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Large-scale desalination based on parabolic trough collectors and double-effect absorption heat pumps

Antonio Colmenar-Santos[a], Andrés León-Betancor[a], Ana-María Diez-Suárez[b], Alberto González-Martínez[b,*], Enrique Rosales-Asensio[c]

[a] *Departamento de Ingeniería Eléctrica, Electrónica, Control, Telemática y Química Aplicada a la Ingeniería, UNED, Juan del Rosal, 12, Ciudad Universitaria, 28040, Madrid, Spain*

[b] *Departamento de Ingeniería Eléctrica y de Sistemas y Automática, Universidad de León, Escuela de Ingenierías Industrial e Informática, Campus de Vegazana, s/n, 24071, LEÓN, Spain*

[c] *Departamento de Ingeniería Eléctrica, Universidad de Las Palmas de Gran Canaria, Las Palmas, Escuela de Ingenierías, Campus Universitario de Tafira, s/n, 35017, Las Palmas de Gran Canaria, Spain*

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Abstract

This paper focuses on an analysis of the current situation of distillation and reverse osmosis technologies and their relationship with renewable energies, to the extent that there is a strong trend in the use of distillation and reverse osmosis technologies. Large-scale seawater desalination using renewable energy is not developed, so a detailed study of the combination of renewable energy facilities, reverse osmosis, and distillation systems are needed to be effective and competitive compared to the use nonrenewable energy. Solar multiple is a very important parameter in the solar thermal industry. This is in the range of 1.5 – 3 and depends on the relationship between storage and plant power. This parameter is important because it reflects a balance between the cost of the parabolic trough collectors and the total of the solar thermal plant. If the same criterion is followed, with a thermal gap of 100 °C, chosen for the parabolic trough collectors sizing, the solar multiple in the system object of this article, has a value higher than 3. The proposed system employs renewable energies for reducing the downtime of the desalination plants, doing possible that the desalination plants being competitive in sites with poor quality solar radiation.

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Keywords: Large scale desalination; Reverse-osmosis; Water costs; Parabolic trough collectors; Double-effect absorption heat pumps

1. Introduction

Nowadays, natural resources cannot supply the demand and it is necessary to obtain potable water by industrial facilities, mainly using seawater. Water use in agriculture is even projected to increase globally at 19% by 2050, with most of this increase in developing countries (up to 90%) [1], and it should be added that these are characterized

* Corresponding author.
E-mail address: agonmar@unileon.es (A. González-Martínez).

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Nomenclature

γ	Regulation variable of the three-way valve
η_{op}	Peak optical performance
A_e	Area lost
h_{80}	Water enthalpy at 80 °C
h_{180}	Water enthalpy at 180 °C
I_{dn}	Direct normal radiation
K_θ	Modifier angle of incidence
L1	Level in the primary tank
L2	Level in the secondary tank
$\dot{m}_{12}$	Mass flow from the primary to secondary tank
$\dot{m}_{ptc}$	Mass flow entering to the collectors
$\dot{m}_h$	Hot water mass flow
$\dot{m}_m$	Hot water mass flow to the intercooler outlet
$\dot{m}_{ref}$	Mass flow entering to the MED plant
$\dot{m}_t$	Mass flow entering the absorber of the double effect absorption heat pump
$\dot{m}_{T1}$	Mass flow in the primary tank
$\dot{m}_{T2}$	Mass flow in the secondary tank
MVC	Mechanical vapor compression
Q_{ca}	Losses collector-environment
T1	Temperature in the primary water tank
T2	Temperature in the secondary water tank
Temp.	Temperature
TF	Outlet water temperature of the collector field
Th	Outlet water temperature, either double effect absorption heat pump or of the intercooler or the mixing valve
TiM	Inlet water temperature to the plant MED
Tm	Hot water mass flow temperature from the exchanger.
TM	Outlet water temperature of the plant MED
TVC	Thermal vapor compression
VC	Vapor compression
W_e	Open collector area

by having a deficient system of electric power supply. Desalinated water is consumed mostly among the urban population with 68%, followed by industry with 22%, and agriculture with 2%. The rest goes mainly to tourist areas and for energy production. It is observed that, in general, desalinated water is almost entirely destined to supply the urban demand and this is mainly due to its high production cost. However, in some regions (deserts and islands) desalinated water is the only way to supply drinking water to urban areas, industries, and even agriculture. Despite a steady increase in potable water production, according to UNESCO estimates, by 2025 more than 3 billion people will not have access to drinking water [2].

The most relevant aspect of drinking water production is the great amount of energy needed to obtain it, being able to have these facilities a time of life that can get over the 25 years. Energy is not only necessary for the production of water, but also for the treatment of wastewater (from which water is obtained for industrial uses and sometimes for agriculture). Currently, drinking water is mainly obtained by RO and by distillation, so these installations are closely related to conventional energies. While RO feeds on electrical energy directly from conventional power plants, thermal systems use their residual energy [3].

Although demand for renewable energy (RE) is estimated to increase up to 60% by 2030 [4,5], RE powered desalination systems today account for only about 0.02% of total desalination capacity [6,7]. The best technology to supply energy to the thermal-desalination plants' multi-effect distillation (MED) and multi-stage flash distillation (MSF) is solar thermal, while the wind energy is the best adapted to RO plants [7].

Between large-scale processes and REs, the MED and solar processes present one of the best prospects for the future: they are simple processes that can be coupled to solar collectors in a viable way, in addition, the coupling of a MED and heat pumps have been proposed as one of the best desalination systems. This is the operating principle of the SOL-14 plant, developed in the Plataforma Solar de Almería (PSA). With the absorption pump, a boiler was used to obtain the hot water at 180 °C (required for the operation of the absorption pump) and flat thermal panels developed for this installation were used for the use of solar energy. This work exposes a principle of operation of the same installation (SOL-14) based entirely on the capture of solar radiation. In order to do this, it is proposed that the entire system be operated with parabolic trough collectors (PTC) (absorption pump included) and with water as the energy transport liquid. In fact, in the first phases (without absorption pump) the SOL-14 system was working with PTC and oil as energy transport liquid presenting high reliability without observing major problems of some kind.

The relationship between RE and MED through PTC is one of the best combinations in the water-energy relationship.

In this work, the design of a large-scale desalination unit is presented based on PTC and double-effect absorption heat pumps and utilizing RE sources, including a techno-economic analysis. The design is presented present by first giving a complete review of the existing reverse osmosis (RO) desalination technologies, followed by the appropriate design and modeling of the system and finally the simulation results are given. The article has been divided into 7 blocks. The Introduction presents the importance of desalination and its relation to energy. In the Technology section, the main characteristics of large-scale plants are described, divided into two sections: large-scale desalination technologies (thermal and RO processes) and the relationship of these technologies with REs. Section 3 of Materials and Methods analyzes the desalination processes and their configurations with REs and proposes a way of functioning of the PTC in order to take advantage of high, medium and low solar radiations. The description of the system and its modeling is carried out in Section 4. Section 5 presents the results. In sections six and 7 the analysis of the content, the discussion and the conclusions are presented.

2. Theoretical background

2.1. Large-scale desalination technologies

The first large-scale desalination method was the MED [8], and subsequently from the 1950s [9] the MSF. During the 1960s, RO was developed and marketed in the 1980s. Table 1 shows a comparison of these technologies.

Normally, water specific-cost is calculated using the equivalent annual cost method [10,11].

MSF desalination systems represent 44% of all installed desalination systems whereas RO systems entail 42%. For its part, the MSF processes represent more than 93% of all thermal processes whereas RO systems entail over 88% of all membrane processes [19,20]. In the medium term, it is expected that MSF, RO, and MED are the dominant systems [21]. A breakthrough of the production capacity taking into account desalination technology is shown in Fig. 1.

2.1.1. Thermal processes

A MED plant operates according to the principle of normal distillation (it reuses the latent heat to vaporize the seawater); in contrast, in an MSF plant, there is sudden evaporation of the water when heating it above the saturation temperature that corresponds to the pressure of the effect.

MSF plants were the technological response to the erosion and corrosion problems of the MED plants, because with sudden evaporation, the contact with the brine is significantly reduced, but in contrast, they have a higher energy consumption than the MED.

Considering that the water Cs is about 4 kJ/kg/K and that its latent heat of vaporization is approximately 2300 kJ/kg, the MED systems have between 4 and 21 effects with a performance factor (PF) in large plants, between 10 and 18 [25]. Its operating temperature is above 70 °C and its size is smaller than MSF plants (the capacity of the MED units ranges from 600 to 30 000 m^3/day, but they have the advantage that they are very efficient systems from

Table 1. Energy consumption, installation and operating costs for different technologies.

	Unit	MSF/ seawater	MED/ seawater	MED-TVC/seawater	MVC/ seawater	RO-brackish water	RO-seawater
Installation cost per m^3/day		€1080–1690[12] €1500[13] €950–1900[3] €1200–2500[14]	€900–1700[3] €900–2000[14]	€780–1080[12]	€1020–1500[12]	€300–1200[14]	€660–1200[12] $900–1200[13] 2500[e][13] €900–2500[3,14] $600–$800[15]
Energy cost and capital recovery		74%[d][13]	NA	NA	NA	NA	NA
Thermal energy consumption		194–291[c][12] 6,75–9,75[a][16] 294[f][3] 7,5–12[a][14]	4,5–6,5[a][16] 123[f][3] 4–7[a][14]	145–194[c][12] 6,5–12[a][16]	0	0	0
Electric energy consumption	kWh/m^3	3,5–4,0[12] 3,25–3,75[16] 2,5–4[14]	2,5–2,9[16] 4–7[14]	1,5–2,0[12] 2,0–2,5[16]	9–11[12] 9,5–17[16]	1,0–2,5[16] 0,5–2,5[14]	3–4,5[b][12] 4,5-8-5[16] 3-4[i][14]
Total energy consumption	kWh/m^3	10,5–13[16] 10–16[14]	7,4–9[16] 5,5–9[14]	9-14[16]	9,5–17[16]	1,0–2,5[16] 0,5–2,5[14]	4,5–8,5[16] 3-4[i][14]
Primary energy consumption	kJ/kg	338,4[g][3]	149,4[g][3]	NA	NA	NA	120[g,h][3] 60[g][3]
Operation and Maintenance	€/m^3	0,05-0,07[12] 17%[d][13]	NA	0,04-0,07[12]	0,05–0,08[12]	NA	0,05–0,10b[12]
Spare parts		9%[d][13]	NA	NA	NA	NA	NA
Spare parts and chemical products	€/m^3	0,02–0,04[12]	NA	0,02–0,03[12]	0,02–0,04[12]	NA	0,02–0,05[b][12]
Membrane spares	€/m^3	0	0	0	0	NA	0,01–0,04[b][12]
Specific water cost	\$/m^3	0,56–1,75[j] (for 23 000–528 000 m^3/d)	0,52-1,01[j] (for 91 000–320 000 m^3/d)	NA	NA	0,26–0,54[j] (for 40 000 m^3/d)	0,45–0,66[j] (for 100 000–320 000 m^3/day)

[a] kWh/m^3.
[b] Plant capacity, between 10 000 and 100 000 m^3/day.
[c] In MJ/m^3, PF (MSF) between 8 and 12. PF (MED-TVC) between 12 and 16.
[d] From total cost plant.
[e] Costs that can be achieved for small capacity desalination plants.
[f] kJ/kg.
[g] Assumes an efficiency in power generation of 30%.
[h] Without energy recovery device
[i] Includes recovery system.
[j] [17,18].

the point of view thermodynamic [26]). In contrast, a typical MSF unit consists of between 19 and 28 stages (in the process of sudden expansion, only a small part of the seawater becomes steam, up to 10% maximum). Moreover, it has a PF that reaches a value of between 8 and 12, conditioned by its working temperature which is between 90 °C and 120 °C (this temperature, in turn, is conditioned by the method of scaling that is used) [27,28].

An important aspect is that the higher the recovery in thermal systems, the less latent heat is wasted and the lower the specific energy consumed [29]. Due to lower temperature and pressure operation, MED energy consumption is lower than the MSF process.

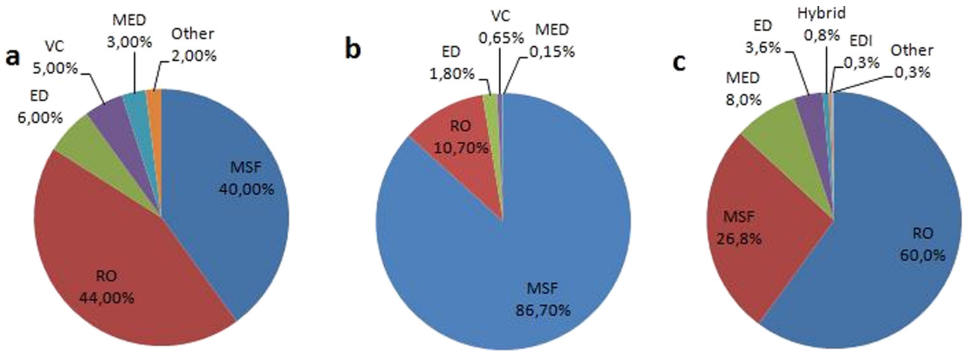

Fig. 1. Desalination capacity breakthrough taking into account process type for (a) the world, 2005. Source [22]; (b) the Middle East (Saudi Arabia, Kuwait, United Arab Emirates, Qatar, Bahrain, and Oman), 1995. Source [23]; (c) shows the distribution in 2016. Source [24].

Table 2. Production cost of large desalination plants [33,34].

Location	Year of commissioning	Capacity (m^3/d)	Contract type	Investment (M USD)	Water specific cost (\$/m^3)
Hadera SWRO	2010	347 900	Build, own, operate and transfer	425	0,63
Shuaiba MSF	2010	880 000	Build, own and operate	2,4 M	0,95
Marafiq MED-TVC	2009	800 000	Independent water and power project	3,4 M	0,83
Skikda SWRO	2008	100 000	Build, own, operate and transfer	110	0,73
Ras Laffan B MSF	2008	272 500	Independent water and power project	900	0,80
Hamma SWRO	2008	200 000	Build, own and operate	250	0,82
Perth SWRO 2-pass	2007	143 700	Build, own, operate and transfer	347	1,20
Palmachim SWRO	2007	110 000	Build, own and operate	110	0,78

2.1.2. Reverse osmosis

In RO systems, a pressure greater than the osmotic pressure of the seawater is applied causing freshwater to go through a membrane. RO is the large-scale desalination method for seawater that has a lower energy consumption and can be as low as 2 kWh/m^3 [30]. They are mainly due to the development of new membranes, the development of pumps of greater energy efficiency and the new energy recovery systems that take advantage of the brine pressure left by the pressurized vessel—are divided into two classes [31]. Among the energy recovery systems, the pressure exchangers have the highest dynamic efficiency and stability—they transfer the hydraulic energy of the brine rejected by the membrane to the feed water [32]. The recovery in RO for seawater (35 000 mg/l) was 25% in the 80 s, 35% in the 90 s and is now around 45% (60% can be achieved if a second stage is applied; in brackish water is 90%). Table 2 shows the production costs of large conventional energy desalination plants.

2.2. Renewable energies in large-scale desalination

The main challenge associated with REs is to optimize their variability with the continuous demand for drinking water. Moreover, the desalination plant's capacity from REs has a direct impact on the price of water, as shown in Fig. 2, that together with the high cost of the installation of RE, make that desalting water through REs is more expensive than employing the conventional systems, Table 3.

The most suitable RE for MED and MSF plants is the solar thermal (solar collectors have been the ones mainly used) [38]. MED units are suitable in places with high solar radiation [39].

Conversion of solar energy into kinetic energy in the form of wind is around 750 EJ [40], of which approximately 10 TW is arranged in the lower areas of the atmosphere, being this amount sufficient to satisfy the electric energy demand in the world. Second, after direct solar energy, wind energy is the most widely used for small-scale desalination plants [3].

Saline ponds have as a main peculiarity the elimination of sudden temperature variations (they have a great potential to store large amounts of energy both solar and residual) so that plants MSF and MED can be coupled.

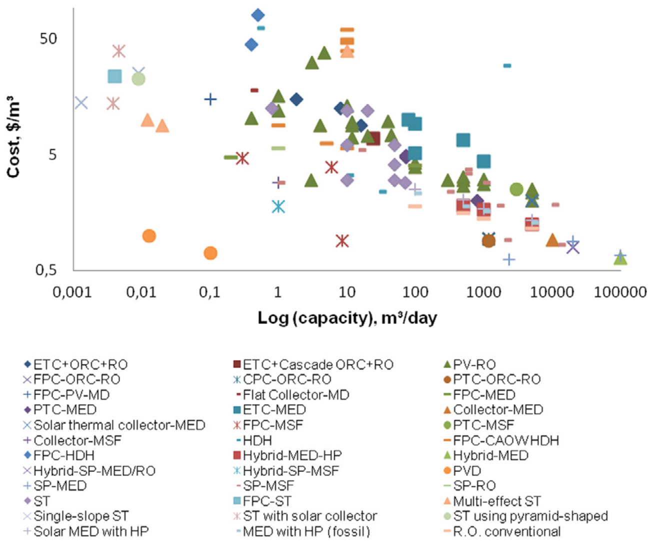

Fig. 2. Solar desalination capacities, RO and MED with heat pump. *Source:* [29,35].

Table 3. Water specific costs for different technologies [36,37].

Solar MD	$10,5/m^3 to $19,5/m^3
SGSP/RO	$0,66/m^3 to $0,77/m^3
Solar photovoltaic/ED	$10,4/m^3 to $11,7/m^3
Solar Pond	$1,3/m^3 to $6,5/m^3
Solar vacuum tube collector/MED	$2,4/m^3 to $2,8/m^3
Solar MEH	$2,6/m^3 to $6,5/m^3
SGSP/MED	$0,71/m^3 to $0,89/m^3
Solar photovoltaic/RO	$6,5/m^3 to $9,1/m^3

However, by working the MED with lower temperatures, its operation with salt gradient solar pond (SGSP) is relatively easier.

In a SGSP, the stored heat can be used in a closed cycle of Rankine directly attached to the high-pressure pump unit of RO [41], or use that cycle to produce electricity. Nevertheless, ponds are competitive with respect to conventional power plants when their surfaces are larger than 100 ha [42], Fig. 3, and they need large maintenance.

3. Material and methods

In general, the connection of an MSF plant to a solar thermal system, such as PTC, is basically the same as in a MED, with the particularities that MSF processes require precise control of the temperature and pressure at which they are operating, So a buffer system is essential to avoid possible variations in the temperature of the hot water entering the brine heater. One way to decrease your dependence on temperature variations and increase performance would be to design the MSF plant to operate within a wide temperature range.

The combination of solar and MED heating technologies, and among them multi-effect distillation-forward feed with heater (MED-FFH) and multi-effect distillation-parallel feed (MED-PF), has very promising applications due to its simplicity and viability. [43].

The "multi-effect stack" (MES), is stable operating between 0% and 100%, allowing flexibility that makes it the most appropriate for solar energy applications [44].

The operation of the double effect absorption heat pump (DEAHP) (with a gas boiler) together with the MED plant and the compound parabolic collector in the PSA (which constitutes the plant SOL-14) proved its feasibility and the highest performance that has been reached [45].

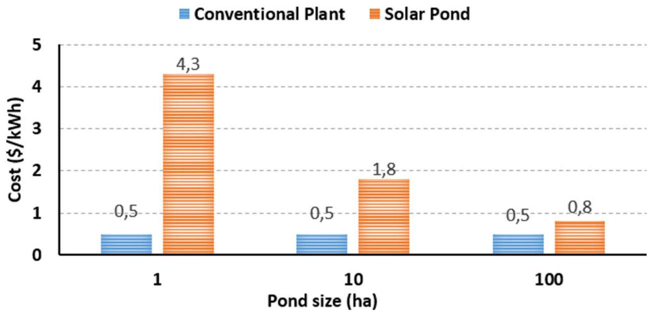

Fig. 3. Electricity production cost with a solar pond.
Source: [42].

An option to work with absorption heat pumps is the PTC. Considering that the current absorber pipes withstand pressures of around 100 bar, a feasible option would be to work directly with water instead of oil (in this way the solar thermal system could be thermal and economically enhanced) [46]. With a DEAHP operating at around 180 °C, the water pressure would be 10 bar and at 200 °C about 16 bar. With these working pressures, neither the absorbent pipes nor their seals will present sealing problems.

The competitiveness of direct vapor generation in MED plants located in the south of Spain mainly depends on the cost of both fossil fuels and solar collectors [47]. The discontinuity of RE hinders the operation of its operation [48]. Water storage is the most economical of all energy storage systems and is suitable for temperatures in the range of 50°C–95°C [49]. In a MED plant, there is also an increase in water production following the same conditions, since in both cases they are distillation processes in several effects or stages [50].

4. Proposal for optimization of MED–PTC

Shown in Fig. 4, This scheme is based on that of the SOL-14 plant, in which the DEAHP works with a gas boiler and its MED plant operates with acceptable values (a TBT of 66.5 °C and a PF of 10). The new design includes a water-mixer and a heat-exchanger, since the gas boiler has been replaced by a PTC field, with the PTCs themselves being used to operate the MED directly.

The PTC would provide hot water at 180 °C to the DEAHP in order to extract thermal energy from the distilled water of the last stage of the MED to heat water to 70 °C. Water, without DEAHP, could be able obtained at 70 °C by mixing the outlet water of the PTC (with a temperature greater than 70 °C) together with water from the tank secondary (which has a temperature below 70 °C). But with high temperature differences, between the water from the PTC and water from the secondary tank, it could be possible the case that the mixture was not uniform, and in theory, regions with higher temperature than the setpoint of 70 °C and others with temperatures below 70 °C could be found, which can cause damage to the plant and misleading the sensors that would control the temperature of the mixture. One way to avoid or at least reduce this problem would be to decrease the water temperature difference to be mixing, and this would be achieved by heating the water of the tank with part of the water of the PTC through an exchanger before mixing. On the other hand, the use of only the exchanger (without the mixer) to obtain the water at 70 °C would reduce the efficiency of the system due to the performance of the exchanger.

The main tank is connected to the MED and water is kept at a temperature of 70 °C. The secondary is used as storage and supply for PTC, DEAHP, low-temperature exchanger and mixer of water less than 70 °C.

4.1. Modeling

The determination of the PTC length is modeled from its energy balance (1) [52]:

$$L_c = \frac{\dot{m} \cdot (h_{180} - h_{80}) + A_e \cdot I_{dn} \cdot K_\theta \cdot \eta_{op}}{W_e \cdot I_{dn} \cdot K_\theta \cdot \eta_{op} - Q_{ca}} \quad (1)$$

For the DEAHP have been used the operating data obtained from [51].

It is assumed that the water tanks are circular, with the volume of water of the secondary tank of 90 m^3 and that of the main tank, 12 m^3. A pipe to prevent overflow connects the tanks [53].

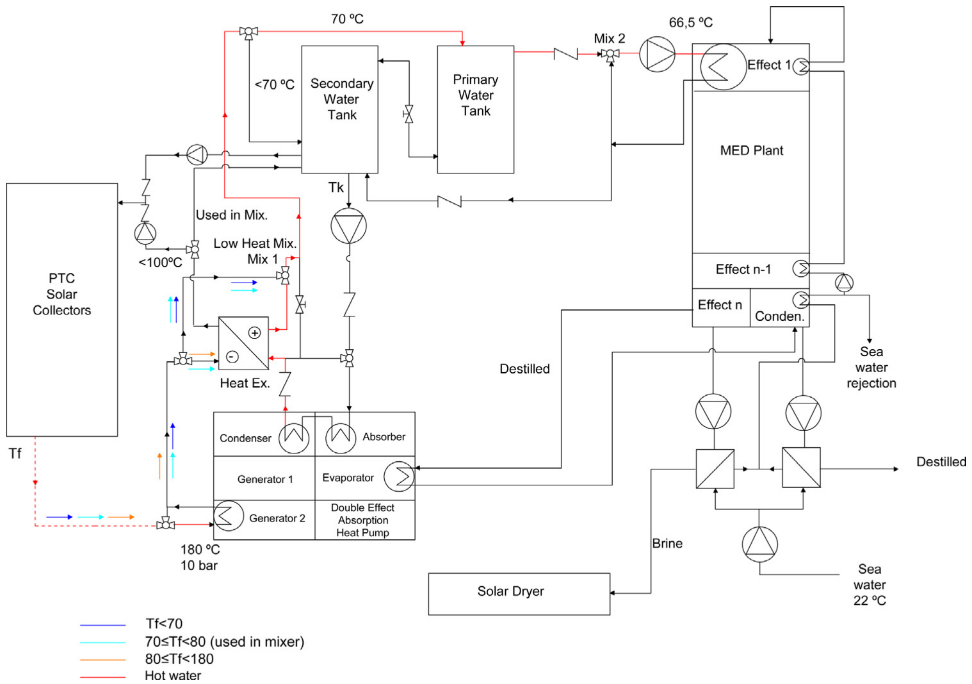

Fig. 4. Modified scheme, based on the plant SOL-14.
Source: Adapted from [51].

The input parameters in the model are:

- $\dot{m}_{ptc}$
- $\dot{m}_t$
- $\dot{m}_{T1}$
- $\dot{m}_{T2}$
- $\dot{m}_m$
- $\dot{m}_{12}$
- $\dot{m}_h$
- $\dot{m}_{ref}$
- TF
- Th
- T_m
- TM
- γ

The state variables are:

- $T1$
- $T2$
- $L1$
- $L2$
- TiM

Four equations of state that define the behavior of the system are proposed, which in turn will be used for the modeling of the tanks and their temperature:

- $\rho A \frac{dL_2}{dt} = \dot{m}_h + \dot{m}_{12} + \gamma \dot{m}_{ref} - \dot{m}_{ccp} - \dot{m}_t + \dot{m}_{T2} + \dot{m}_m$
- $\rho A L_2 C_p \frac{dT_2}{dt} = \dot{m}_h T_h C_p + \dot{m}_{12} C_p T_1 + \gamma \dot{m}_{ref} C_p T_M - \dot{m}_{ccp} C_p T_2 - \dot{m}_t C_p T_2 + \dot{m}_{T2} C_p T_2 + \dot{m}_m C_p T_m$
- $\rho A \frac{dL_1}{dt} = \dot{m}_h - \dot{m}_{12} - \gamma \dot{m}_{ref} + \dot{m}_{T1}$
- $\rho A L_1 C_p \frac{dT_1}{dt} = \dot{m}_h T_h C_p - \dot{m}_{12} C_p T_1 - \gamma \dot{m}_{ref} C_p T_1 + \dot{m}_{T1} C_p T_1$

The main function of the model is to verify that water can be used throughout the system as an energy transport fluid and that the operation of the MED plant can be extended with low solar radiation, not suitable for running the DEAHP. Keeping at all times the 66.5 °C required by the MED for its operation. For the simulation, the solar radiation in the PTC will be used as an input variable, which will be a sine wave signal between 0 W/m^2 and 800 W/m^2.

5. Results and discussion

The temperature of the PTC water outlet decreases as the radiation of the place is reduced. Particularly to the situation of the PSA, the coordinates 37º05’27.8” N and 2º21’19” W through [54], the direct, daily and monthly

Table 4. PF distribution depending on the direct global radiation on the horizontal surface. Source: Own elaboration.

PF												
Lat 37,091 Lon -2,355	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AVG-01	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
AVG -04	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
AVG -07	0,00	0,00	0,00	0,56	1,69	2,26	1,98	0,84	0,27	0,00	0,00	0,00
AVG -10	3,96	5,95	9,64	12,77	14,47	16,18	15,89	13,90	11,63	8,51	5,38	3,68
AVG -13	10,21	12,77	15,32	18,16	19,58	22,71	22,99	21,00	16,74	12,48	10,21	8,79
AVG -16	5,95	8,51	11,35	13,34	14,47	16,46	17,03	15,04	11,35	7,94	5,10	4,25
AVG -19	0,00	0,00	0,27	1,41	2,54	3,96	3,96	2,26	0,27	0,00	0,00	0,00
AVG -22	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

PTC+DEAHP+MED

PTC+MED

radiation, is known. With a PF greater than 10, see Table 4, the absorption heat pump will work (if it is smaller, only the MED plant will operate without the pump) [55].

This is the operating principle on which the model development has been based (a necessary resource, the PTC, has also been optimized with this other possibility, making it work to obtain water at a temperature of 70 °C), Fig. 5.

Simulation continues with the incorporation into the model of a high-temperature exchanger to obtain water at 70 °C, Fig. 6.

This modification allows increasing the operation time of the plant to its maximum PF, by taking advantage of the hours of low solar radiation and may, increasing the profitability and efficiency of the system. However, its operation and instrumentation are complicated.

The MED plant can only be started when the main tank water temperature reaches, in this case, 66.5 °C. Starting from a water temperature of the main tank of 22 ° C and solar radiation of 0 W/m2, the 66.5 °C is reached after about 4 h, as seen in Fig. 7 shows. When the radiation is high, the output temperature of the PTC reaches 180 °C and the DEAHP is started.

The storage temperature of the main tank should be slightly above the operating temperature of the MED plant so that the plant can be put into operation in a finite time, otherwise, in the case of small consumption, the water temperature would fall below 66.5 °C and the plant would stop.

The temperature of the storage water, in both the main and secondary tanks, depends mainly on the performance of the DEAHP. If we increase the water production of the DEAHP, in Fig. 8 is observed that as the MED and DEAHP start, the water temperature of the main tank rises abruptly, due to a larger volume of water at 70 °C produced by the DEAHP, which is transferred to the secondary tank to prevent overflow of the primary one. This increases the water temperature of the secondary tank. With a high DEAHP performance is had a greater energy storage capacity and a faster start of the MED plant.

Given the research on technologies in desalination, there is no doubt that there will be new proposals in the long term. Freeze desalination and direct osmosis may be technologies to be considered for a large-scale in the future. For direct osmosis, the yield is very small. A concentrated solution that generates a higher osmotic pressure is needed. The energy consumed in this step is very small (between 0.25 kWh/m^3 and 0.84 kWh/m^3 [56,57]), but today, a large amount of energy is required for the regeneration of the solution.

In terms of MSF processes, these are the majority compared to the MED processes, but the new materials, resistant to erosion and corrosion, are causing the MED processes to regain reliability against MSF, increasing the number of these processes facilities. If we analyze the distribution of desalination processes at the global level, distillation is the majority in countries where there is abundant residual energy (countries in the Middle East), so we can deduce as long as the energy production is with fossil fuels the RO process will have the lowest specific cost

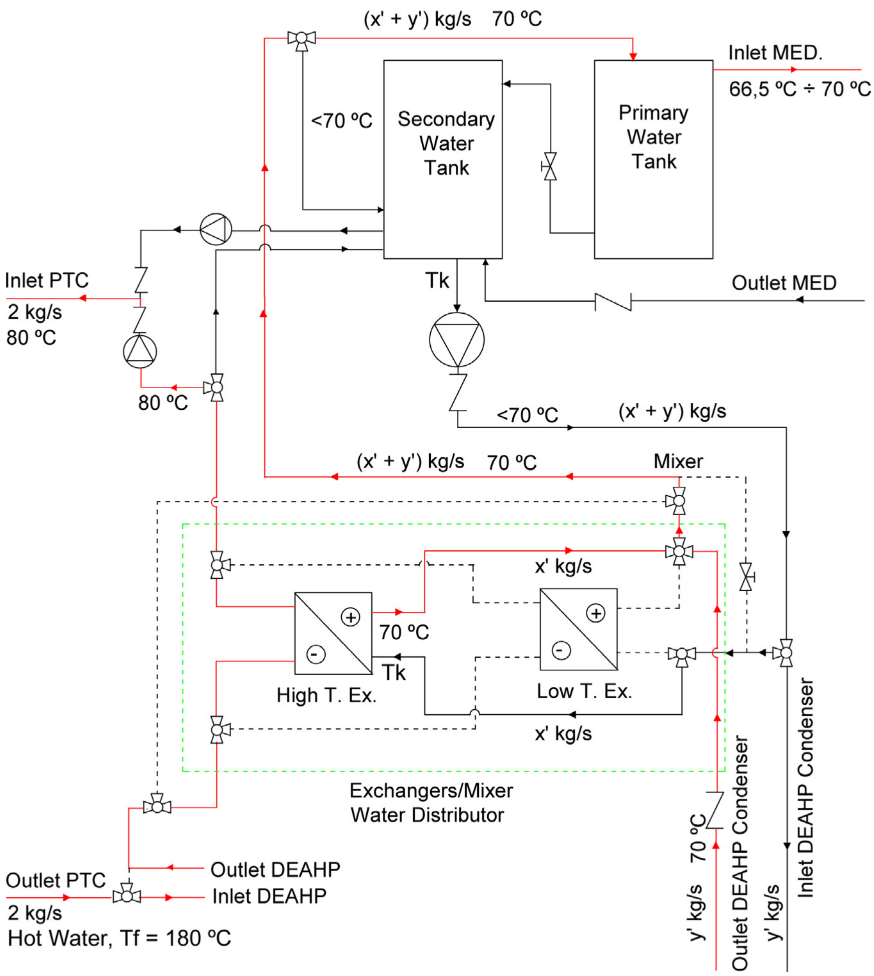

Fig. 5. Subsystem operation "Exchangers/mixer" with the DEAHP.
Source: Own elaboration.

of water. Only if residual energy is available, the distillation processes will be competitive. That is, with residual energy, the specific cost for distillation is cheaper than with RO.

There are many factors involved in the cost of producing potable water, and perhaps the most important, along with the cost of energy, is the cost of the installation itself. The number of large-scale desalination plants needed by countries is relatively small. If consumption in cities such as London is 158 l/hr/day or Madrid at 131 l/hr/day, large desalination plants supply or have the capacity to do it to a very important population. These industries capable of design and build such facilities are scarce, so that the internationalization of projects is essential to get competition to reduce prices. Definitely, governments with long experience in desalination will be able to obtain more economic facilities than others with less experience and contracts of the type build, own and operate (BOO) or build, own, operate and transfer (BOOT) allow them to face the cost of them.

By coupling desalination plants to RE facilities, the specific cost of water is released from the cost of the fossil fuel and depends mainly on the cost of the RE installation: RE is free. The cost of installing the renewable source is very important within the cost of the water and therefore must be carefully calculated to obtain the maximum yield. Energy consumption is important when it comes from fossil fuels but with REs energy consumption goes into the background, although the greater is the need for RE the greater is the cost of renewable facilities. The relationship between energy production and Cost of installation is not linear. Large RE installations have lower specific costs than small installations, so the specific cost of water from desalination plants will depend on the cost of installing RE rather than on energy consumption.

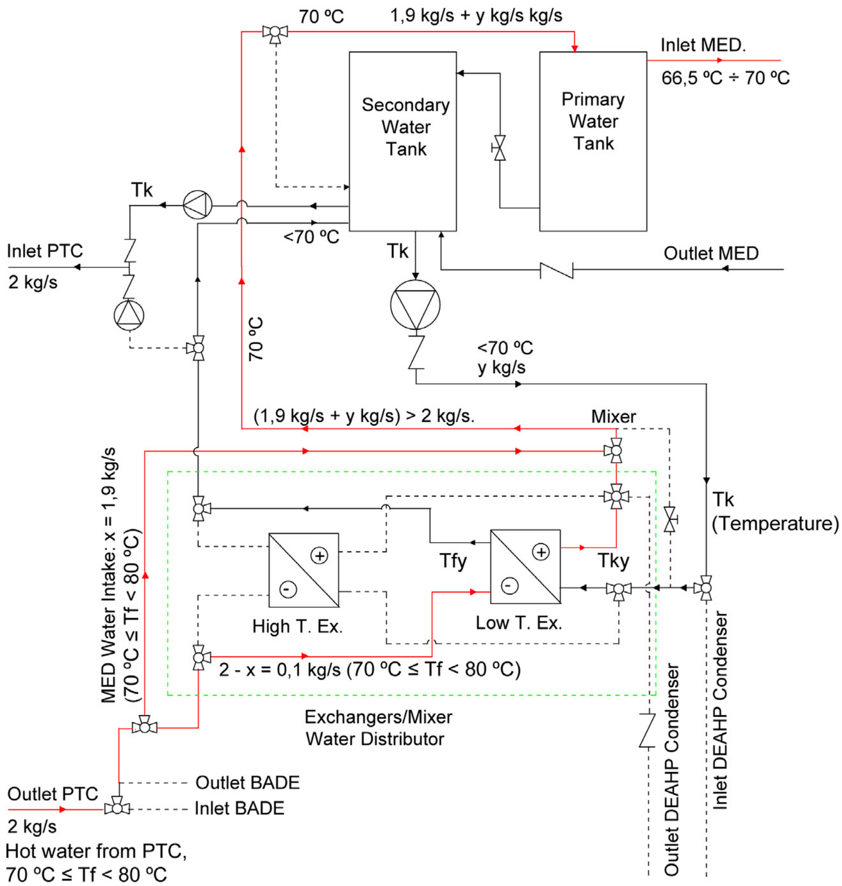

Fig. 6. Subsystem operation "Exchangers/mixer".
Source: Own elaboration.

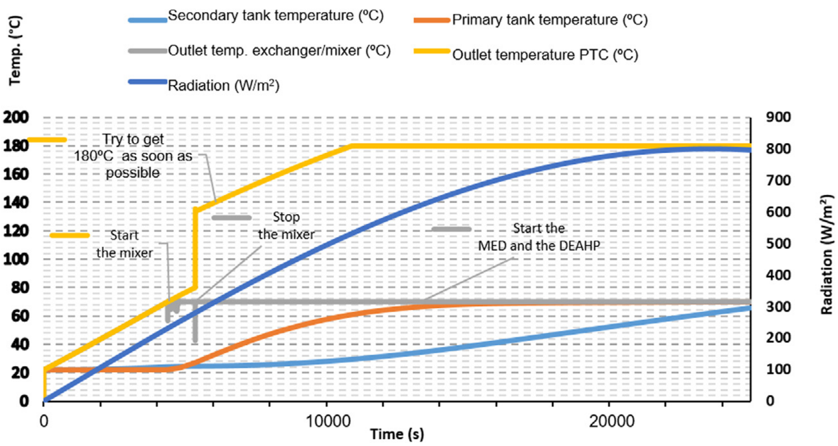

Fig. 7. Water temperature variations vs solar radiation.
Source: Own elaboration.

There are a large number of companies and factories dedicated to RE facilities globally, so that competition is increasing and the price of facilities will be decreasing. The desalination plant will depend on the installation of RE to which it is coupled. As the distillation plants will not depend on the residual energy to be competitive, it

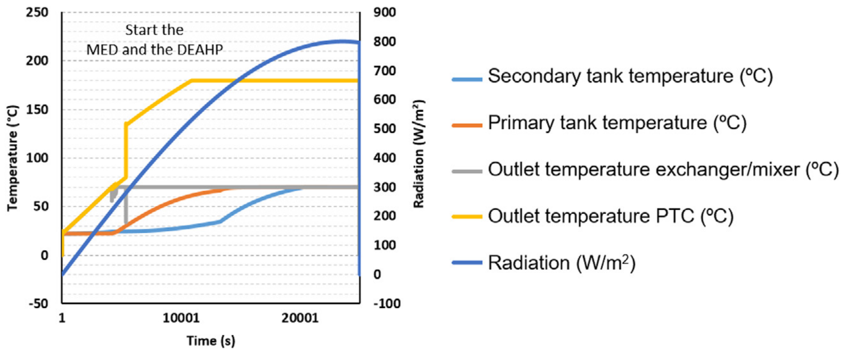

Fig. 8. Water temperature variations vs solar radiation Influence of DEAHP performance.
Source: Own elaboration.

will be essential to know the price of the RE installation to know, if the specific cost of water in a region will be cheaper with distillation and PTC or with RO and wind. Although SGSP appears as a great alternative to large-scale desalination, experience in large ponds has not continued.

The specialization of the facilities in large-scale desalination plants with REs is the next step that would have to be achieved about a greater reduction in the cost of water. The specialization can come both from the desalination plant, the PTC as from the wind turbines. In this work the PSA experience has been used with a MED process connected to a DEAHP, as it is a viable possibility for the large scale, besides being able to be connected to PTC with water as working thermal fluid. There are other configurations different from the one exposed in this work, but this is one of the most generalist so its results can serve as a base for future studies.

In the proposed installation, all the solar radiation that reaches the PTC is used. The PTC installation is calculated for an inlet temperature of 80 °C and an outlet h_{180} at 10 bar. One of the consequences of operating the low-temperature heat-exchanger together with the mixer is that the outlet temperature of the water heated to 70 °C in this heat-exchanger (from the secondary tank) depends on the initial temperature which will vary over time, and will depend on the solar radiation and consumption of the MED. If the consumption of the MED is small, more water at 70 °C is transferred to the secondary tank.

Of course, the part of the outlet water of the PTC used in the low-temperature heat-exchanger transfers thermal energy (to heat the cold water from the secondary tank) decreasing its temperature (below 70° C, at starting to work). Note that the recirculated water by the PTC has a temperature very close to 70 °C moments before the low and mixer exchanger starts operating.

If this outlet water (from the PTC used in the low temperature heat-exchanger) was recirculated through the PTC (together with water from the secondary tank to reach the flow rate used in the absorber pipe, 2 kg/s), the temperature of the incoming water to the PTC would be lower than the one previously (water of the secondary tank plus the portion coming from the PTC without going through the low temperature exchanger) and as a consequence the water outlet temperature in the PTC would drop below 70 °C (which is the minimum temperature at which the mixer and the low-range exchanger starting).

This would cause temperature oscillations in a range between 70 °C and slightly below 70 °C which would be dampening as the water temperature of the secondary tank increasing. At the end, there would come a time when there would be at the outlet of the absorber pipe, water with a minimum temperature of 70 °C and the oscillations would disappear. In order to avoid these oscillations when the mixer is used, the part of the water of the PTC used to heat the water in the low temperature heat-exchanger is not recirculated through the PTC but is sent directly to the secondary tank. That is, at the PTC inlet only water from the secondary tank is used, which has a steadily rising temperature, without oscillations, mainly due to the thermal inertia of the volume of water it contains. However, the same problem of oscillations could occur if the water temperature of the secondary tank were not uniform (due to the effects of stratification or interior regions with different temperatures). It should be added that constant recirculation of the hot water through the PTC has as main advantage that the setpoint temperature at the outlet of the absorber pipe is reached in a shorter time, allowing the MED to be started before. The validation of the model with real data will indicate the importance of these oscillations.

It is also observed in Fig. 7 that the mixer does not reach the setpoint temperature of 70 °C immediately, but after a few minutes. A three-way valve will send the water to the primary (70 °C) or secondary (< 70 °C) tank.

In the thermosolar industry with PTC usually a thermal gap of 100 °C is used. Using the same thermal gap, when the PTC output temperature reaches 80 °C, the water is recirculated back to the PTC to obtain the 180 °C needed by the DEAHP, for working as quickly as possible with the PF higher. The DEAHP gets the heat from the distillate and sends it to the first effect (primary tank) so it does not make sense to start it until the MED is started. The MED will not start until at least the temperature in the primary tank is 66.5 °C.

The volumes of water in the tanks must be balanced in relation to the installation of PTC. As water enters 70 °C in the primary tank and reaches the maximum level of the tank, the same flow of incoming water has to exit to the secondary tank. The consequence is that the water of the secondary tank will increase its temperature, being possible to have in the two tanks, primary and secondary, water at a temperature of 70 °C.

If the water temperature in the secondary tank is close to 70 °C, in order to take advantage of the heat of the water of the PTC, the water flow from the secondary tank would be very important in the high temperature exchanger. This explains because the energy needed to heat the water of the tank to 70 °C would be very small and therefore for a use of solar thermal energy, the water flow of the secondary tank should increase. This flow may be impracticable due to the physical dimensions of the exchanger and the connecting pipes. In that case it would not be taking advantage of solar radiation. The system should stop because the consequence would be an increase in the temperature of the water being stored above 70 °C, which could lead to a malfunction of the MED.

If molten salts were used instead of water for the storage of thermal energy from the water of the PTC, the water temperature should be between 290 °C and 390 °C. Given the characteristics of the Eurotrough PTC and the absorber pipe (eg the Schott PTR 70), there would be no problem, but to produce water at 290 °C, with medium and low solar radiation, would require a very important oversizing of the installation of PTC, and there will be an underutilization of medium and low solar radiation. Then, the use of the maximum range of solar radiation (high, medium and low radiations) occurs when the temperature of the outlet water of the PTC is as close as possible to the final working temperature of the equipment (in this case, around 70 °C). Or put another way, the longer you are taking advantage of solar radiation, the more energy you get.

When solar radiation permits, water must be produced at 180 °C to operate the DEAHP and when the solar radiation is medium or low, the water from the PTC should be used for obtaining water at 70 °C. With a low storage temperature of 70 °C, the thermal storage by water is the most suitable, Table 5.

There are several parameters to consider when designing a system as described, but it is of special importance the sizing of the PTC, the exchanger system with the mixer and the volume of the water tanks. Considering that the low and medium radiations are going to be the predominant ones, it will be necessary to study, mainly, the dimensioning of the PTC and the volume of the water tanks, since they have a direct influence on the thermal inertia of the system, that is, on its start-up.

The size of the reservoirs is a major problem in this type of facility, given the inertia of the water to increase its temperature or lower it. In Figs. 7 and 8, it is observed how the temperature of the main tank increases until reaching 66.5 °C. If this deposit were smaller, the temperature would be reached earlier, but the hot water reserves between 66.5 °C and 70 °C would be low (in the main tank) and the desalination plant could be affected in prolonged periods of low radiation, producing prolonged inactivity intervals and an impact on the water supply. If the principal tank is very large it would not reach the temperature of 66.5 °C in the whole day and the desalination plant would not be started or, in the best case, the start of the MED plant would be very slow, starting when solar radiation was very high, which could also affect with long periods of inactivity. The heat-exchanger with the mixer is the one that makes it possible for the PTC, DEAHP and MED to operate without the need to insulate them by means of heat-exchangers.

If the main tank is properly calculated the start of the MED would be relatively fast and its downtimes could be reduced to a minimum. The secondary tank will increase its temperature appreciably in function of its volume. In a very large secondary tank the stored water would not exceed 66.5 °C and would not serve as a heat store for the MED when the main tank temperature was below 66.5 °C. The secondary tank should be just the right size so that the daily solar radiations allow reaching a water temperature around 70 °C and be useful as a heat store.

In general, thermal inertia can be low. Its starting could be achieved quickly, and even, depending on the size of the tanks, it could be stored hot water at 70 °C for MED plant operation during several days

It should be noted that the absorption pumps operate under special conditions of pressure and temperature, so that the absorber pipe and the water circuit that feeds the absorption pump must be maintained under a certain pressure.

Table 5. Materials and technology applications in desalination and power industries.
Source: [58–63].

Technology	Molten salt	Concrete	Phase change material	Water/steam	Hot water
Capacity range (MWh)	500–3000	1–3000	1–3000	1–2000	1–3000
Annual efficiency	98%	98%	98%	90%	98%
Heat transfer fluid	Oil	Oil, water/steam	Water/steam	Water/steam	Water
Temperature range (°C)	290–390	200–500	Mayor de 350	Mayor de 550	50–95
Investment cost ($/kWh)	40–60	30–40	40–50	180	2–5
Advantages	High storage capacity at relatively low cost Experience in industrial	Experience in industrial Well suited for preheating and super-heating	Latent heat storage allows for constant temperature	Latent heat storage allows for constant temperature	Very low-cost storage for processes heat below 100 °C
Disadvantages	Danger of solidification Molten salt freezes at 230 °C	Recent development	Very early-stage development	Not suitable for preheating and superheating	Sensible heat storage requires temperature drop at heat transfer
Applications	MSF, MED, MVC y RO	MSF, MED, MVC y RO	MSF, MED, MVC y RO	Large scale applications District heating and cooling	Low-temperature desalination processes

In the case of the DEAHP of the SOL-14 is 10 bar. It is a low pressure that can be reached with the pumps of impulsion joint to pumps of pressure. Keep in mind that by means of frequency inverters a greater efficiency of the electric motors is obtained allowing a precise control of the pressure in the system.

The heat-exchanger with the mixer is the one that makes it possible for the PTC, DEAHP and MED to operate without the need to insulate them by means of heat-exchangers. Indicate that in order to maintain the quality of the water (which is used as thermal fluid) and reduce maintenance costs, proper sealing of pipes and tanks must be provided. If heat-exchangers were interposed to separate the PTC, DEAHP and MED systems, the surface of these exchangers would have to be large (as the storage temperature of the water must be close to that used by MED), and therefore with an expensive investment and maintenance cost. Eliminating them reduces costs and losses that would occur in them.

There are experiences on desalination with PTC, proving to be a system with high reliability, but to date has not been achieved continuous operation, so would be to venture to say that a system as this could do so. Its empirical development is key to obtain data on the same and to verify the viability of its continuous operation.

6. Conclusions

The adaptation of RE generation technology to the thermal processes analyzed, intensive in energy consumption, is a prerequisite for the choice of desalination system. In this sense, solar thermal energy through the PTC is ideal for distillation processes, as is wind energy for IO. However, the different installations carried out do not indicate that there is a completely satisfactory link between desalination and RE, because, in most cases, it is not continuous. The adaptation of existing desalination to a technology based on RE has not reduced costs below those of desalination with fossil fuels. One of the RE desalination systems with the best results has been the one developed by the PSA with the desalination of a MED plant and a DEAHP. However, in the proposed system, the PTC performs the relatively high-temperature water supply (required by the DEAHP). In the facility proposed in the research here presented, all the solar radiation that reaches the PTC is used. The PTC installation is calculated for an inlet temperature of 80 °C and an outlet h_{180} at 10 bar. One of the consequences of operating the low-temperature heat-exchanger together with the mixer is that the outlet temperature of the water heated to 70 °C in this heat-exchanger (from the secondary tank) depends on the initial temperature which will vary over time and will depend on the solar radiation and consumption of the MED. If the consumption of the MED is small, more water at 70 °C is transferred to the secondary tank. This would cause temperature oscillations in a range between 70 °C and slightly below 70 °C, which would be dampening as the water temperature of the secondary tank increasing. In the end, there would come a time when there would be at the outlet of the absorber pipe, water with a minimum temperature of 70 °C and the oscillations would disappear. To avoid these oscillations when the mixer is used, the part of the water of the PTC used to heat the water in the low-temperature heat-exchanger is not recirculated through the PTC but is sent directly to the secondary tank. In any case, it has been proved that with some solar resources conditions, the RE powered system proposed in this research might reduce the downtime of the desalination plants.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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