Increasing the storage capacity of a solar pond by using solar thermal collectors: Heat extraction and heat supply processes using in-pond heat exchangers

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Abstract

In this study, an experimental investigation of the performance of a salinity gradient solar pond (SGSP) integrating solar collectors is presented. The SGSP is located in Barcelona (Spain) and has a cylindrical tank 3 m in height and 8 m in diameter with a total area of 50 m^2. For this purpose, four solar thermal collectors (10 m^2) are integrated, as an external source of heat, with the solar pond pilot plant in order to increase the storage capacity and its overall efficiency. The aim of this study is to evaluate heat extraction and heat supply processes from and to the SGSP under different seasonal conditions. Two in-pond heat exchangers are used, a conventional one situated on the bottom of the pond and a second one covering the lateral wall area of the pond.

Heat extraction and supply experiments are performed using both heat exchangers individually or both at the same time. The experiments are conducted under two different seasonal temperature conditions: winter (February and March) and summer (July). The variations of the temperature inside the pond during the heat extraction/supply tests are monitored and analyzed. The results have indicated that the use of solar collectors as an extra source of heat for the solar pond led to a 50% increase in the daily efficiency during the cold season tests, while heat extraction only appeared as the best option during the warm season tests. Higher daily efficiency and heat supply results can only be obtained if large amounts of heat are extracted, otherwise, the daily efficiency of the solar pond could decrease. Finally, the solar collectors can be considered a good alternative for avoiding a significant decrease in solar pond temperatures (especially during the cold season), which would not only result in a significant energy storage efficiency improvement but also increase the capacity of the solar pond to supply heat to an external application.

Keywords: salinity gradient solar pond; energy storage; pilot plant; solar radiation; solar collectors; heat extraction/ supply; efficiency

Nomenclature

Acronyms	
SGSP	Salinity Gradient Solar Pond
UCZ	Upper Convective Zone
NCZ	Non-Convective Zone
LCZ	Low Convective Zone
LHS	Lateral Heat Supply
BHS	Bottom Heat Supply
LHE	Lateral Heat Extraction
BHE	bottom Heat Extraction
General signs	

T	Temperature
Q	Heat
A	Area
H	Radiation
ΔE	Energy change
$\dot{m}$	Mass flow rate
Subscripts	
SC	Solar collectors
SP	Solar pond
$stored$	Stored in the system
ext	Extracted from the system
sup	Supplied to the system
$balance$	Variables measured by the sensors
$bottom$	Variable referred to the bottom heat exchanger
$lateral$	Variable referred to the lateral heat exchanger
in	Input water flow to the heat exchanger
out	Output water flow from the heat exchanger
Greek Characters	
Δ	Increment
η	Efficiency
τ	Time period
τ	Daily

1. Introduction

Heat storage technologies, systems, and applications are currently of great interest in the field of solar energy (Dincer, 1999; 2002) due to environmental awareness of climate change and the need to minimize the dependence on non-renewable fuels (Bozkurt and Karakilcik, 2012). Solar ponds and collectors are very important solar energy systems that generate heat energy from solar energy. A salinity gradient solar pond (SGSP) is a body of water that typically has three main regions (from top to bottom) (Tabor and Weinberger, 1981; Zangrando, 1980): the upper convective zone (UCZ), the non-convective zone (NCZ), and the lower convective zone (LCZ). The UCZ is a homogeneous area formed by low salinity water. Below it, there is an intermediate zone consisting in a thermally insulating layer that contains several layers of different density such that the layers near the bottom area are more saline than those near the surface zone. This salinity gradient prevents the occurrence of convection currents and, as a result of solar energy absorption, a gradient of temperature is also established. This NCZ is the key feature of the solar pond technology. The LCZ is a homogeneous area with the highest salinity: near to saturation. In this zone, solar energy is absorbed and stored.

Solar ponds have been investigated during the last five decades and research efforts have been directed to improve their efficiency (Akbarzadeh et al., 2009; Andrews and Akbarzadeh, 2005; Bozkurt and Karakilcik, 2012; Ganguly et al., 2017; Kumar and Rosen, 2011; Leblanc et al., 2011; Yaakob et al., 2011). Recently, it has been proposed to extract the absorbed solar energy by simultaneously extracting heat from the LCZ and NCZ to increase the efficiency of the solar pond (Alcaraz et al., 2016; Andrews and Akbarzadeh, 2005; Date et al., 2013; Leblanc et al., 2011; Yaakob et al., 2011). It has been demonstrated that heat extraction from the NCZ improves the overall efficiency of the solar pond compared to conventional heat extraction from the LCZ. The main advantage of solar ponds is their long-term thermal energy storage capability, which can supply sufficient heat along the entire year. The idea of using solar ponds as a thermal energy storage system has been proposed in recent years (Singh et al., 2015, 2012). However, few studies have been devoted to increasing the solar pond performance by coupling solar pond technology with any external source of heat. Also limited studies have reported the integration of a solar pond with solar collectors, i.e., Bozkurt and Karakilcik (2012) evaluated the integration of a cylindrical solar pond with a radius of 0.8 m and a depth of 2 m and solar collectors. The system energy balance analysis concluded that energy efficiency was slightly higher when the solar collectors are used, moreover allowed storing more thermal energy in the LCZ and the performance of the integrated solar pond depended upon the total radiation reaching its zones and collector's surface.

Ganguly et al., (2017, 208) also studied the addition of heat from an external source by using Evacuated Tube Solar Collector (ETSC). The addition of external heat proved to enhance both the heat extraction and thermal efficiency of a solar pond but with certain constraints, e.g., it is necessary to prevent the heat loss from the LCZ by extracting more heat from the LCZ. In our previous studies, the solar pond pilot plant construction, the establishment of the salinity gradient and a numerical model based on the energy balance of the solar pond have been reported (Bernad et al., 2013; Valderrama et al., 2011). The evaluation of an alternative system of heat extraction to enhance the thermal efficiency of the system has recently been proposed, with this purpose, an in-pond heat exchanger covering the pond wall (NCZ & LCZ) has been used and compared with the traditional heat-extraction method using an in-pond heat exchanger placed at the bottom of the pond (Alcaraz et al., 2016). In view of state of the art and taking into account our preliminary knowledge, it is proposed to experimentally evaluate the solar pond pilot plant storage capacity by integrating an external source of heat and to analyze its impact on the energy efficiency of the system.

The aim of this study is to increase the solar pond performance of a 50-m^2 pilot plant by using an external source of heat (10-m^2 of solar collectors) in order to benefit from the storage capacity of the solar pond technology. Energy obtained from the solar collector is transferred to the solar pond through two in-pond heat exchanger systems that are placed in LCZ, bottom of the pond, and lateral wall of the pond (NCZ&LCZ). Heat extraction and heat supply experiments have been carried out using both heat exchangers on a single or coupled basis. The study covers the experiments performed under two different temperature conditions: cold season (February and

March) and warm season (July). The variations of the temperature inside the pond during the heat extraction/supply tests have been monitored and analyzed in order to determine the solar pond's performance by estimating the overall system energy efficiency.

2. Materials and methods

2.1 Solar pond description

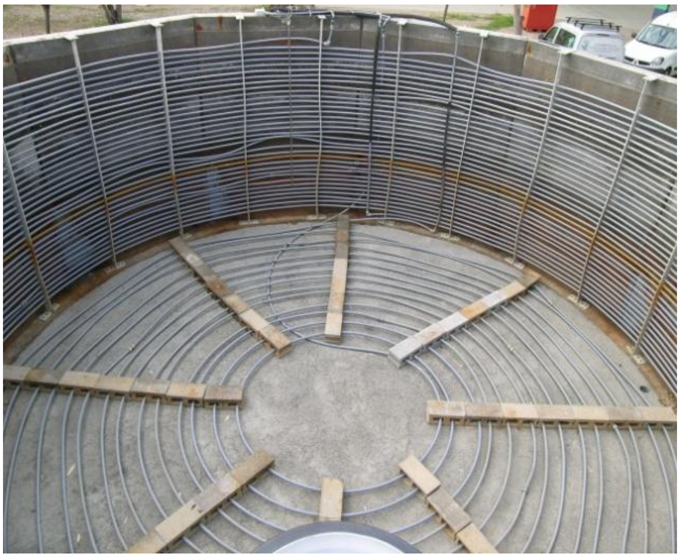
The solar pond pilot plant located in Martorell (Barcelona, Spain) has been described previously. The solar pond has a surface area of 50 m^2 and a depth of 3 m and the level of the water in the pond has been fixed at 2.6 m by using an overflow system. The heights of the LCZ, NCZ and UCZ are approximately 0.55, 1.35 and 0.70 m, respectively. The storage zone contains about 25% of saturated brine by weight. The UCZ concentration is 1–3 % wt. of salt. The temperature measurements, at different solar pond heights, have been performed by means of 21 sensors (thermoresistances PT-100-K type, Abco, Spain) distributed at intervals of 14 cm (starting at 0.5 from the bottom) and installed in a plastic support fixed to the pond wall. The solar radiation intensity (MJ/m^2) incident on the horizontal surface has been measured at intervals of 10 s; the hourly average has been recorded as well as the daily average by using a pyranometer Apogee SP-110 silicon photocell with an uncertainty of ± 5%. The lateral pond wall has been insulated with 60 mm of rock wool and then covered with 0.8 mm of smooth aluminum plates. The pond bottom area has been insulated with 40 mm of polystyrene and then covered with a concrete slab with a thickness of 150 mm. Details of the solar pond construction, monitoring and gradient settling can be found in Valderrama et al., (2011); Bernard et al., (2013); Alcaraz et al., (2016). A view of the experimental solar pond in Martorell including the solar collectors and the cooler system used in heat extraction experiments is shown in Figure 1.

Figure 1. Solar pond pilot plant in Martorell: a) the solar thermal collectors used in the heat supply experiments and b) cooler system used in the heat extraction test.

2.2 Heat extraction system

The heat extraction system has been described in previous work. “The system is composed of a cooler system (HRS024-AF-20 2.1 kW SMC) and two in-pond heat exchangers, one located at the LCZ and the other located at the wall lateral area of the pond from 0.1 to 2.7 m above the bottom.

a



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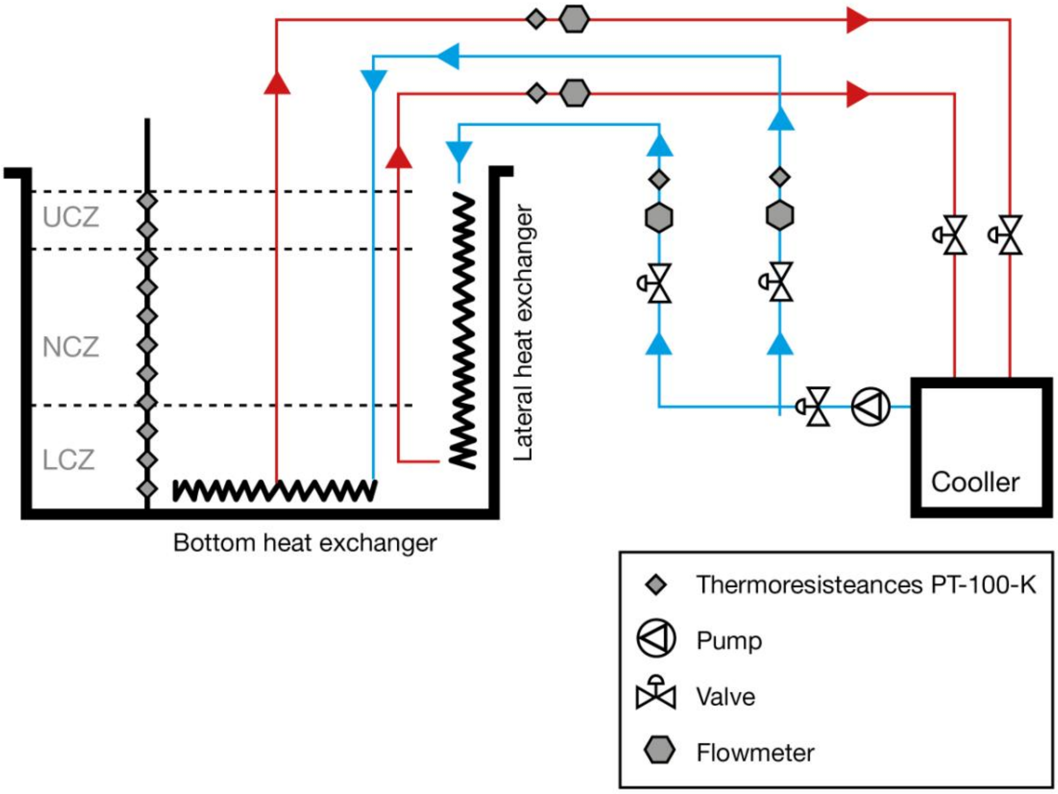

Figure 2. Experimental set-up describing: a) Installed heat exchangers in the Martorell solar pond pilot plant and b) scheme of heat extraction using the lateral and bottom heat exchangers.

Both heat exchangers are made of polybutylene pipe, with an internal diameter of 26 mm, an external diameter of 30 mm, and a thermal conductivity of approximately 0.22 W/m K. The bottom and lateral heat exchangers are 250 m and 730 m in length, respectively.

The cooler unit is an air-cooled system formed by two circuits: the working fluid circuit and the refrigerant circuit. The working fluid, water in this case, runs through the circuit, removing the heat from the solar pond". Details of the heat extraction experiments can be found elsewhere (Alcaraz et al., 2016). A scheme of the heat extraction system is shown in Figure 2.

2.2 Heat supply system using solar collectors

The heat supply system is composed of the same circuit of both heat exchangers located at the bottom and in the lateral area of the solar pond. In this case, solar collectors are installed in order to study the performance of the integrated system. This system consists of four solar thermal collectors of 2.4 m^2 each. The solar collectors have been oriented directly toward the equator, facing south, while the tilt angle of the collector has been adjusted to the latitude of the Solvay facilities (41°S). The solar collectors have been connected to the heat exchangers by using PVC pipes, and all external pipes have been thermally insulated with neoprene. A scheme of the heat extraction system is shown in Figure 3.

As in the heat extraction system, the heat is supplied to a specific area of the solar pond depending on the heat exchanger used (bottom or lateral). A temperature sensor (PT100) and a flow meter (SMC) located in the inlet and outlet pipes have been employed to measure the flow rate and the temperature of the working fluid for each heat exchanger. For the operation of the heat supply system, two temperature sensors (Pt1000) have been installed. One of them is located at the top of the LCZ (0.5 m from the bottom of the pond approximately), where the maximum temperature of the system is reached. A second sensor is installed at the exit of the solar collectors' pipe.

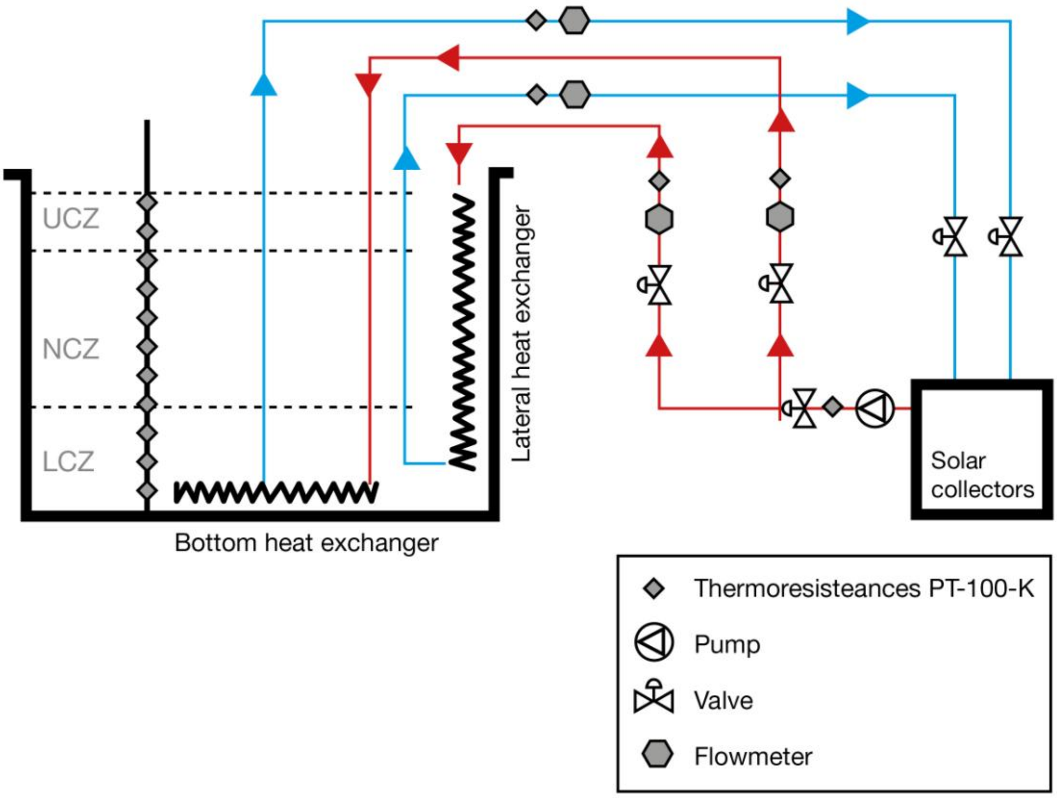

Figure 3. Solar collectors' heat supply to the solar pond in Martorell using lateral heat exchanger and bottom heat exchanger.

When the system supplies heat to the LCZ, the hot water is pumped from the solar collectors to the heat exchanger located in the bottom area of the pond. The working fluid transfers the energy to the storage zone and then returns at a temperature near to the temperature of LCZ, to be heated by the solar thermal collectors (Figure 3). When the heat is supplied to the lateral area, the hot water is pumped from the solar collectors to the lateral heat exchanger. The hot water flows through the pipe from the top to the bottom of the pond along the lateral heat exchanger, transferring the heat through the NCZ and the LCZ and then exiting the pond to the solar collectors at a temperature approaching the temperature of the storage zone (Figure 3). The water, after being heated, is then pumped back to the pond to start a new cycle. The cycle continues as long as the temperature difference between the two sensors remains above 15 ºC.

The heat supply circuit operates under manual control. To operate in "heat supply" mode, the valves must be opened (Figure 3) and the pump that drives the working fluid, turns on when the difference between the two sensors is 15 º C. The first sensor measures the water temperature in the solar collectors and the second sensor measures the temperature at the LCZ, the highest temperature in the pond. The heat will only be provided when this difference is above 15º to ensure that heat is supplied to the solar pond. The heat supply stops when the temperature difference is less than 15ºC. When the heat supply is carried out using the lateral heat exchanger, the system is activated and deactivated in the same way, temperature difference between the fluid of the solar collectors and the higher temperature in the solar pond (LCZ).

The total uncertainty in temperature measurements have been estimated by combining the sensor accuracy and measuring instrument accuracy using the root-sum-of squares method as has been described in previous study (Valderrama et al., 2011).

The aim of the study is to evaluate the influence of weather conditions on the heat supply and heat extraction experiments and to measure data in two different seasons of the year covering a range of ambient air temperature from 10 to 30 °C.

3. Estimation of the solar pond efficiency

Solar radiation goes through the different zones of the solar pond, increasing the temperature and resulting in energy being stored at each point of the system. Initially, solar radiation reaches the pond surface region. Part of this energy is lost as radiation is reflected into the atmosphere, another part is stored in this pond surface area, increasing the temperature of the entire zone, and the rest is transmitted towards the gradient area. In the NCZ, part of the solar radiation is absorbed and stored. So, the NCZ temperature increases in each layer of the salinity gradient, leading to the establishment of a thermal gradient. The rest of the solar radiation is transmitted to the LCZ where most of this energy is absorbed and stored as thermal energy. For that reason, the T_{LCZ} is increased, reaching the highest value of the system. Different studies have defined the efficiency of a solar pond from the standpoint of thermal energy stored in the system relative to the radiation incident on the pond (Bozkurt and Karakilcik, 2015a; Dehghan et al., 2013; Karakilcik et al., 2006). On the contrary, other studies have focused on defining the efficiency of the solar pond as the ratio between the extracted energy and the incident radiation (Andrews and Akbarzadeh, 2005; Leblanc et al., 2011). In both cases, the system performance is underestimated. A system that is capable of collecting solar radiation and storing it as heat (Hull et al., 1989; Tabor and Weinberger, 1981) to be supplied afterward to an external application is the most common description of a solar pond. Additionally, the potential of the solar pond may increase when a secondary heat supply system is introduced.

In this direction, this work analyses the impact of introducing solar collectors, as a secondary source of heat, on the efficiency of the solar pond. It is worth mentioning that some studies have assessed the effect of solar collectors on the efficiency of solar ponds (Ganguly et al., 2017). Both heat extraction and heat supply are carried out considering the needs and conditions of the secondary heat supply, the solar pond and the heat demand systems. Hence, these activities would only be considered in energy efficiency calculation if they take place in the period under analysis.

Bozkurt et al., (2014) and Bozkurt and Karakilcik, (2015b, 2012) have defined the heat stored as the heat gain by the solar collectors and the heat entering and absorbed by the solar pond from the solar radiation. Date et al., (2013) have proposed the "instantaneous efficiency" concept as the ratio of the instantaneous change in the energy content of the LCZ to the daily incident average solar radiation when heat is extracted from LCZ and NCZ simultaneously. In this case, daily incident average solar radiation would be the radiation incident on the top surface of the pond and on the solar collectors when the heat supply system is operating; and only the solar radiation incident on the pond when no heat is provided by the solar collectors. In this experimental solar pond, thanks to the isolation installed in the bottom of the pond and considering previous experiments carried out in the system and described by (Alcaraz et al., 2016), the energy change due to ground losses may be neglected.

Date et al., (2013) reported that the NCZ has a large potential to store heat and provide it to an external application as it has been recently demonstrated by Alcaraz et al., (2016) using the solar pond pilot plant. Therefore, this work suggests that both the LCZ and the NCZ can be useful for the heat extraction processes; consequently, the daily change in the energy content of NCZ is also considered as an input parameter. The daily efficiency of the solar pond is determined according to Equation (1):

$$\eta_{daily_{SP}} = \frac{\Delta E_{LCZ}^{\tau} + \Delta E_{NCZ}^{\tau}}{A_{SC} \cdot H_{SC}^{\tau} + A_{sp}\, H^{\tau}} \tag{1}$$

where ΔE_{LCZ}^{τ} and ΔE_{NCZ}^{τ} are the daily energy change (MJ) in the LCZ and NCZ, respectively, during the analyzed day. In the LCZ, the temperature and density can be assumed to be constant along the whole zone, whereas in the NCZ, both temperature and density take significantly different values from the top to the bottom. Thus, ΔE_{LCZ}^{τ} is the result of the daily energy change obtained using the average temperature of the zone and ΔE_{NCZ}^{τ} is the result of analyzing the daily energy change in 11 different sub-layers. A_{sp} and A_{SC} are the surface area (m^2) of the solar pond and the solar collectors, respectively. H^{τ} and H_{SC}^{τ} are the daily average solar incident radiation on the solar pond surface and on the solar collectors, respectively (MJ/m^2).

4. Results and discussion

Three different sets of experiments have been carried out in the solar pond of Martorell during February, March, and July 2014 (Table 1). Firstly, the Lateral Heat Supply (LHS) through the lateral heat exchanger, the Bottom Heat Supply (BHS) through the bottom heat exchanger, and the simultaneous heat supply to the bottom and lateral areas (LHS & BHS) using both heat exchangers have been tested.

Table 1. Details of the heat supply/extraction experiments including the main parameters monitored for each experiment.

Heat supply using solar collectors												
February and March 2014	**Bottom**			**Lateral**								
	$\dot{m}$ (kg/min)	**T_{in}** (°C)	**T_{out}** (°C)	$\dot{m}$ (kg/min)	**T_{in}** (°C)	**T_{out}** (°C)	**Q_{ext}** (MJ)	**Q_{sup}** (MJ)	**T_{LCZ}** (°C)	**ΔT_{bottom}**	**$\Delta T_{lateral}$**	**η** (%)
BHS (07/02/2014)	0.83	60.4	21.8	-	-	-	-	34.0	24.15	-	38.61	52
BHS (14/02/2014)	0.82	49.4	21.9	-	-	-	-	14.3	25.2	-	27.5	35
BHS (10/03/2014)	2.35	51.4	27.6	-	-	-	-	81.0	29.2	23.8	-	13
LHS (11/03/2014)	-	-	-	2.30	47.3	27.0	-	66.2	29.6	-	20.3	9
BHS & LHS (17/03/2014)	0.94	54.7	30.2	0.97	54.7	30.2	-	82.1	34.4	24.4	24.5	18
Heat extraction and heat supply using solar collectors												
July 2014	**Bottom**			**Lateral**								
	$\dot{m}$ (kg/min)	**T_{in}** (°C)	**T_{out}** (°C)	$\dot{m}$(kg/min)	**T_{in}** (°C)	**T_{out}** (°C)	**Q_{ext}** (MJ)	**Q_{sup}** (MJ)	**T_{LCZ}** (°C)	**ΔT_{bottom}**	**$\Delta T_{lateral}$**	**η** (%)
BHS & LHE (24/07/2014)	3.75	76.0	55.0	0.75	24.7	51.3	24.5	95.8	58.0	21.0	26.6	8
LHE (25/07/2014)	-	-	-	0.70	20.7	50.3	29.8	-	57.8	-	29.6	11
LHS & BHE (26/07/2014)	0.78	24.1	51.5	2.78	71.1	53.9	31.2	83.6	57.7	27.4	17.2	18
BHE (27/07/2014)	0.76	23.48	49.46	-	-	-	29	-	56.65	25.98	-	22
Daily heat supply using solar collectors and heat extraction during night hours												
Feb 2014	**Heat extraction**			**Heat supplied**								

	$\dot{m}$ (kg/min)	T_{in} (°C)	T_{out} (°C)	$\dot{m}$ (kg/min)	T_{in} (°C)	T_{out} (°C)	Q_{ext} (MJ)	Q_{sup} (MJ)	T_{LCZ} (°C)	ΔT_{bottom} extraction	ΔT_{bottom} Supplied	η (%)
LHS & BHE (03/02/2014)	0.96	4.10	12.20	0.80	46.22	18.65	0.65	13.59	22.86	8.10	27.57	5
LHS & BHE (04/02/2014)	0.81	4.68	13.9	0.83	54.75	20.38	3.45	30.99	23.01	9.22	34.37	18
LHS & BHE (05/02/2014)	0.93	3.85	13.40	0.85	59.31	21.07	0.75	30.21	23.36	9.55	38.24	63
LHS & BHE (06/02/2014)	0.69	4.78	14.03	0.82	59.70	21.85	4.07	33.31	23.70	9.25	37.85	24
LHS & BHE (07/02/2014)	-	-	-	0.83	60.37	21.76	-	33.99	24.15	-	38.61	52
LHS & BHE (08/02/2014)	0.66	4.12	12.67	0.82	49.46	21.77	0.97	16.50	24.44	8.55	27.69	29
LHS & BHE (11/02/2014)	0.75	3.88	14.33	0.73	37.15	18.58	1.92	9.34	24.14	10.45	18.57	11
LHS & BHE (12/02/2014)	0.78	4.81	14.18	0.80	58.84	20.66	3.63	39.34	24.28	9.37	38.18	23
LHS & BHE (13/02/2014)	0.92	3.80	13.40	0.81	63.34	22.86	0.37	34.56	24.73	9.6	40.48	37
LHS & BHE (14/02/2014)	-	-	-	0.82	49.44	21.86	0.37	14.32	25.20	-	27.58	35

The heat supply experiments have been carried out during daytime over approximately 6 hours for practical operations reasons. Secondly, on one hand, Lateral Heat Extraction (LHE) has been compared with combined simultaneous heat extraction from the lateral area and heat supplied to the bottom area (LHE & BHS); on the other hand, Bottom Heat Extraction (BHE) has been compared with simultaneous heat extraction from the bottom area and heat supplied to the lateral area (BHE & LHS). This second set of experiments has been carried out during four days. The final set of experiments comprises continuous BHS during the day and BHE during the night lasted almost two weeks.

The heat supplied from the solar collectors and the heat extractions performed according to the several configurations mentioned above have been evaluated in terms of the daily efficiency of the system. Thermal efficiencies are compared in each section with the overall efficiency of the system. The overall efficiency of the system has been calculated considering Equation (1) but instead of daily solar radiation and daily energy change, yearly values have been used. The yearly values take into account the data monitored throughout 2010-2011 (Valderrama et al., 2011), due to the fact that during this period, the heat extraction tests were not carried out.

This efficiency analysis is based on four main variables: the solar radiation, the heat stored, the heat extracted and the heat supplied. The solar radiation has been measured using the sensors installed in the meteorological station. As for the heat supplied (Q_{sup}) and the heat extracted (Q_{ext}), the mass flow rate through each heat exchanges as well as the input and output temperatures have been recorded to determine both parameters. Finally, the heat stored (Q_{stored}) in the system cannot be directly measured, the sensors installed in the solar pond measure the temperature changes, which is also affected by heat extracted and supplied. Hence, the total energy balance ($Q_{balance}$) may be accounted using the temperature variation in each layer of the pond. Then, the heat stored in the system can be estimated using the equation 2:

$$Q_{balance} = Q_{stored} - Q_{ext} + Q_{sup} \quad (2)$$

It is worth mentioning that the system is highly susceptible to some weather conditions, with solar radiation and air ambient temperature being the most influential. Some differences in the weather conditions have observed over the experimental period, although the solar radiation and air ambient temperature have shown the same trend, as can be seen in Figure 4. In February and March, similar values have been recorded, whereas in July, the average solar radiation is about five times higher and the average air ambient temperature approximately three times higher.

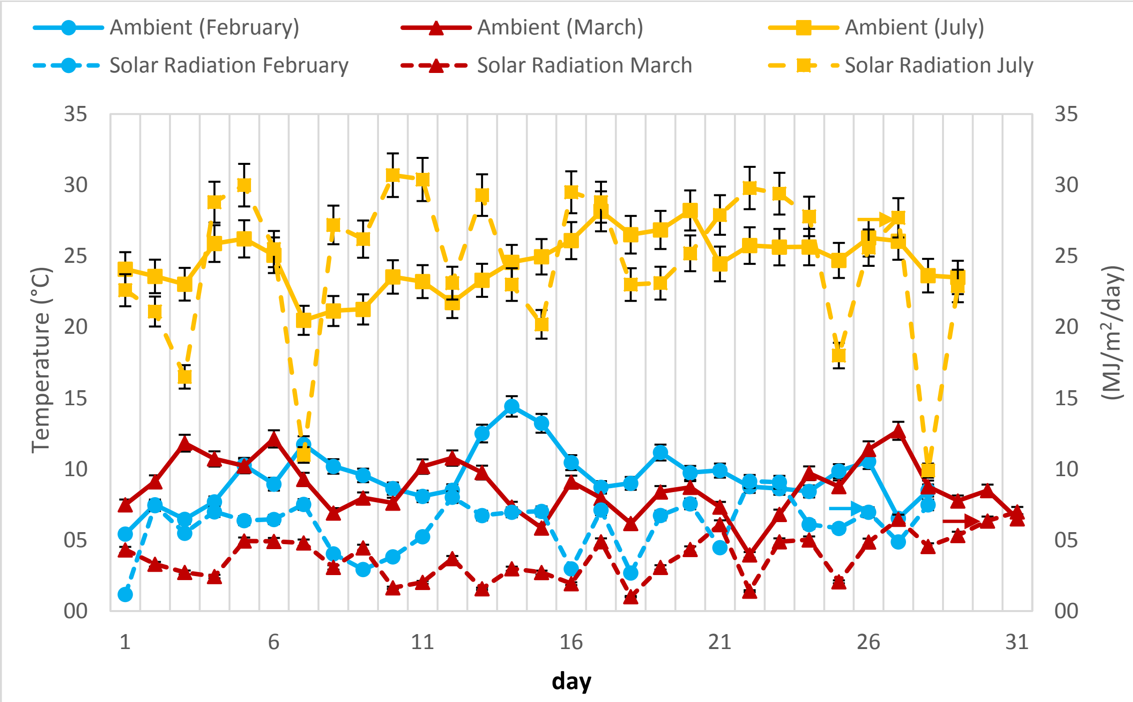

Figure 4. Solar radiation and air ambient temperature evolution during February, March, and July 2014 when heat extraction/supply tests were carried out.

Furthermore, the gradient inside the solar pond and, consequently, its stability, has remained constant throughout the months in which the tests were carried out. Figure 5 shows the evolution of temperature inside the solar pond and the three zones are clearly distinguished, as throughout the period of analysis, the depth has remained constant.

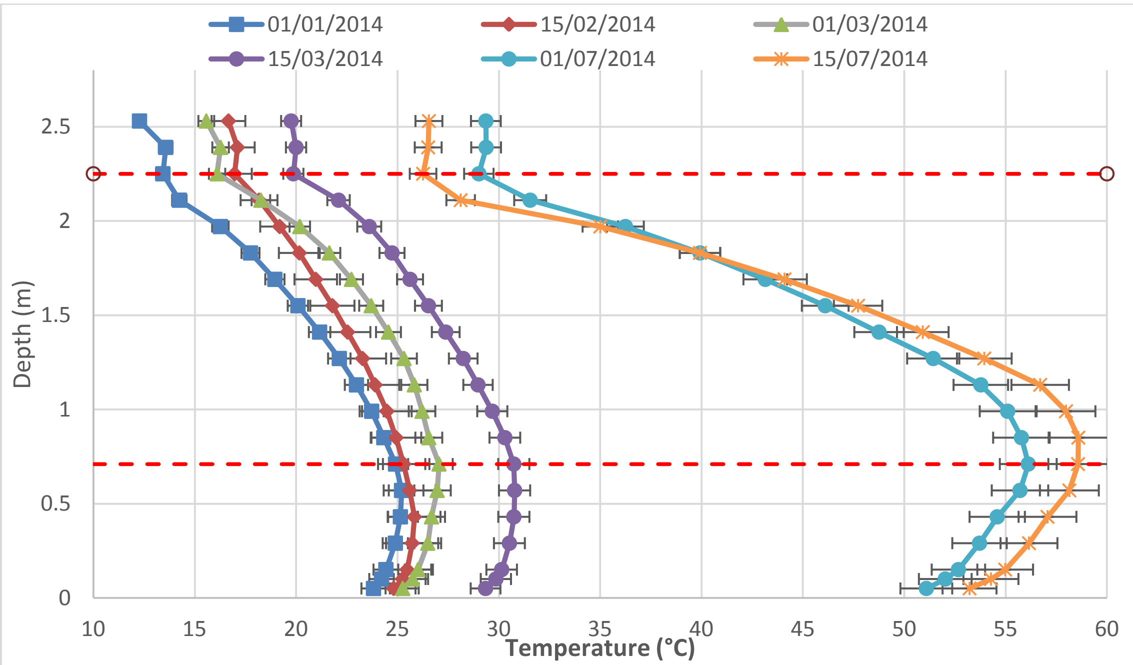

Figure 5. Evolution of the temperature gradient as a function of solar pond depth during the heat supply/extraction experiments from January to July 2014.

4.1 Heat supply using solar collectors.

The heat supply experiments have been performed in February and March 2014. Alcaraz et al., (2016) have demonstrated that the BHE could provide a significant contribution to enhancing the energy efficiency of the solar pond compared to LHE when heat extractions from the solar pond have been carried out using both heat exchangers. In this sense, the first set of experiments (February) have focused on the use of the bottom heat exchanger, but in this case to supply heat from the external solar collectors. The test in March have been performed in order to compare the impact on energy efficiency when the bottom and lateral heat exchangers are used, independently and simultaneously, to supply heat from the solar collectors.

The results of these experiments are plotted in Figure 6. The solar radiation during the tests in February was significantly lower than the values measured during the test in March. Consequently, the capacity of solar collectors to supply heat to the solar pond was lower in the February tests (first (34 MJ), and second (14.3 MJ)) than in the March tests (first (81 MJ), second (66.2 MJ), and third (82.1 MJ)). On the other hand, the capacity of the solar pond to store solar radiation was slightly higher in February due to the lower average temperatures in both the LCZ and the NCZ: 24.6 and 20.6 ºC, respectively. In March, the initial average values of T_{LCZ} and T_{NCZ} were 26.2 and 24.4 ºC, respectively. As a result, the fraction of solar radiation stored in the solar pond during the February test was significantly higher than in March.

As for the efficiency of the system, in February, the BHS showed a significant impact because the solar pond had a higher capacity to store heat. The efficiencies obtained in the February tests, 52% on 7th February and 35% on 14th February, (Figure 6) were above the overall efficiency of the solar pond obtained during 2010 and 2011 (Valderrama et al., 2011) when no extractions were carried out (7.1%) and above the average efficiency for February 2011 (11%) when no heat extraction tests were conducted. The tests performed in March reflected the effectiveness of each heat exchanger used to supply heat. First, during the BHS test, the efficiency reached a value of 12.8%, which was above the average efficiency of the solar pond and the average efficiency for March 2011 (9.3%). However, the value was lower than those obtained during the February tests because the capacity to store heat in March is slightly lower and the solar radiation incident directly on the top of the solar pond is considerably higher (Figure 6). Moreover, during the LHS test, the efficiency was slightly lower than that obtained in the BHS test, but it is worth mentioning that the solar radiation was 15% lower during the LHS experiments. Finally, the results of simultaneous BHS and LHS were the best in terms of energy efficiency, with a value of up to 18%, representing 29 and 49% increases in efficiency, respectively, when compared to BHS and LHS tested independently.

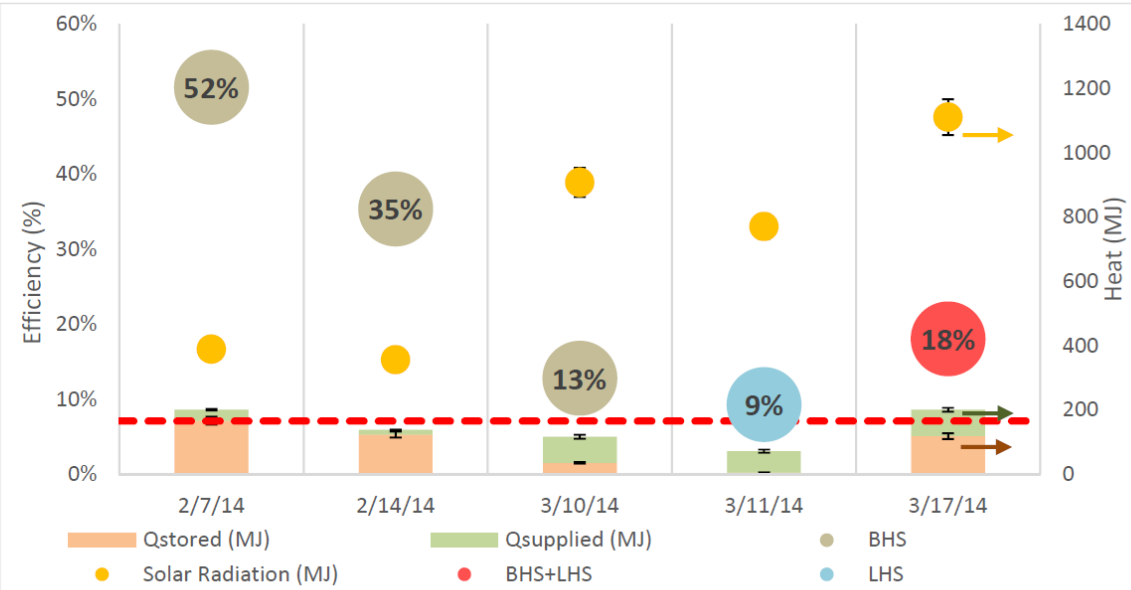

Figure 6. On the right axis: solar radiation, fraction of solar radiation stored in the LCZ and the NCZ (Qstored), and heat supplied (Qsupplied) from solar collectors. On the left axis: daily efficiency and overall efficiency of the system during the heat supply tests carried out in February and March 2014.

4.2 Heat extraction and heat supply using solar collectors

Heat supply tests have (during February and March) proved that heat supply is more effective when T_{LCZ} and T_{NCZ} are relatively low and the solar radiation is not extremely high since in that context the solar pond has a larger capacity to absorb heat. In July 2014, the initial average temperatures in the solar pond were 53.3 and 47.1 ºC in the LCZ and the NCZ, respectively, and the average solar radiation was approximately five times higher than that achieved during February and March. Besides, the average efficiencies in July 2010 and 2011, when no heat extraction tests were performed, were 6.5 and 5%, below the overall efficiency of the system for the same period (7%). As a conclusion, to improve the efficiency of the solar pond, the system needs to increase its capability to retain heat. In that context, the tests in July 2014 were based on heat extraction; the use of each heat exchanger to extract heat was proved independently, using the other heat exchanger to supply heat from the solar collectors, and the results are depicted in Figure 7. The four experiments were conducted during four consecutive days to minimize variations in solar radiation per unit of surface; however, the incident solar radiation was significantly higher on the days with heat supply, as can be seen in Figure 7.

First, two tests were carried out on 24th and 25th July using LHE and BHS simultaneously and LHE alone, respectively. On 24th July, 24.5 MJ was extracted from the system and 95.8 MJ was supplied; the large amount of heat supplied from the solar collectors during that day and the high temperatures in the LCZ and NCZ saturate the capacity of the solar pond to store heat, avoiding the storage of heat from the solar radiation. As a result, the efficiency of the system was 8.3%, slightly above the overall efficiency of the solar pond for 2010 and 2011 (7%). On 25 July, the same test was performed but without BHS; 29.8 MJ was extracted from the system, which enlarged the fraction of solar radiation absorbed and stored by the solar pond. Therefore, the performance of the system in terms of efficiency increased up to 11% in this scenario.

Secondly, BHE and LHE simultaneously and BHE independently were conducted on 26th and 27th July, respectively. The BHE enlarges the heat transfer between the NCZ and the LCZ, increasing, in turn, the capacity to store heat in both layers. On 26th July, 31.2 MJ was extracted from the bottom and 83.6 MJ was supplied through the lateral heat exchanger. In this case, the LHS did not completely reduce the capacity of the solar pond to absorb heat from solar radiation since the value of solar energy absorbed was somewhat below that achieved when no heat supply took place. Under this test, the daily efficiency, 18%, was more than twice the average efficiency of the solar pond and more than three times the monthly efficiency for July 2010 and 2011. As in the previous set of experiments, on 27 July, the test was replicated but with BHE alone; 29 MJ was extracted from the system, which increased the capacity to retain heat, resulting in the highest amount of energy stored from solar radiation, 270.1 MJ. In turn, the efficiency of the system obtained under this test was 22%, the best result obtained under warmer conditions.

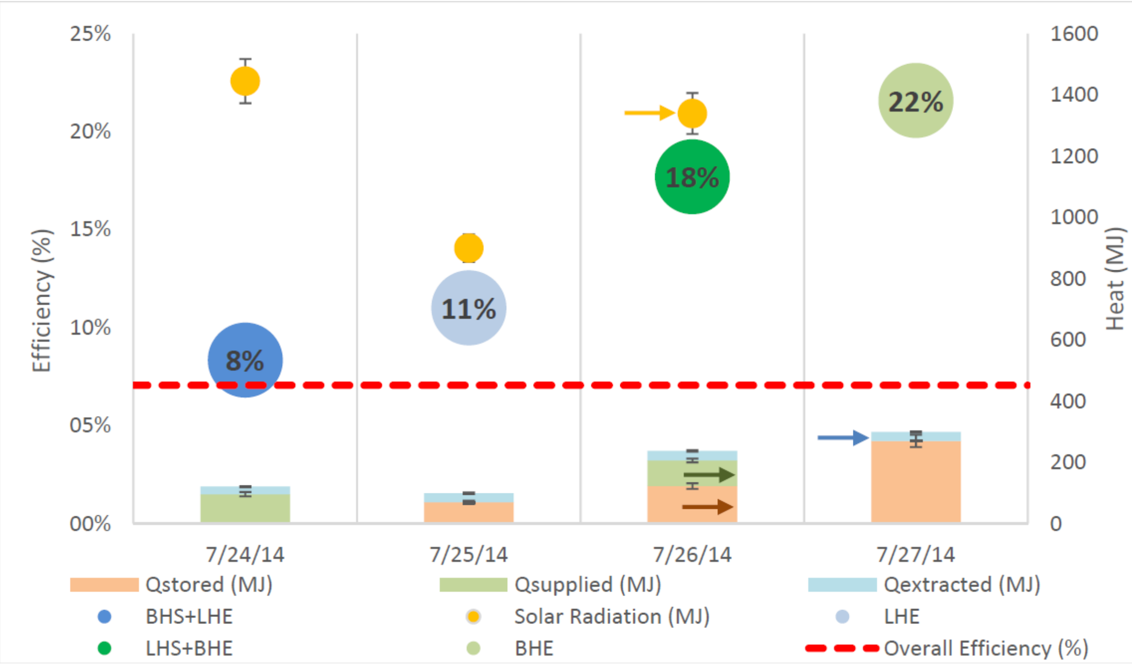

Figure 7. On the right axis: solar radiation, the fraction of solar radiation stored in the LCZ and NCZ (Qstored), heat extracted from the pond (Qextracted), and heat supplied from solar collectors (Qsupplied); on the left axis, the daily efficiency and overall efficiency of the system during the heat supply and heat extraction tests carried out in July 2014.

The stability of solar pond is a key parameter of this technology and according to the data recorded in this study; no impact on the density profile has been observed during the heat supply/heat extraction experiments as has been reported in a previous study (Alcaraz et al., 2016). However, it should be mentioned that stability is an issue for large solar ponds as has been reported by Alcaraz et al., (2018). The non-significant impact of heat extraction on stability of the Martorell solar pond can be due to two main reasons: i) the experiments have been carried out in closed-loop configuration, which can minimize local convective differences during heat extraction test and ii) the flow rates that have been used in the heat extraction experiments are quite low compared to those used in large solar ponds.

4.3 Daily heat supply using solar collectors and heat extraction during night hours

The heat supply in cold months has proved to improve the efficiency of the solar pond as described in Section 4.1. In addition, the results that have been reported in the previous set of experiments indicate that the bottom heat exchanger is the most effective when the heat extraction and supply processes are conducted. In view of that, during eight days in February 2014, the heat supply and the heat extraction have been integrated alternately. With the main aim of maximizing the energy efficiency of the system, both heat extraction and supply processes were carried out on the LCZ using the bottom heat exchanger. Additionally, in the colder months, it is crucial to take advantage of all solar radiation during the daily hours, and in that context, the extractions were carried out during the night-time periods, which also facilitated the refrigeration of the working fluid in the closed-loop heat extraction configuration. Figure 8 plots the results obtained in this test and compare them to the ones obtained in February when BHS was used. In order to describe the performance of the solar pond, it is important to analyze the evolution of the incident solar radiation. This test was carried out during the longest period, and a correlation between the values of solar radiation and the values of efficiency cannot be clearly established since the performance of the solar pond on one day is highly influenced by previous days; e.g., the efficiency of the system would be likely to be higher if a higher value of solar radiation were achieved after a day of low radiation, because the system would have a larger capacity to absorb heat, than if it were preceded by a favorable solar radiation period.

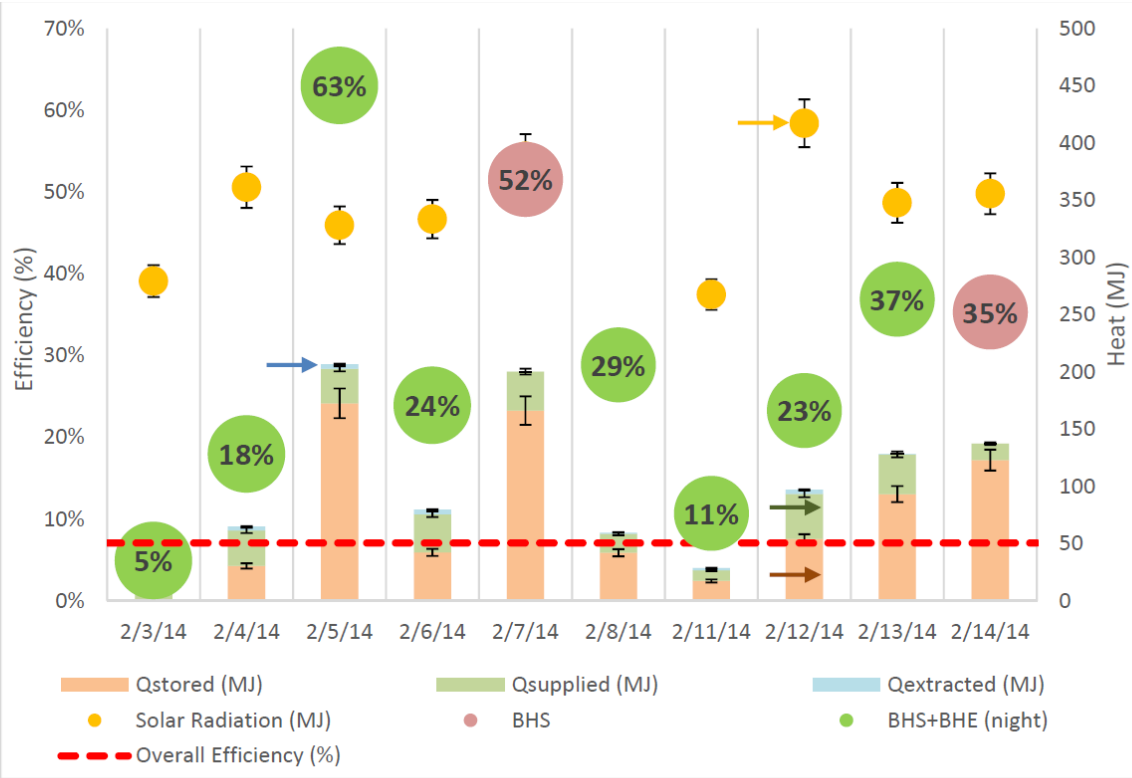

Figure 8. On the right axis, solar radiation, fraction of solar radiation stored in the LCZ and NCZ (Qstored), heat extracted from the pond during night periods (Qextracted), and heat supplied from solar collectors (Qsupplied); on the left axis, daily efficiency and overall efficiency of the system during the heat supply and heat extraction tests carried out in February 2014.

The capacity of the system to provide heat was extremely limited during the days on which the tests were conducted, firstly because the heat extraction tests were carried out for periods of 10 to 190 minutes, secondly because the maximum difference in temperature of the working fluid between the outlet and inlet of the heat exchanger was 13.4 ºC with an average value of 9.4 ºC, and finally because the maximum mass flow rate was 0.96 kg/min with an average value of 0.76

kg/min. As a result, the heat extracted ranged from 1 to 21% of the heat supplied to the system during the day.

As for the heat supply test, the amount of heat transferred from the solar collectors achieved similar values regardless of the heat extraction. The maximum heat supplied was 39.3 MJ on 12th February, coinciding with the highest incident solar radiation. In turn, the minimum heat supply was 9.3 MJ on 11th February, which was the second least favorable day in terms of solar radiation.

Regarding the energy efficiency during this set of experiments, the days with higher heat supply tended to result in higher efficiency. A correlation between the solar radiation, the heat extracted or supplied, and the daily efficiency cannot be clearly identified due to the large influence of weather parameters and the dynamics of the solar pond on the tested day. Nevertheless, the efficiency of the system was clearly enhanced when the BHS and BHE processes were conducted compared to the overall efficiency of the solar pond when no heat supply/extraction tests were performed.

5. Conclusions

This work presents the results of the performance of a salinity gradient solar pond integrated with solar collectors as an external source of heat. Heat extraction and heat supply test were conducted simultaneously in order to increase the storage capacity and also to assess the overall efficiency of the system. Three different scenarios were studied and all showed a significant enhancement of the daily efficiency of the system. Results indicate that coupling the solar pond with solar collectors, as an external source of heat, notably increases the energy efficiency. From tests carried out in cold season (e.g., March), the operation of BHS and LHS at the same time resulted in the most effective configuration, increasing the efficiency up to 18% and 49% compared with BHS and LHS independently used, respectively. Moreover, when heat extraction was performed in a colder month (e.g., February), the energy efficiency was almost the same as when only the heat supply was tested (Figure 8). It can be associated to the fact that the amount of heat that can be extracted from the solar pond was quite low compared to the heat supplied from the solar collectors. The results of simultaneous BHS and LHS were the best in terms of energy efficiency, with a value of up to 18%, representing 29 and 49% increases in efficiency, respectively, when compared to BHS and LHS tested independently.

During the test in warm season (e.g., July), using BHE alone; the amount of heat extracted from the system was 29 MJ, which increased the capacity to retain heat, resulting in the highest amount of energy stored from solar radiation, 270.1 MJ. In turn, the efficiency of the system obtained under this test was 22%, the best result obtained under warmer conditions.

Third, in those warmer months with the most favorable weather conditions, the capacity of the solar pond to store energy is overcome and the fraction of the solar radiation absorbed is reduced. In that context, only the heat extraction process could be considered in order to maximize the daily efficiency of the system and the heat supply process can only be considered if large amounts of heat are extracted; otherwise, the daily efficiency of the solar pond could decrease slightly.

In summary, the solar collectors or any other extra source of heat can be considered an appropriated solution to avoid a large decrease in the T_{LCZ} and T_{NCZ}, which would not only result in a significant improvement in energy efficiency but also increase the capacity of the solar pond to provide heat to an external application during the colder months, which are the most unfavorable in terms of solar radiation. Future work will be focuses on optimizing the heat supply/extraction processes to and from the solar pond throughout the year under different weather conditions and making it practical in order to reduce the manual control of some operations.

Acknowledgments

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