11	4.96	4.95	5.11

From the results obtained, the optimum design would be an RO unit with 600 pressure vessels (each one with 8 elements) and a RR of 42%. A slightly lower RR than the allowable one has been selected (lower than 44.75%) in order to avoid all the problems related to the membrane in cases of power surplus.The resulting power required, the SPC and the permeate concentration for each case are shown in Table 2. It is observed that, in the cases of an RO system with a wheel turbine and a pressure exchanger, the required power is 29% and 52%, respectively, lower than the required power for RO unit without any ERD.

Likewise, the design of the solar plants can be seen in Table 3.

Table 2

Required power and specific power consumption at the design point for the CSP-RO and PV-RO systems

RO unit	Power (kW)		Specific power consumption (kWh/m^3)		Permeate concentration (g/L)
	PV plant	CSP plant	PV plant	CSP plant	
Basic RO	13748	14216	6.6	6.8	0.21
RO-TWR	9692	10022	4.7	4.8	0.21
RO-PEX	6549	6772	3.1	3.3	0.21

Table 3

Results from the design of the solar power plants

	RO Basic			RO- WPT			RO-PEX		
	Power (kW_e)	Solar field area (m^2)	Storage thermal capacity (MWh)	Power (kW_e)	Solar field area (m^2)	Storage thermal capacity (MWh)	Power (kW_e)	Solar field area (m^2)	Storage thermal capacity (MWh)
PV	13748	86547	----	9692	58617	---	6549	39077	---
CSP (0h)	14216	130056	---	10022	89936	---	6772	58913	---
CSP (8h)	14216	189118	277.4	10022	136764	195.6	6772	98589	132.1
CSP (10h)	14216	235503	346.7	10022	161825	244.4	6772	113203	165.2
CSP (12h)	14216	267421	416.1	10022	195382	293.3	6772	14080	198.2
CSP (14h)	14216	308583	482.4	10022	216263	324.2	6772	146313	231.2

5.2. Operation of the RO unit under power fluctuation

The operation of the several RO configurations (with and without ERD) coupled to either a CSP or a PV plant has been simulated for one spring day (March 22nd) for the two scenarios mentioned previously and the main parameters that represent the performance of the system have been represented.

Scenario 1 (whole unit)

Figure 4 shows the variation of the generated power by the solar power plants for the several RO configurations. As observed, the power fluctuation is more pronounced for the PV plant and the CSP plant without thermal storage. In fact, it can be seen that the width of the power curve is larger in the case of the CSP-0h plant (CSP without storage), which means that the total energy produced by this solar plant during the day is higher. It can be due to the different solar radiation considered in both cases because of the different locations selected (PV plant close to the sea and CSP located inland). In addition, the results show that the PV plant operates always below the nominal capacity (13.75 MW_e, 9.96 MW_e and 6.55 MW_e for the RO basic case, RO-WPT, and RO-PEX respectively). However, in the case of the CSP-0h plant, it operates only one hour under nominal capacity in the RO-basic case. In the case of the RO-WTR and RO-PEX units, the CSP-0h plant even produces a surplus of power compared to the nominal capacity during one hour, which can be used to produce more freshwater. This surplus is not a danger for the membrane since a lower pressure than the critical one (69 bar) was established for the membrane. When thermal storage is considered for the CSP plant, it enables the RO plant to operate a certain number of hours at nominal conditions depending on the number of storage hours.

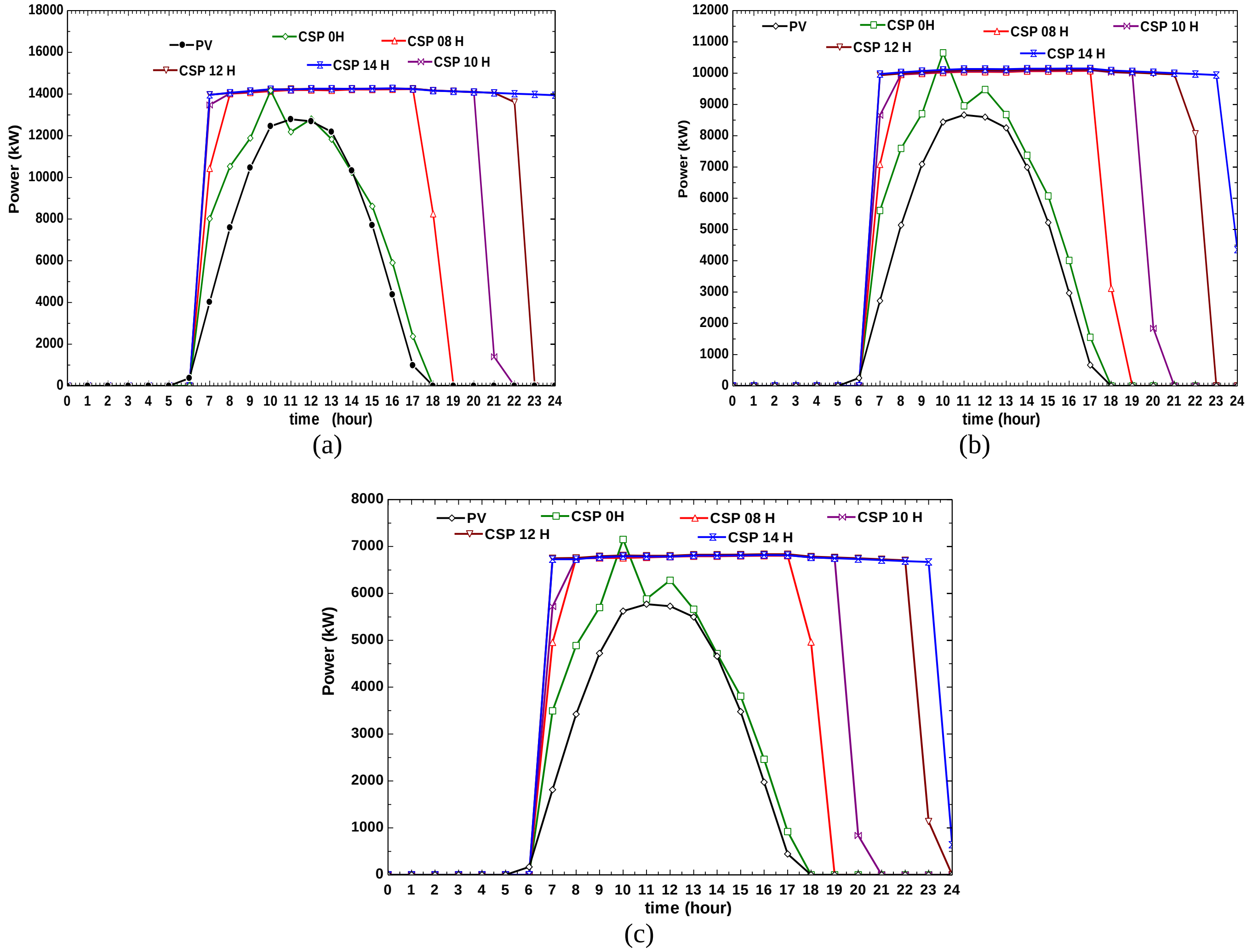
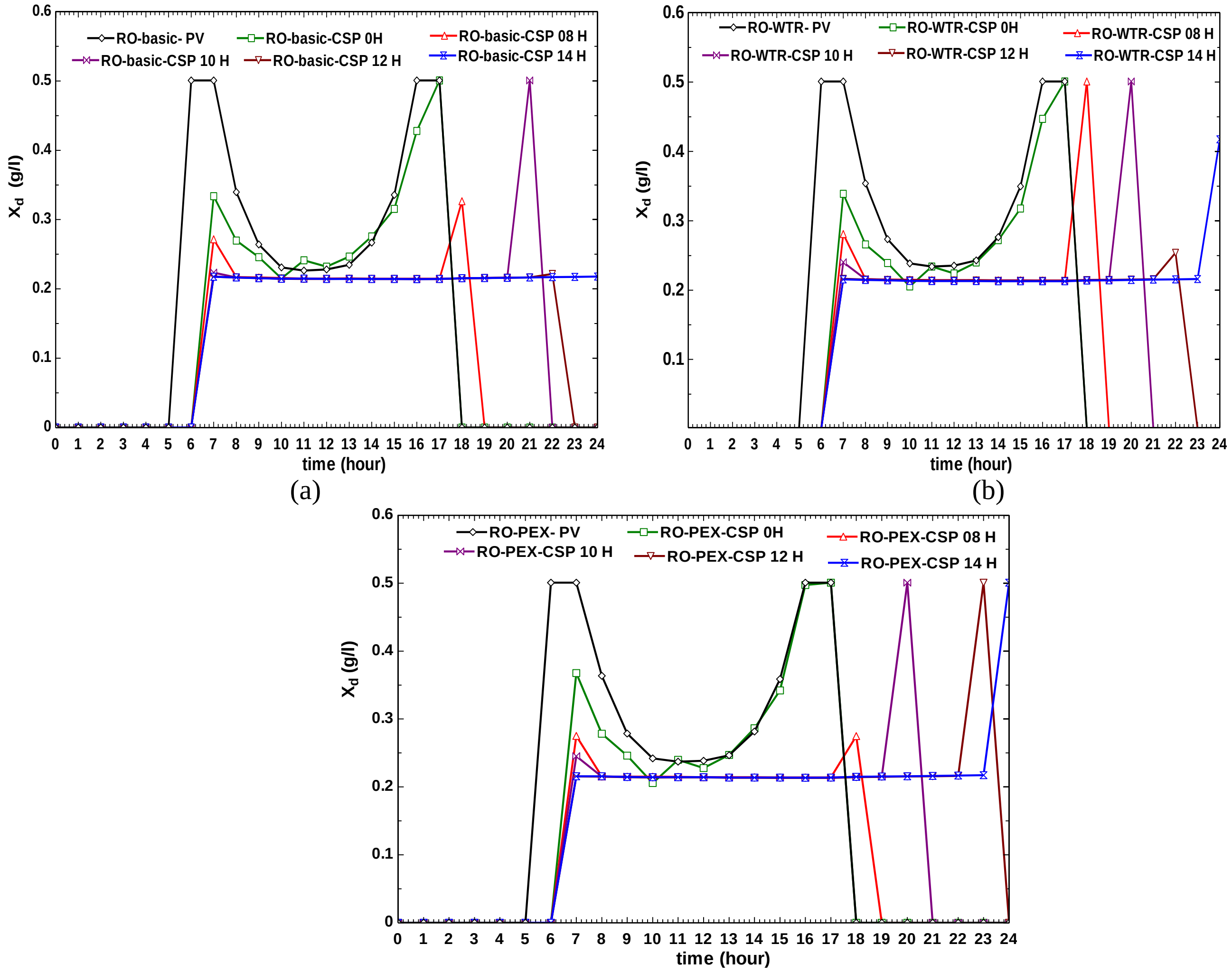


Fig. 4. Power produced by the solar power plants during the whole day to drive the RO plant in the different configurations: (a) RO unit without ERD, (b) RO-WTR, (c) RO-PEX

Figure 5 shows the variation of the permeate concentration during the selected day. It is clearly remarkable that the permeate concentration is reversely proportional with the power generation increase. It is seen that when the power generated by the solar power plants is lower than P_{min}, the operation of the RO unit is able to keep the quality of the produced water at 0.5 g/L following the second strategy within scenario 1. On the other hand, when the available power is higher than P_{min}, the quality of the produced water is always lower than 0.5 g/l, following the first strategy of this scenario.



(c)

Fig. 5. Permeate concentration variation: (a) RO unit without ERD, (b) RO-WTR, (c) RO-PEX

The hourly evolution of the produced fresh water by the RO unit during the selected day has the same tendency as the one of the power produced. The results indicated that, in the cases of PV-RO and CSP-RO without storage, the permeate flow is lower due of the power fluctuation, but in the cases in which the integration of the thermal storage in the CSP plants is considered, the RO units operate with hourly permeate flow close to the design value. It was found that the solar desalination plant, for the case of the CSP without thermal storage, produced an increase of 8%, 14%, and 12% for RO basic, RO-WTR and RO-PEX, respectively, in the water produced during the reference day compared with the PV plant. Comparing the CSP plant without storage with respect to the ones integrating thermal storage, the percentage of the additional fresh water produced with the RO plant in the basic case due to the thermal storage was 40%, 72%, 95% and 120% higher than the quantity produced in the absence of the thermal storage (CSP-0h) for CSP-8h, CSP-10h, CSP-12h and CSP-14h plants, respectively. For the RO-WTR case, the additional water produced by the desalination plant powered by the CSP with thermal storage compared to the one powered by the CSP-0h plant was 35% for CSP-8h, 59% in the case of CSP-10h, 91% for CSP-12h and 112% for CSP-14h. Finally, in the case of the RO-PEX plant, the difference in the freshwater production was 45.64%, 64%, 104%, and 115% more for the CSP-8h, CSP-10h, CSP-12h and CSP-14h plants, respectively, than the freshwater produced by the desalination plant coupled to the CSP-0h plant.

Figure 6 shows the hourly variation of the specific power consumption during the selected day. Obviously, the SPC varies during the day according to the power fluctuation. It can be seen that the SPC is lower for the cases of the RO units (with and without ERD) connected to the PV and CSP-0h plants, when the performance of the desalination plants is adjusted according to the power availability (strategy 1). Therefore, in these cases, the freshwater is produced with the minimum power consumption. However, the quality of the freshwater is lower in these cases since the applied pressure is lower than the design one. Comparing the SPC for the RO units with and without ERD, it resulted between 5.3 kWh/m^3 and 6.8 kWh/m^3 for the RO unit without ERD system, between 3.7 and 4.8 kWh/m^3 for the RO with WTR, and finally between 2.7 kWh/m^3 and 3.3 kWh/m^3 when the pressure exchanger was integrated in the RO unit. For the case of the CSP plant integrating the thermal storage, the SPC was close to that at design for the different RO configurations.

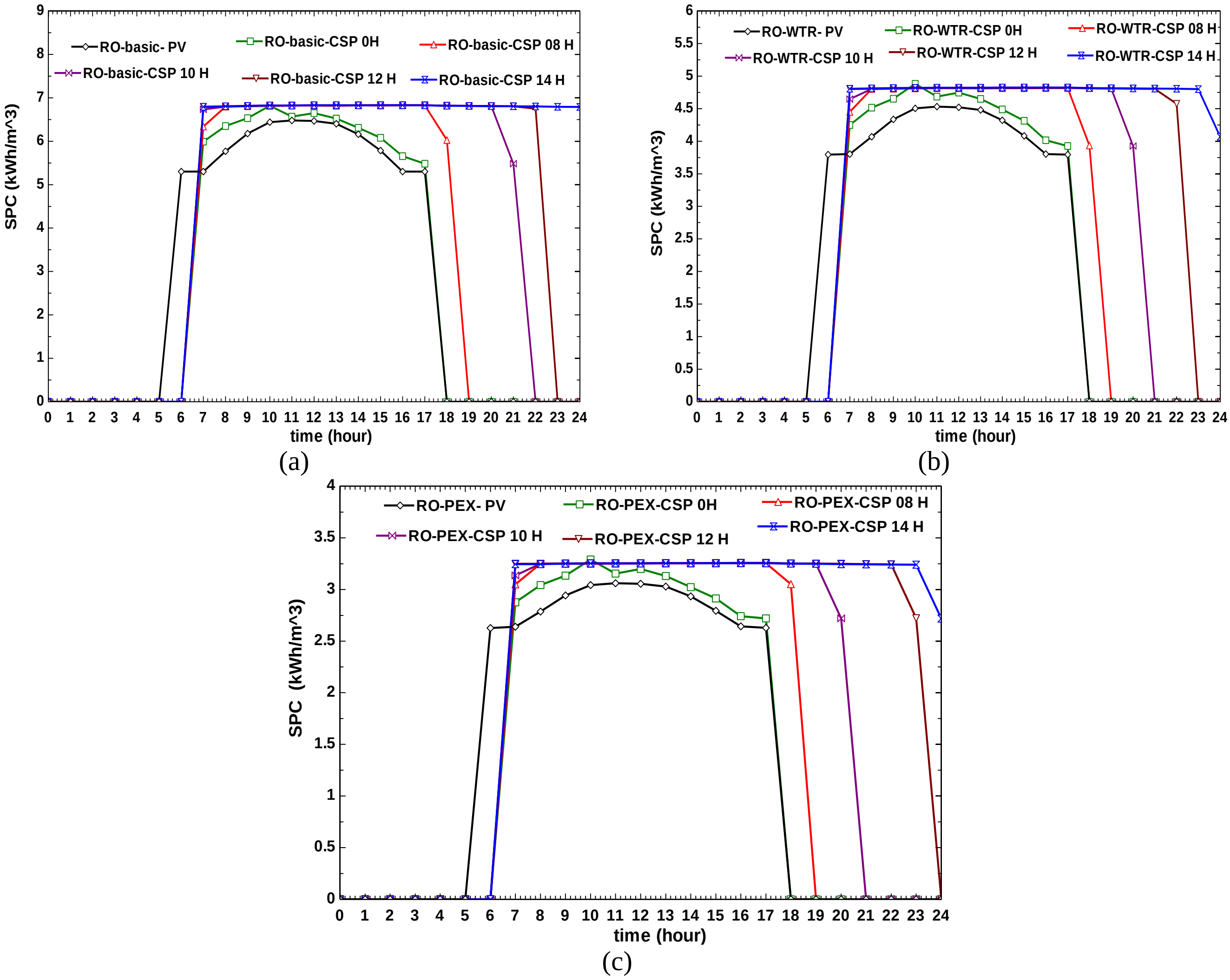


Fig. 6. Specific power consumption: (a) RO unit without ERD, (b) RO-WTR, (c) RO-PEX

5.2.1 Scenario 2 (gradual capacity)

Table 4 represents the results obtained for the design point in terms of the power and the SPC required by one sub unit, for the different configurations of the RO unit and for both solar plants. In the case of the solar plants, the same design results that in the first scenario have been established in order to quantify the difference between the two studied scenarios. The number of the RO sub-units switched on every hour during the day selected was calculated according to the electric power produced, for the different RO configurations and for both solar power plants. On one hand, in the case of PV and CSP-0h plants, it was obtained that the maximum number of the sub-units switched on was 8 during four hours in the selected day for RO basic case, while in the rest of the time, the active sub-units varied between 2 and 7. In the case of RO-WTR, the RO unit operated with full active sub-units for one hour for the CSP-0h plant. In the rest of the time, the active sub-units varied between 6 and 9 except in the sunset. In the case of RO-WTR powered by the PV plant, 9 sub-units were switched on during four hours as a maximum, and between 3 and 8 sub-units in the rest of operating hours. For the RO-PEX configuration, 10 sub-units operated for one hour in the selected day for the CSP-0h plant. For the PV plant combined with RO-PEX, the maximum sub-units switched on were 9 (during 4 hours). On the other hand, the desalination plant mostly operated with full sub-units (between 9 and 10) when the presence of thermal storage was considered for the CSP plant, except in the start-up and stop of the power plant (from 0 to 7 h in the morning, and from 19 to 24 h in the evening).

Table 4
Power and specific power consumption required by the RO unit connected to the solar power plant

	Power (kW)		Specific power consumption (kWh/m^3)		Permeate concentration (g/L)
	PV	CSP	PV	CSP	
Basic RO	1375	1422	6.6	6.8	0.21
RO-TWR	839	991.3	4.0	4.8	0.21
RO-PEX	517.4	658.3	2.5	3.2	0.21

Figure 7 represents the total fresh water produced during the selected day by each configuration using the two scenarios considered: whole unit (WU) and gradual capacity (GC). Regarding the two scenarios, it can be seen that the fresh water production was always higher in the WU scenario than in GC one. This result proves that WU scenario operating under the proposed strategies becomes more flexible and better than when it operates under gradual capacity. Comparing the results for the two solar power plants, the daily production of the RO-CSP-0h plant varied from 15,000 to 16,557 m^3/day (which means a 30% of the design capacity), and the one for the PV plant from 12,229 m^3/day to 14,758 m^3/day, which represents a 27% of the design capacity. In the cases of CSP with thermal storage the daily freshwater produced was much higher, as expected. In the case of the CSP-14h plant, the RO unit is able to produce more than 35,000 m^3/day, which represents the 72% of the nominal daily capacity of the RO unit, from 31,000 m^3/day to 33,000 m^3/day when the RO is connected to the CSP- 12h (about the 65% of the nominal capacity), more than 25,000 m^3/day when is driven by the CSP-10h plant (55% of the design capacity), between 21,917 m^3/day and 24,104 m^3/day in the case of the CSP-8h plant (46% of the nominal capacity) and more than 17,500 m^3/day in the case of CSP plant without thermal storage (32% of the nominal capacity).

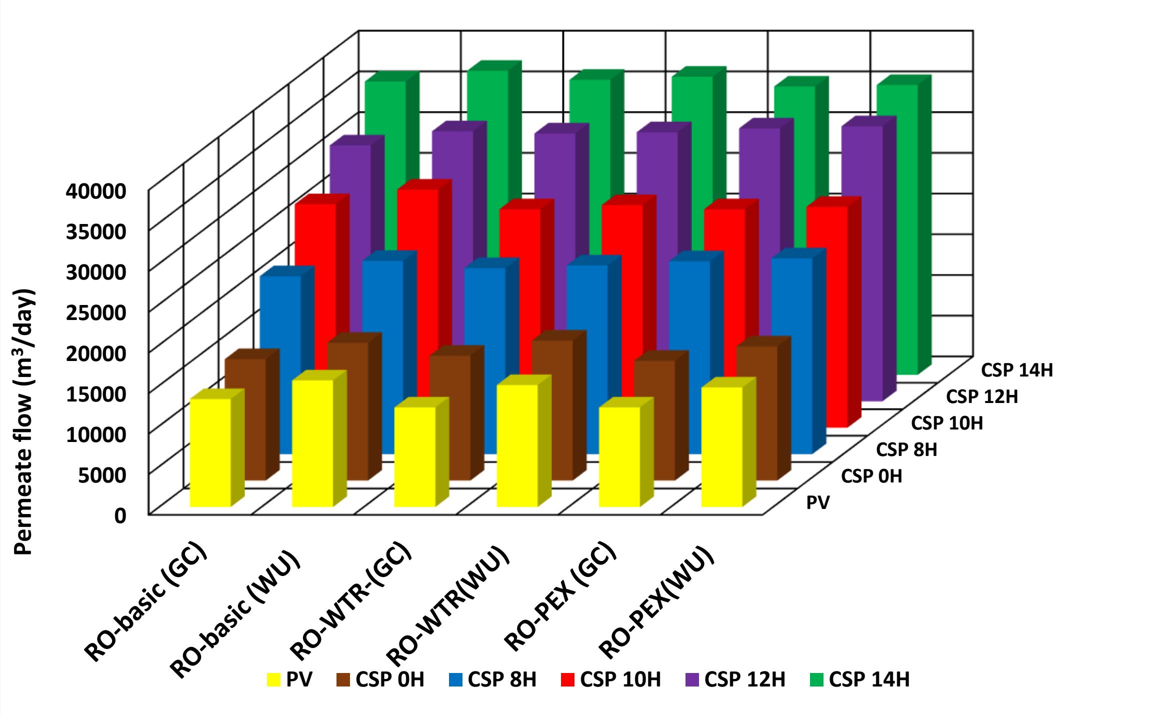


Fig. 7. Fresh water produced with the different cases

5.3. Economic results

Before highlighting the economic results and according to the design, the cost of the high pressure pumps is evaluated for the both scenarios based on the feed water flow rate. According to the RR obtained for the RO plant (42%), the feed water flow rate is 4960.32 m^3/h for the whole unit and 496 m^3/h for one sub-unit. Therefore, using the method explained in Section 4, in the first scenario the whole RO unit requires 11 pumps from category (A) while in the second scenario each sub-unit requires one pump from category (A) and one pump from category (C).

The results of the levelized water costs (LWC) of the different options studied are presented in Table 5. The LWC resulted inversely related with the thermal storage hours in the case of the CSP plant, which prove the effect of the presence of thermal storage in CSP plants on the water cost. The results also showed that LWC are lower in the case of the whole RO unit operating under the two strategies proposed than when the RO unit operates under gradual capacity. The best results were for the case of the RO-PEX whole unit connected to a CSP-14h plant (LWC of 0.85 \$/m^3), being even competitive against the water costs of today powered fossil RO plants (price between 0.60 €/m^3-1.90 €/m^3).

Table 5
Results obtained from the economic analysis

	RO-basic GC	RO-basic	RO-WTR-GC	RO-WTR	RO-PEX GC	RO-PEX
PV (\$/m^3)	2.14	1.81	1.91	1.55	1.60	1.32
CSP-0H (\$/m^3)	2.10	1.77	1.66	1.47	1.42	1.26
CSP-8H (\$/m^3)	1.83	1.68	1.39	1.37	1.08	1.06
CSP-10H (\$/m^3)	1.61	1.51	1.28	1.25	1.01	1.00

CSP-12H (\$/m^3)	1.51	1.43	1.13	1.12	0.88	0.83
CSP-14H (\$/m^3)	1.42	1.37	1.08	1.07	0.86	0.85

6. Conclusions

A techno-economic analysis of the combination of large-scale stand-alone RO unit with CSP and PV plants is presented in this paper, in which several configurations of RO and different strategies have been analyzed for its operation at variable load conditions. It was found that the operation of the RO plant with the adaptation to the power fluctuation is more suitable in terms of freshwater production and water costs than the usual scenario proposed in the literature so far (gradual capacity). The results showed that the combination of a RO plant with CSP is more favorable than the combination between RO and PV, from technical and economic points of view. The presence of thermal storage in the case of CSP improves even more the operation of the RO unit, especially in the cases of high number of thermal storage hours (12 and 14 h), in which the freshwater produced is close to the nominal one. The best RO configuration resulted the RO unit using a pressure exchanger as an ERD coupled with a CSP plant with 14 h of thermal storage (very low water costs 0.85 \$/m^3), being even similar to those ones of a RO unit operating with fossil sources (0.60 €/m^3-1.90 €/m^3). These potential results can make this kind of solar desalination plants a feasible option for sites as Algeria where the solar potential is high and there is an important water scarcity. However, it is important to highlight that the capital costs of this type of solar desalination plant are high, especially for the CSP plant with thermal storage, in which the annual capital cost is in the order of 10-15 M\$. Subsidies policies for producing freshwater with solar energy would solve this kind of problems.

Nomenclature

AC	Alternative current
ACC	Annualized capital cost, (\$/year)
CSP	Concentrating solar power
DC	Direct current
EES	Engineering Equation Solver
ERD	Energy recovery device
GC	Gradual capacity
HP	High pressure
HPP	High pressure pump power
HTF	Heat transfer fluid
I	Interest rate, %
LF	Load factor
LP	Low pressure
LT	Life time, year
LWC	levelized water cost, \$/m^3
MED	Multi effect distillation
MENA	Middle East and North Africa
ORC	Organic Rankine cycle
PEX	Pressure exchanger
PV	Photovoltaic

RO	Reverse osmosis
SWRO	Seawater Reverse Osmosis
SAM	System Advisor model
SPC	Specific power consumption, kWh/m^3
WPT	Wheel Pelton turbine
WU	Whole unit
A_e	Membrane area, m^2
FF	Fouling factor
k_s	Salt permeability, $m^3/m^{2\cdot}$ S
k_w	Water permeability, m^3/m^2.s.kPa
M_d	Permeate flow, m^3/day
M_b	Brine flow, m^3/day
M_f	Feed flow, m^3/day
T	Temperature, °C
TCF	Temperature correction factor
n_e	Number of elements
n_v	Number of pressure vessels
RR	Recovery ration, %
X_d	Permeate concentration, mg/l
X_f	Feed concentration, mg/l
X_b	Brine concentration, mg/l
π	Osmosic pressure, kPa

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