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Research Paper

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

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HIGHLIGHTS

- Comparison between RO with CSP and RO with PV under variable power loads.
- Configurations of RO with and without Energy Recover System have been considered.
- Two main scenarios are analyzed: RO as whole unit and RO composed by sub-units.
- Different strategies proposed to adapt the operation of RO to the power fluctuation.

ARTICLE INFO

Keywords:
Reverse osmosis
Partial load operation
CSP
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Gradual capacity
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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. Two scenarios and different strategies within each scenario have been proposed to adapt the operation of the RO unit at partial load in order to assure a stable operation. In the first scenario, the RO unit is represented as a whole unit with variable performance according to the power availability. In the second scenario, the RO unit is composed of 10 sub-units that are switched on/off depending on the power availability. The analysis has been done for a specific location in Algeria and the dynamic performance of the RO unit has been presented for each scenario, together with an 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 leads to the use of seawater desalination technologies 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 and with CSP, which give promising economic results when it is compared with the operation of Reverse Osmosis (RO) driven by fossil energy.

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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
SEC	specific energy consumption, kWh/m^3
WTR	wheel turbine recovery
WU	whole unit
A_e	membrane area, m^2
FF	fouling factor
k_s	salt permeability, m^3/m^2 S
k_w	water permeability, m^3/m^2 s kPa
M_d	permeate flow, m^3/day; m^3/h
M_b	brine flow, m^3/day; m^3/h
M_f	feed flow, m^3/day; m^3/h
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

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. Manolakos et al. [4] presented a technical and economic comparison between a PV-RO system and a RO-Solar Rankine system with a capacity of 0.1 m^3/h and 0.3 m^3/h of fresh water, respectively. The study was carried out in Thirasia Island (Greece). The cost of desalination using the PV-RO system resulted 7.77 €/m^3 while that of the RO-Solar Rankine system was as high as 12.53 €/m^3. The authors concluded that the PV-RO cost is very close to that of water transport cost, thus the PV-RO system could be a realistic solution for the problem of water scarcity in this region. Triki et al. [5] studied the feasibility of using 1MW$_e$ wind turbine to power a brackish water RO unit including pressure exchanger recovery system for three southern locations in Algeria (Adrar, Timimoun and Tindouf), in which storage batteries were used to cover the intermittence and fluctuation of the wind power. The authors revealed that the daily nominal water production based on the annual electricity production delivered by the wind turbine was 3720 m^3/day in Adrar, 3315.36 m^3/day in Timimoun and 2843.52 m^3/day in Tindouf. Moreover, the levelized water costs were found to be 0.66 $/m^3 at Adrar, 0.7 $/m^3 at Timimoun, and 0.75 $/m^3 in Tindouf, with the RO unit operating only under design point. Nafey et al. [6] performed an energy, exergy, and cost analysis for a combined solar organic Rankine cycle (ORC) and a RO desalination unit. The study was carried out taking the same specifications as Sharm El-Shiekh RO desalination plant (Egypt). Several solar thermal collectors (Flat Plate, Parabolic Trough and Compound Parabolic Concentrator) were investigated for the heat input required in the ORC where different working fluids were examined for such cycle. The results showed that Parabolic Trough collectors are the best choice for the thermal energy supply. Dehmas et al. [7] presented an analysis of a 5000 m^3/day SWRO system powered by a wind power plant with a nominal capacity of 10 MW$_e$ in the region of Tenes (Algeria). An economic analysis of the environmental benefits was done but the operation of the desalination plant under intermittence and fluctuated wind power was not presented. Finally, Caldera et al. [8] did a global estimation of the seawater desalination cost based on solar PV and wind energy for 2030. The authors concluded that the levelized water cost for regions with a desalination demand in 2030 is found to lie between 0.59 €/m^3-2.81 €/m^3, which are very similar to those of today in the case of powered fossil seawater RO (SWRO) plants (price between 0.60 €/m^3-1.90 €/m^3).

There are only few works in the literature that consider the intermittent power source. Wenyu Lai et al. [9] 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. [10] 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. Peñate et al. [11] presented the assessment of a stand-alone wind powered RO desalination plant with isobaric energy recovery device applying the gradual capacity strategy to adapt the fresh water production to the wind power availability. The nominal production of this plant was 1000 m^3/day with a fixed recovery ratio of 35%, and it was compared to a conventional fixed capacity desalination plant with a recovery ratio varying between 34% and 40%. The authors concluded that the fixed capacity plant allows the production of a greater amount of water per year in comparison with the gradual capacity strategy, but the desalination unit does work more hours in the year in the latter case.

Regarding the combination of RO units with solar thermal plants, Palenzuela et al. [12–14] investigated several configurations of the coupling between multi-effect distillation (MED) units and parabolic trough concentrating solar power (CSP) plants and compared them to the combined CSP-RO system. In all the configurations studied, the net electric power was 50 MW$_e$. A detailed techno-economic analysis was carried out for two locations, Almeria (southern Spain) as Mediterranean region and Abu Dhabi (UAE) in Arabian Gulf. The work was performed considering three different conventional refrigeration processes for the power cycle in the CSP plant (dry cooling, once through cooling, and evaporative cooling). It was found that for Mediterranean region, the combined CSP-RO system using the evaporative cooling technology is better from a thermodynamic and economic point of view, being the electricity and water costs in this case 18.79 c€/kWh and 1.01 €/m^3, respectively.

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. Three 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 recovery (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. 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

Figs. 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.

2.1. Description of the systems

The RO system unit, with a total nominal capacity of 50,000 m^3/day, is composed of several pressure vessels that contain certain number of membranes elements in series. Two scenarios have been considered for the RO system: in the first one, the RO operates as a whole unit with capacity of 50,000 m^3/day; and in the second one, the RO system is composed of 10 independent sub-units, each one with a capacity of 5000 m^3/day (notice that each sub-unit accounts with a high-pressure pump). Additionally, for both scenarios, three different RO systems have been considered (Fig. 3), all of them with a single stage: the first one is the basic RO unit without recovery system (see Fig. 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 Fig. 3b and c, 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 [15], since this technology is more efficient, has a more favorable land area per energy output, require lower operating and maintenance expenses and lower upfront investment. 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 (it is based on molten salts, consisting in a mixture of 40% KNO_3 - 60% $NaNO_3$) is heated by the energy reflected by the mirrors. The thermal storage system consists of two tanks: the hot tank (with a temperature of 570 °C for the molten salt) and the cold tank (with a temperature of 290 °C). 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).

2.2. Modeling and design of the systems

The RO unit has been modeled using the equations outlined in [6,16,17] (see the Appendix), 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

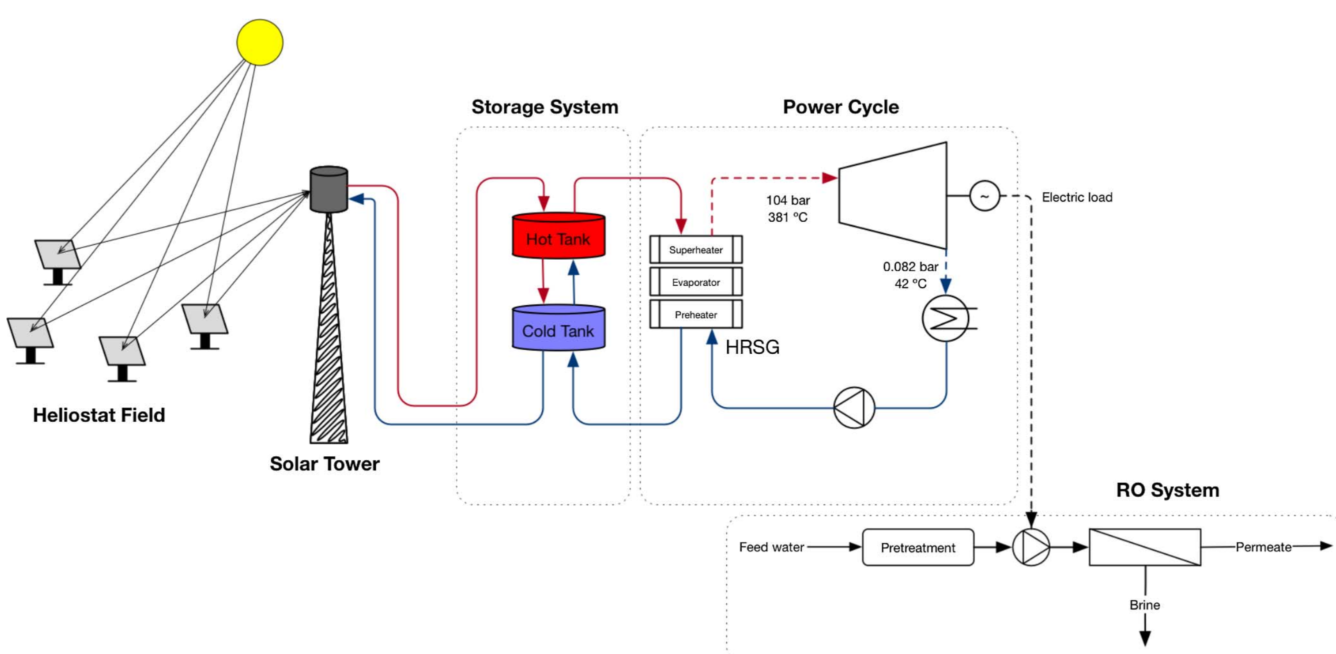

Fig. 1. Flow diagram of the system consisting of an RO unit connected to a central receiver CSP plant.

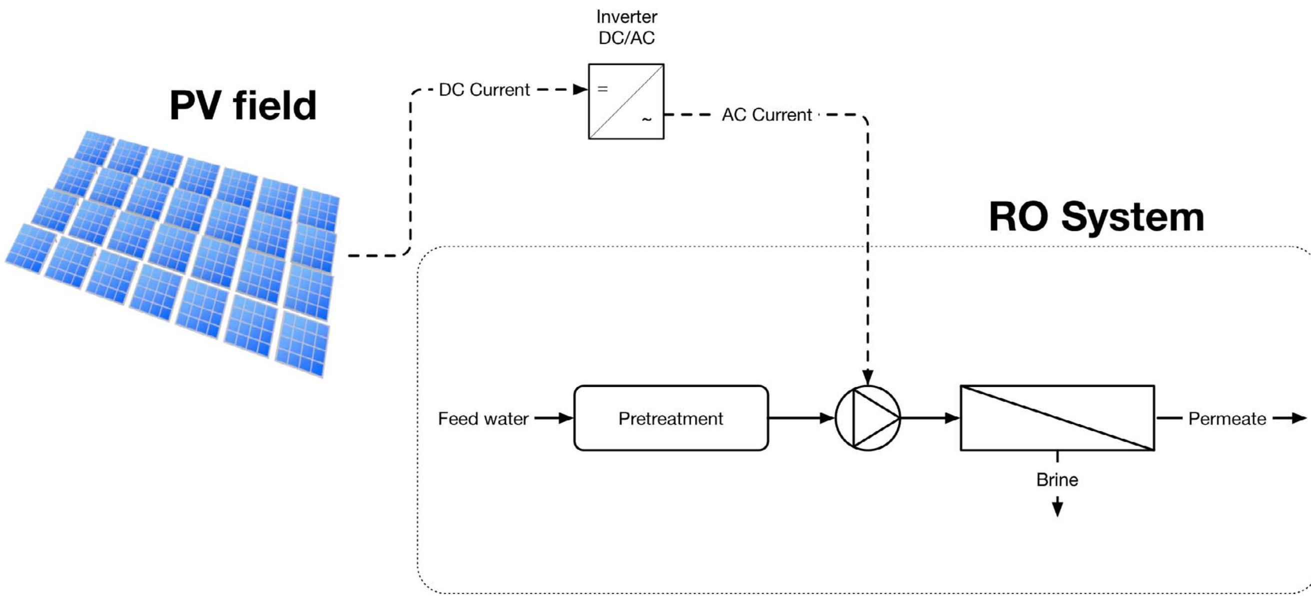

Fig. 2. Flow diagram of an RO unit connected to a PV plant.

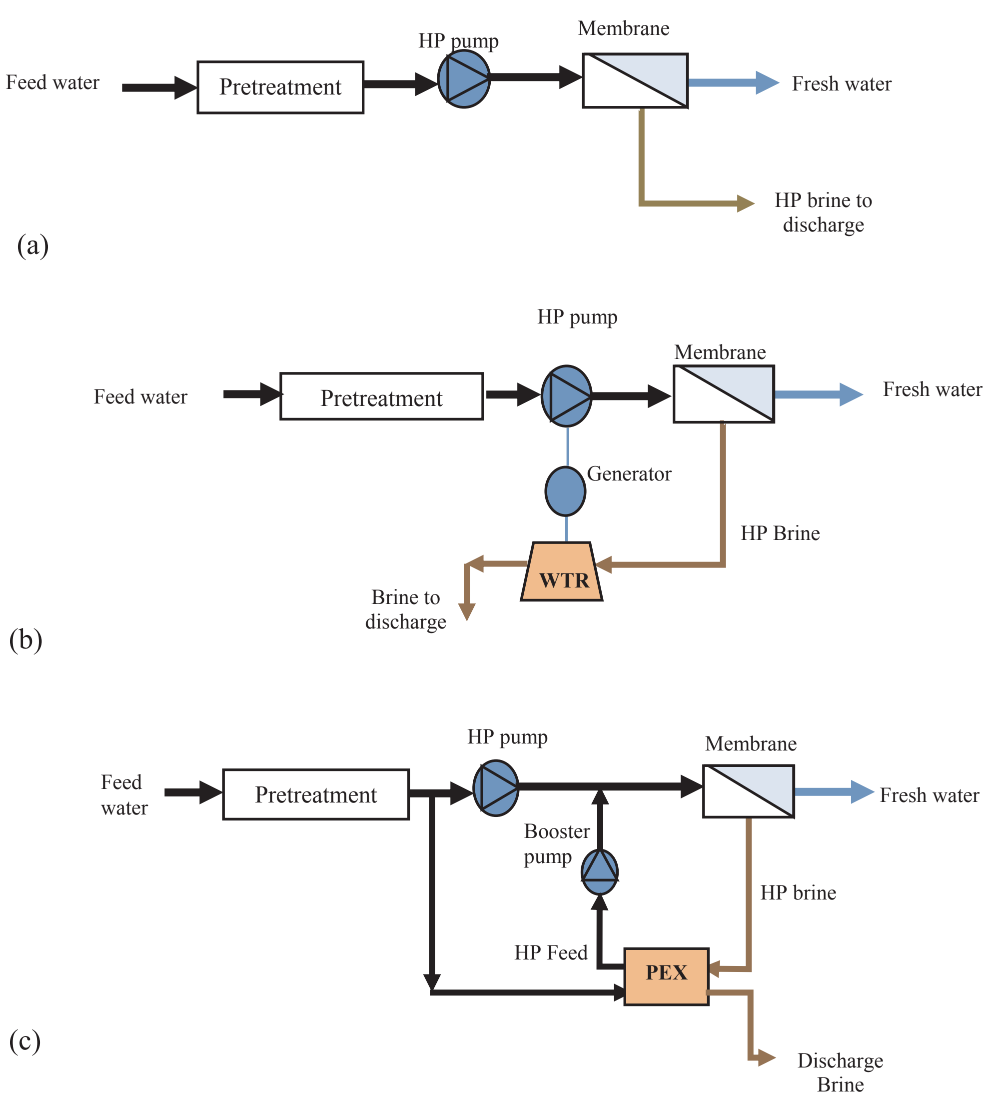

Fig. 3. RO configurations: (a) basic concept without ERD (b) with ERD based on Pelton wheel turbine, (c) with ERD based on pressure ex-changers.

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 estimated using the feed flow (M_f)(m^3/h), the feed density (ρ_f), the membrane applied pressure $P(bar)$, and the pump efficiency (η_p), by the following equation:

$$HPP = \frac{1000 \cdot M_f \cdot P}{3600 \cdot \rho_f \cdot \eta_p} \quad (1)$$

The numbers 3600 and 1000 are conversion factors: 3600 is used to convert hour to second and 1000 resulted by the multiplication of the conversion factor from bars to kPa (100) by the gravity force (10).

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

$$SEC = \frac{HPP}{M_d} \quad (2)$$

An optimum design of the RO plant in terms of the number of elements, number of pressure vessels, Recovery Ratio (RR) and Specific Energy Consumption (SEC) 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 found 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 SEC, 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 and the booster pump have been considered as 98% and 80%, respectively [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 SEC 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 37,000 mg/L [23], a fouling factor of 0.85 [24] and a fixed average feed water temperature of 20 °C [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). Different thermal storage capacities have been considered in the present study: 0, 8, 10, 12 and 14 h 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 specific power consumption of the cooling system has been assigned as 0.0329 MW_e/MW_e (power consumed in MW_e for each MW_e of total electricity produced by the power plant) and the specific water consumption as 3 m^3/MW_e [25,26]. On the other hand, the design of CSP plants (the solar field area required for each storage thermal capacity) was determined with the software System Advisor Model (SAM). These parameters were used to predict the instantaneous power produced using TRNSYS 17.01 software exploiting the STEC (Solar Thermal Electric Components) library components. This library is based on steady-state energy conservation (1st and 2nd laws) formulated in thermodynamic properties (temperature, pressure, enthalpy). It contains the component models for the Rankine cycle, the solar system (central receiver, heliostat field) and the thermal storage [27]. For the PV system, System Advisor Model (SAM) software has been used both for the design and to predict the instantaneous power produced by the plant.

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 for each mentioned scenario (1 and 2). 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 [28]) 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. Fig. 4 shows a flow diagram of the strategy followed in this case. Two strategies are considered within this scenario (see Fig. 4):

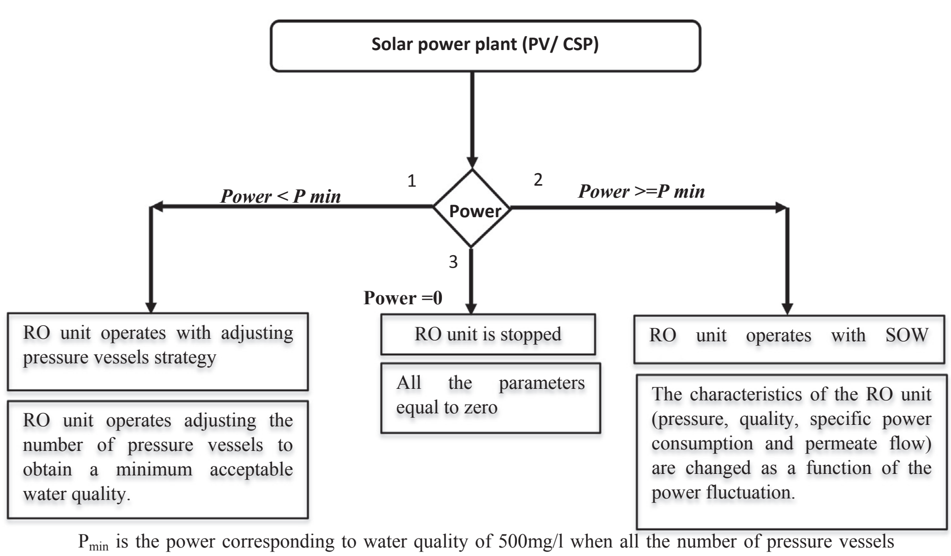

Fig. 4. Flow diagram for the operation strategy followed in Scenario 1.

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
SEC (kWh/m^3) EES	5.97	5.64	5.37	5.15	5.46	5.22	5.03	4.88
SEC (kWh/m^3) ROSA	5.81	5.44	5.15	4.92	5.25	4.98	4.79	4.64
SEC error (%)	2.77	3.6	4.75	4.96	4.11	4.96	4.95	5.11

(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) in the respect of the good functioning of membrane.

(2) when the power produced by the solar plants results lower than P_{min}, some pressure vessels are stopped 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 SEC do not change with the power availability, assuming that the high pressure pump operates under fixed efficiency (80%).

3.2. Scenario 2 (sub-units)

The strategy followed within this scenario is called gradual capacity. In this strategy, 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 ($ACC_{powerplant}$) and the annual fresh water production ($M_{d-annual}$):

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

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 [6,24–26,28–30]. It is needed to specify the calculation of the pump cost used in the RO unit (C_{HPpump}). It is based on the correlations described by Malek et al. [29], 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): $M_f = 450$ m^3/h (where M_f is the feed flow)

$$C_{HPpump} = 393000 + 10710\ P_f \tag{4}$$

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

Category (B): 200 m^3/ h< M_f < 450 m^3/h

$$C_{HPpump} = 81\cdot(P_f\cdot M_f)^{0.96} \tag{5}$$

Category (C): M_f < 200 m^3/h

$$C_{HPpump} = 52\cdot(P_f\cdot M_f) \tag{6}$$

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 SEC.

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 SEC 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. It can be also observed that the RO-PEX unit needs lower energy than RO-WTR (see Table 3).

Likewise, the design of the solar plants can be seen in Table 2.

Table 2
Required power and specific energy consumption at the design point for the CSP-RO and PV-RO systems.

RO unit	Power (kW)		Specific energy consumption (kWh/m^3)		Permeate concentration (g/L)
	PV plant	CSP plant	PV plant	CSP plant	
Basic RO	13,748	14,216	6.6	6.8	0.21
RO-TWR	9692	10,022	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- WTR			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	13,748	86,547	–	9692	58,617	–	6549	39,077	–
CSP (0h)	14,216	130,056	–	10,022	89,936	–	6772	58,913	–
CSP (8h)	14,216	189,118	277.4	10,022	136,764	195.6	6772	98,589	132.1
CSP (10h)	14,216	235,503	346.7	10,022	161,825	244.4	6772	113,203	165.2
CSP (12h)	14,216	267,421	416.1	10,022	195,382	293.3	6772	14,080	198.2
CSP (14h)	14,216	308,583	482.4	10,022	216,263	324.2	6772	146,313	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.

5.2.1. *Scenario 1 (whole unit)*

Fig. 5 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-WTR, and RO-PEX

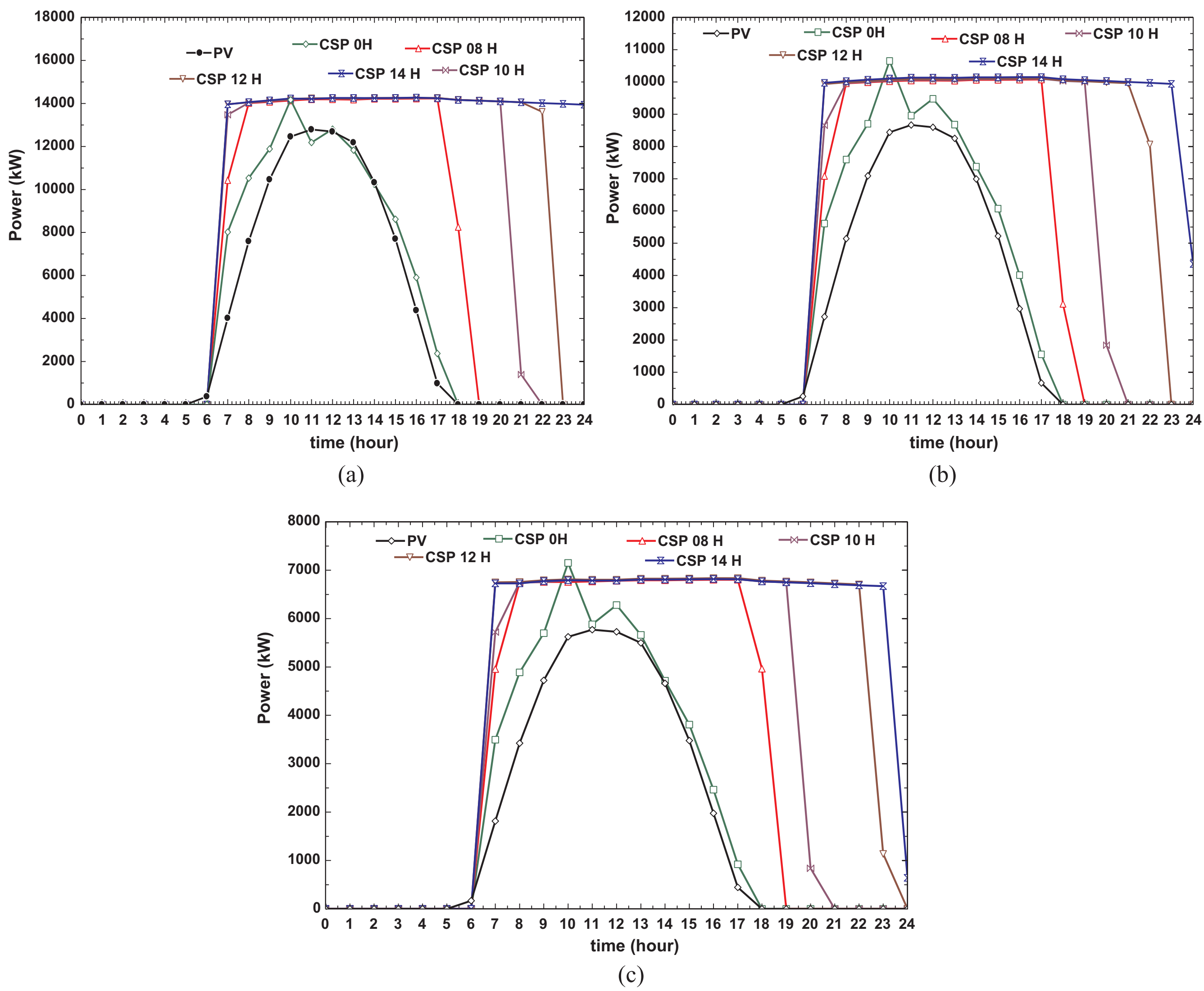

Fig. 5. Power produced by the solar power plants during the whole day to drive the RO plant in the different configurations: (a) RO unit without ERD, (b) RO-WTR, (c) RO-PEX.

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. 6 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.

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.

Fig. 7 shows the hourly variation of the specific energy consumption during the selected day. Obviously, the SEC varies during the day according to the power fluctuation. It can be seen that the SEC is lower for the cases of the RO units (with and without ERD) connected to the PV

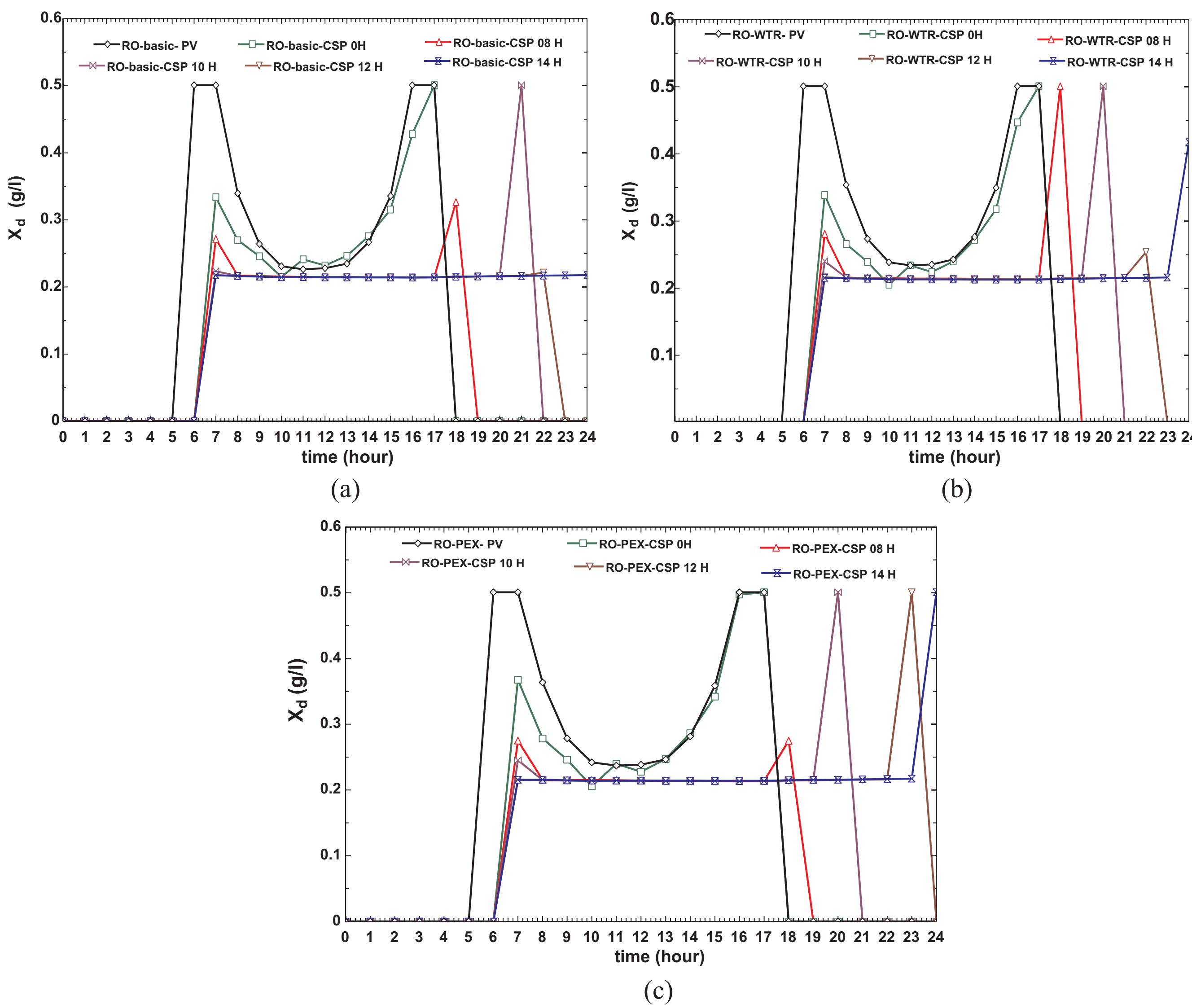

Fig. 6. Permeate concentration variation: (a) RO unit without ERD, (b) RO-WTR, (c) RO-PEX.

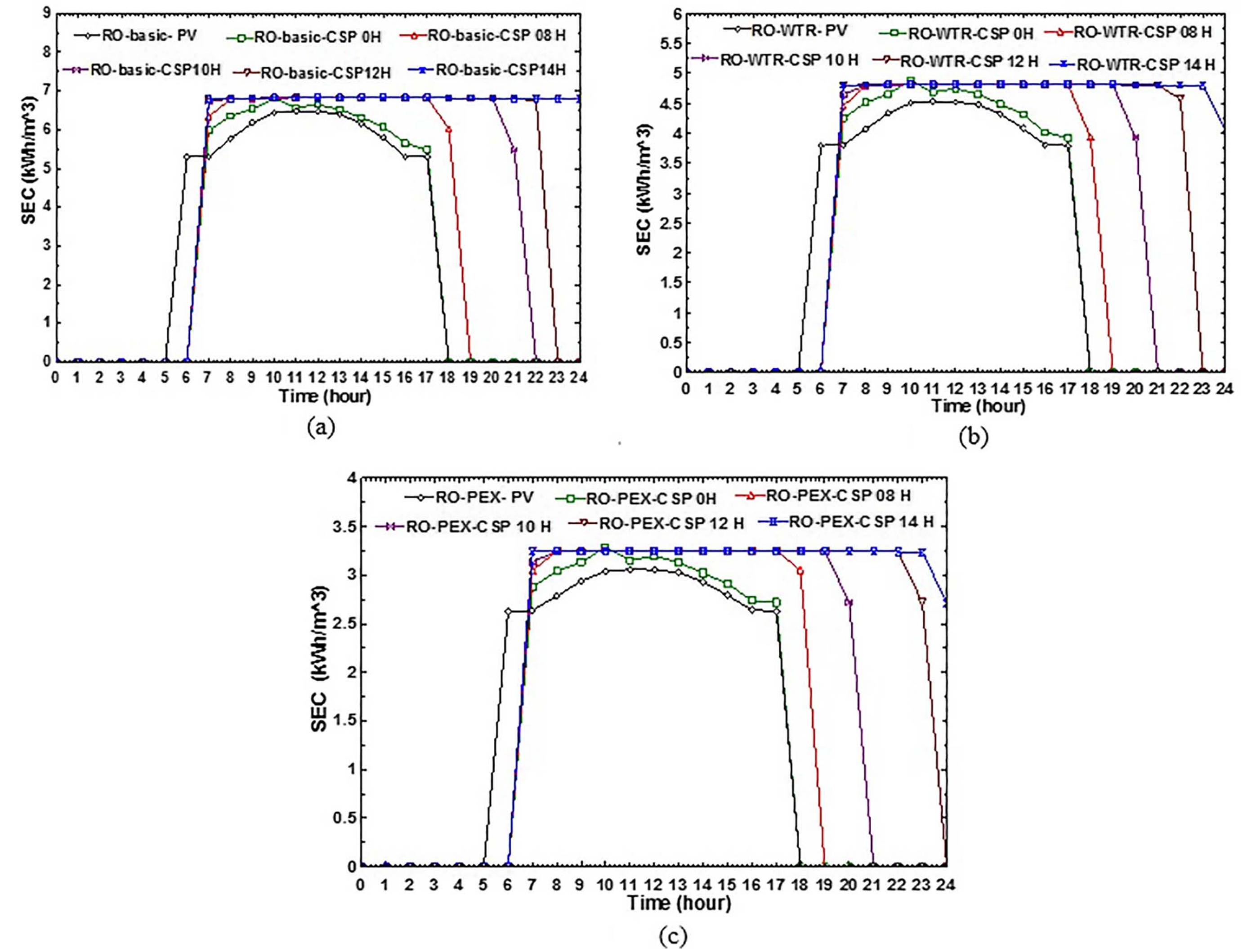

Fig. 7. Specific energy consumption: (a) RO unit without ERD, (b) RO-WTR, (c) RO-PEX.

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 SEC 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 SEC was close to that at design for the different RO configurations.

5.2.2. Scenario 2 (gradual capacity)

Table 4 represents the results obtained for the design point in terms of the power and the SEC 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 h). 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-WTR	839	991.3	4.0	4.8	0.21
RO-PEX	517.4	658.3	2.5	3.2	0.21

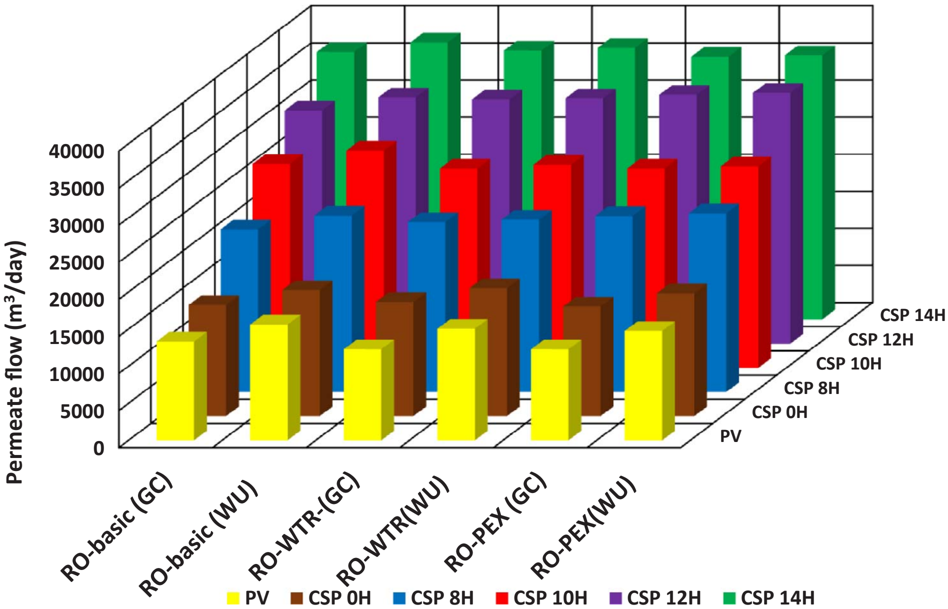

Fig. 8. Fresh water produced with the different cases.

Fig. 8 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).

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 annual capital cost ($) for the different configurations for the combination between RO unit and the solar plant are presented in Table 5.

The results of the levelized water costs (LWC) of the different options studied are presented in Table 6. 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 and

Table 6
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$)	1.51	1.43	1.13	1.12	0.88	0.87
CSP-14H ($/$m^3$)	1.42	1.37	1.08	1.07	0.86	0.85

Table 5
The annual capital cost in ($).

	RO-basic (GC)	RO-basic (WU)	RO-WTR-(GC)	RO-WTR (WU)	RO-PEX (GC)	RO-PEX (WU)
PV	10,401,458	10,348,342	8,581,396	8,528,280	7,171,010	7,117,894
CSP-0H	11,496,269	10,977,929	9,325,670	9,272,554	7,641,599	7,588,482
CSP-8H	14,637,240	14,584,124	11,659,363	11,606,247	9,402,421	9,349,305
CSP-10H	16,143,566	16,090,450	12,545,612	12,492,496	9,948,831	9,895,715
CSP-12H	17,318,505	17,265,389	13,627,515	13,574,399	10,792,452	10,739,336
CSP-14H	18,685,856	18,632,740	14,303,716	14,250,600	11,129,477	11,076,361

1.90 €/m^3). The obtained result in the LWC for the combined CSP-8h and RO-PEX was 1.08 €/m^3, which has been compared with that outlined in [12]. The referenced work considers a combined parabolic trough CSP (with thermal storage of 6.5 h) with reverse osmosis, located in Almeria (Southeast of Spain) with a capacity of 47,723 m^3/day. The study obtained a LWC of 1.01 €/m^3 based on a SEC of 3 kWh/m^3, which shows the similarity with the result of the present paper.

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 (0.60–1.90 €/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.

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Appendix A. The RO model

The model 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 feed flow rate is evaluated as function of the recovery ratio and the permeate flow rate by the following equation:

$$M_f = \frac{M_d}{RR} \tag{A.1}$$

where RR is the recovery ratio, M_d is the permeate flow rate (m^3/day) and M_f the feed water flow rate (m^3/day).

The brine flow rate is determined using this equation:

$$M_b = M_f - M_d \tag{A.2}$$

The salt concentration of the brine (X_b) is determined as follows:

$$X_b = \frac{M_f \cdot X_f + M_b \cdot X_f}{M_b} \tag{A.3}$$

where X_f is the feed salt concentration. It has been considered a feed salt concentration for the Algerian coastal equal to 37,000 mg/L [23].

The permeate concentration is calculated by using the following equation:

$$X_d = \frac{1}{M_d}[k_s \cdot A_s \cdot X_{av}] \tag{A.4}$$

where k_s is the salt permeability (which is defined in the Eq. (A.5)), A_s is the membrane total area and X_{av} the average concentration, that is calculated by Eq. (A.7).

The salt permeability is defined by [6]:

$$k_s = FF \cdot TCF \cdot 4.72 \cdot 10^{-7}[0.06201 - (5.31 \cdot 10^{-5} \cdot (T + 273))] \tag{A.5}$$

where FF is the membrane fouling factor, that is 0.85 [24], and TCF is the temperature correction factor. This last parameter is calculated with the following correlation [18]:

$$TCF = exp\left[3020 \cdot \left(\frac{1}{273 + T} - \frac{1}{298}\right)\right] \tag{A.6}$$

where T is the feed water temperature (°C). In this study a fixed average feed water temperature of 20 °C has been considered for the Algeria coast zone [23].

The average salt concentration is estimated as follows:

$$X_{av} = \frac{M_f \cdot X_f + M_b \cdot X_b}{M_f + M_b} \tag{A.7}$$

The osmotic pressures of the feed, brine and permeate sides are evaluated by the following equations [17]:

$$\pi_f = 75.84 \cdot X_f \tag{A.8}$$

$$\pi_b = 75.84 \cdot X_b \tag{A.9}$$

$$\pi_d = 75.84 \cdot X_d \quad (A.10)$$

The average osmotic pressure on the feed side is calculated by:

$$\pi_{av} = 0.5 \cdot (\pi_f + \pi_b) \quad (A.11)$$

The pressure across the membrane is determined as follows:

$$\pi = \pi_{av} - \pi_d \quad (A.12)$$

Finally, the pressure to be applied on the membrane is evaluated using the following expression:

$$P = \frac{M_d}{TCF \cdot FF \cdot A_e \cdot n_e \cdot N_v \cdot k_w} + \pi \quad (A.13)$$

where k_w is the membrane permeability that is determined by the correlation given by Eq. (A.14) [19]:

$$k_w = 6.84 \cdot 10^{-8} \cdot (18.6865 - (0.177 \cdot X_x)) \quad (A.14)$$

The required power (in kW) for the high-pressure pump is evaluated using the feed density (ρ_f) and the pump efficiency (η_p), by the following equation:

$$HPP = \frac{1000 \cdot M_d \cdot P}{3600 \cdot \rho_f \cdot \eta_p} \quad (A.15)$$

Finally, the specific power consumption (in kWh/m^3) is calculated with the equation below:

$$SPC = \frac{HPP}{M_d} \quad (A.16)$$

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