

1 Thermal performance of 500m² salinity gradient solar pond in Granada, Spain under 2 strong weather conditions

3 A. Alcaraz ¹, M. Montalà ^{1,2}, C. Valderrama ^{1,2}, J. L. Cortina ^{1,2}, A. Akbarzadeh ³, A. Farran ^{1,2}

4 ¹ Chemical Engineering Department, UPC-BarcelonaTECH, 08930 Barcelona, Spain

5 ² Barcelona Research Center for Multiscale Science and Engineering, 08930 Barcelona,
6 Spain

7 ³ School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University,
8 Australia

9
10 *Correspondence should be addressed to: César Valderrama

11 Departament d'Enginyeria Química, Universitat Politècnica de Catalunya-Barcelona TECH

12 C/ Eduard Maristany, 10-14 (Campus Diagonal-Besòs), 08930 Barcelona, Spain

13 Tel.: 93 4011818

14 Email: cesar.alberto.valderrama@upc.edu

15 16 Abstract

17 In this study, an experimental investigation of temperature performance and efficiency of an
18 industrial solar pond during strong winter conditions is presented. Several temperature
19 sensors connected to a data logger were used to measure the temperature gradient in a 500
20 m² solar pond. During the winter 2015 there was a snowfall in the solar pond of Granada
21 (Spain), reaching a minimum air ambient temperature of -2.4 °C. The temperature of the
22 storage zone in Granada solar pond remained constant (around 40 °C) indicating the system
23 responds positively to weather variations and confirming the fundamental role of the salinity
24 gradient as a thermal insulation layer. The stored energy during January 2015 was 13.3 GJ,

1 the weekly efficiency reached 10% and finally, the solar pond was able to provide 247.1 MJ to
2 the flotation unit during the week of the snowfall.

3 Keywords: solar energy; energy efficiency; snowfall; industrial solar pond; mineral flotation

4 **1. Introduction**

5 World is now facing challenges in meeting its energy demand through burning fuels. Elevated
6 level of CO₂ in the atmosphere is contributing to climate change. Therefore, there is an urgent
7 need to conserve energy and move towards clean and renewable energy sources. Thermal
8 energy storage is a key function enabling energy conservation across all major thermal energy
9 sources, although each thermal energy source has its own unique context. Absorbing and
10 storing the solar energy is the most important challenge in this field. Different collectors can be
11 used for absorbing the solar energy for different purposes such as power generation,
12 desalination, water heating, space heating, etc. A solar pond is a low cost solar collector for
13 collecting and storing the thermal energy for a long period of time (Khalilian, 2017; Swift et al.,
14 1987) .

15 The solar pond is a technology that meets all requirements to be considered an energy
16 storage device. It can store solar energy, charging during the months of high solar incidence
17 (Spring-Summer), storing the energy through the time and making possible its use when it is
18 requested. In broad terms, a solar pond is a large body of water that collects and stores solar
19 energy in the form of heat.

20 A typical salinity gradient solar pond (SGSP) consists in three distinct zones (Zangrando 1980;
21 Tabor & Weinberger 1981). The surface area formed by fresh water or low salinity water is
22 called upper convective zone (UCZ) and it is a zone of constant temperature, close to the air
23 ambient temperature, and salinity, between 2-3%. The thickness of this area varies from 0.1 to
24 0.4 m.

1 Below this UCZ, there is an intermediate zone consisting of several layers with different
2 density. The brine density gradually increases towards the bottom of the pond causing a
3 concentration gradient. This gradient prevents the occurrence of convection currents and, as a
4 result of solar energy absorption, a gradient of temperature is also established. The gradient
5 zone is known as a non-convective zone (NCZ) and it is the key of this technology. The
6 thickness of this intermediate area ranges from 1 to 1.5 m. The lower zone has the highest
7 density (highest salinity content), near saturation, and it is known as low convective zone
8 (LCZ). This zone acts as a thermal storage with temperature ranging between 50-90°C
9 depending on the size of the pond.

10 In the last years, several studies have been carried out to analyse and evaluate the
11 performance of salinity gradient solar ponds and to increase their overall performance.
12 Experimental studies have focused on i) alternative applications (Zhang et al., 2016; Rahaoui
13 et al., 2017; Ziapour et al., 2017; Karakilcik et al., 2018); ii) the addition of heat from external
14 sources (Ganguly et al., 2017); iii) the performance analysis to enhance the overall efficiency
15 (Sayer et al., 2108; Simic and George, 2017; A.A.Abdullah et al., 2017; Torkmahalleh et al.,
16 2107; Bozkurt and Karakilcik, 2015a); and iv) the analysis of exergy efficiencies (Njoku et al.,
17 2017; Khalilian, 2017a, 2017b; Bozkurt and Karakilcik, 2015b).

18 The weather conditions determine the performance of any solar pond facility and can affect its
19 long-term storage capability. Solar radiation, wind, heavy rain can cause instability in the
20 system and make its efficiency decrease. The aim of this study is to evaluate a 500-m²
21 industrial solar pond in Granada (Spain) during an event of extreme weather conditions of
22 snowfall during the winter of 2015. The present note studies the influence of the weather
23 conditions on the storage capacity and on the thermal efficiency of the solar pond. The
24 rationality of the analysis is to evaluate if the technology of solar ponds is able to store energy
25 even in extreme weather conditions and continue to provide the energy required in the

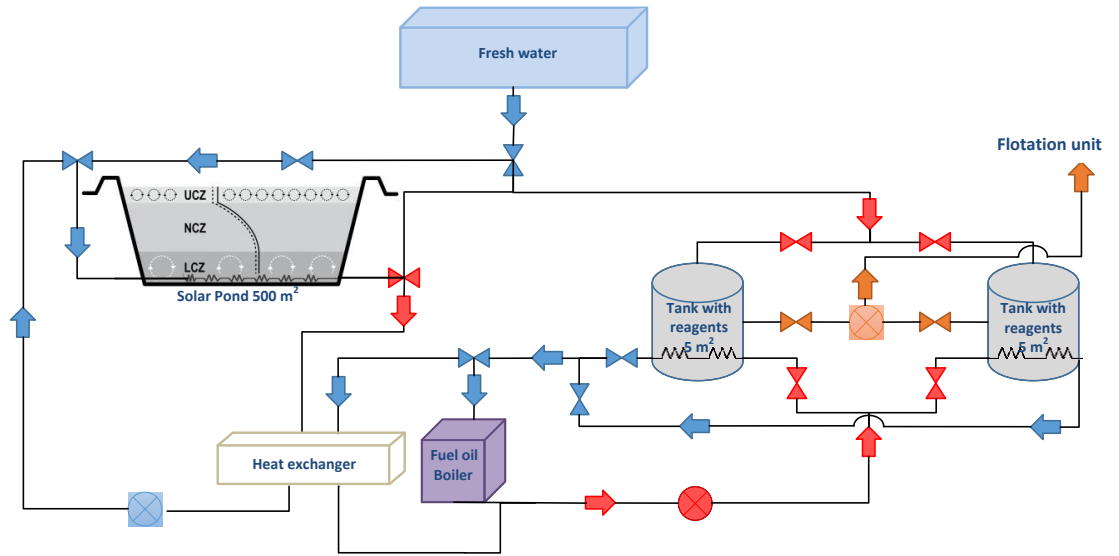
1 flotation unit of the mining facility. This is of great interest in terms of the operation, as well as
2 the ability to supply energy to an external application under unfavourable environmental
3 conditions.

4 5 **2. Materials and methods**

6 In 2014, a salinity gradient solar pond was constructed in the Solvay Minerales facilities in
7 Granada (South Spain). The solar pond design, construction and operation was described by
8 (Alcaraz et al., 2018): The solar pond was constructed to deliver the heat needed to preheat
9 the water (> 60 °C) used in the mineral flotation unit. Some features of this solar pond are: the
10 total area of the pond is 500 m² (20 × 25 m) with a depth of 2.2 m. The thickness of the LCZ,
11 NCZ and UCZ was 0.6 m, 1.4 m and 0.2 m, respectively. The heat extraction was carried out
12 through a heat exchanger (PE pipe with an internal diameter of 28 m) located at the LCZ with
13 a total length of 1200 m, which was divided into six independent spirals of 200 m. The solar
14 pond is installed in a mine facility devoted to produce celestine (SrSO₄). The processed rock,
15 with a celestine content of 30-50%, is milled and then concentrated up to a content of 90% by
16 using a flotation stage. The aqueous solution containing the reagents should be heated to 60-
17 65°C. Before the installation of the solar pond, this was carried out using a boiler fed with
18 gasoil. The solar pond was integrated with the flotation unit by connecting a pipe from the
19 freshwater tank that travels through the LCZ of the solar pond and joins the existing pipe line.
20 A view of the experimental solar pond in Granada is shown in Figure 1.

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5 Figure 1. Schematic view showing: a) the integration of the solar pond in Solvay facilities and
6 b) view of the 500 m² solar pond at Solvay Minerales facilities (Granada, Spain)

8 3. Thermal efficiency of a salinity gradient solar pond

9 The solar energy can be collected and stored by the salinity gradient solar pond as follows,
10 when solar radiation is incident on the solar pond, part of the radiation is reflected away from
11 the top surface while most of the incident sunlight is transmitted down through the top surface

1 of the UCZ. A fraction of the transmitted radiation is rapidly absorbed in the surface layer.
 2 However, this absorbed heat is lost to the atmosphere by convection and radiation heat
 3 transfer. Some of the remaining radiation is absorbed in the middle NCZ before the rest of the
 4 radiation reaches the bottom of the pond. In the LCZ, the absorbed solar energy is converted
 5 to heat and stored as sensible heat in the high concentration brine (Valderrama et al., 2016).
 6 The efficiency of the solar pond has been defined in different ways, for instance: i) the thermal
 7 energy stored in the system relative to the incident radiation up on the pond (Nie et al., 2011;
 8 Bozkurt and Karakilcik, 2015; Karakilcik et al., 2006; Dehghan et al., 2013; Erden et al., 2017);
 9 or ii) the heat extracted from the system relative to the incident solar radiation (Andrews and
 10 Akbarzadeh, 2005; Leblanc et al., 2011). Both methods underestimate the solar energy
 11 storage capacity over the months with high solar radiation. Alcaraz et al., (2018) defined a
 12 different approach to estimate the thermal efficiency of a solar pond supplying heat to an
 13 external system throughout the year:

$$\eta = \frac{\sum_i Q_{stored_i} + \sum_i Q_{extracted_i}}{\sum_i Q_{incident_i}} \quad (1)$$

14 where $Q_{incident_i}$ is the total incident radiation measured throughout day i , $Q_{extracted_i}$ is the
 15 amount of heat extracted from the system, if any, during day i and is estimated according to
 16 (Leblanc et al., 2011), and Q_{stored} represents the part of the solar radiation that the system is
 17 capable to store in the LCZ along period i . The temperature in the LCZ may decrease in some
 18 days, therefore, the system losses its capability to store energy due to unfavorable solar
 19 radiation conditions, consequently, Q_{stored} is assumed to be zero. Thus, Q_{stored_i} and
 20 $Q_{extracted_i}$ are calculated as follows:

$$Q_{stored_i} = \begin{cases} V_{LCZ} \cdot C_p \cdot \rho \cdot (T_{LCZ_i} - T_{LCZ_{i-1}}) & (T_{LCZ_i} - T_{LCZ_{i-1}}) > 0 \\ 0 & (T_{LCZ_i} - T_{LCZ_{i-1}}) < 0 \end{cases}$$

22 (2)

1 $Q_{extracted_i} = \dot{m} \cdot C_p \cdot (T_{out} - T_{in}) \cdot time$

2 (3)

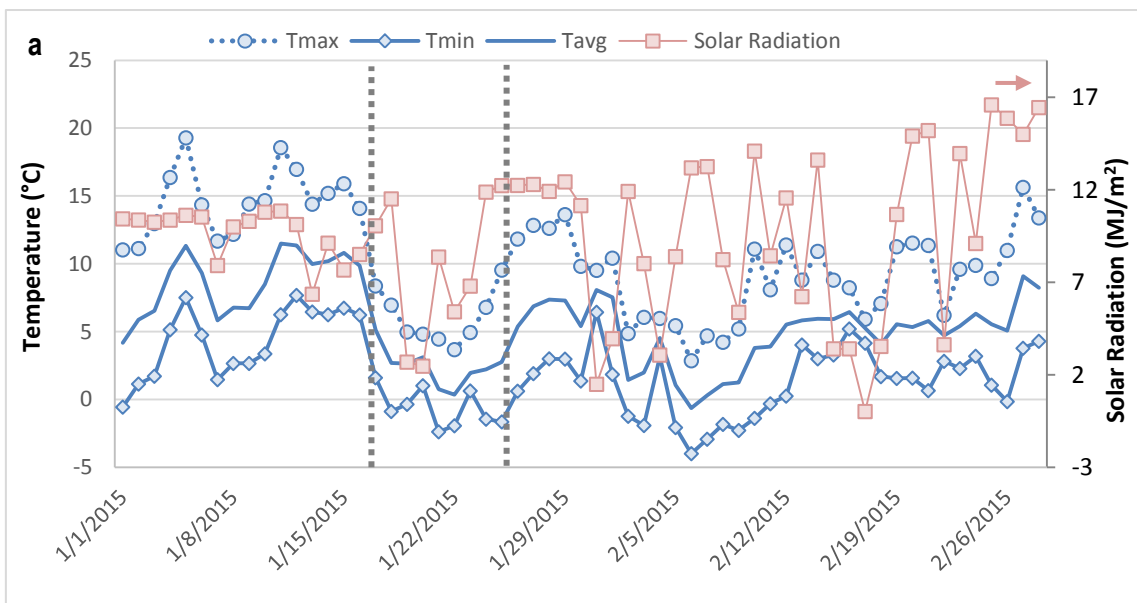
3 T_{LCZ} is the temperature measured by the sensors installed in the LCZ, ρ is the density
4 measured by routinely control of the density profile, V_{LCZ} is the volume of the LCZ calculated
5 using ρ and the geometry of the system, \dot{m} is the mass flow rate through the heat exchanger,
6 T_{out} and T_{in} are the outlet and inlet temperatures of the heat exchanger, $time$ is the period
7 of time while heat is extracted from the system and C_p is water heat capacity, calculated
8 considering the density and temperature.

9 The performance of solar pond need to be analyzed in long-term perspective due to its
10 capacity to provide heat stored throughout year. Alcaraz et al., (2018) proved that efficiencies
11 for short periods are not representative due to the variability of weather conditions from one
12 period to another. However, to analyze the impact of snowfalls on the operation of Granada
13 solar pond, weekly efficiencies have been used in order to compare the performance before,
14 during and after the snowfall. The values obtained cannot be in any case assumed as solar
15 pond overall efficiencies.

17 **4. Results and discussion**

18 During the night of 21/01/2015 a snowfall took place in the facilities of the solar pond of
19 Granada. Low temperatures favoured this unusual phenomenon reaching a minimum
20 temperature of -2.4°C. Figure 2a shows the evolution of average, minimum and maximum air
21 ambient temperatures and incident solar radiation during January and February of 2015.

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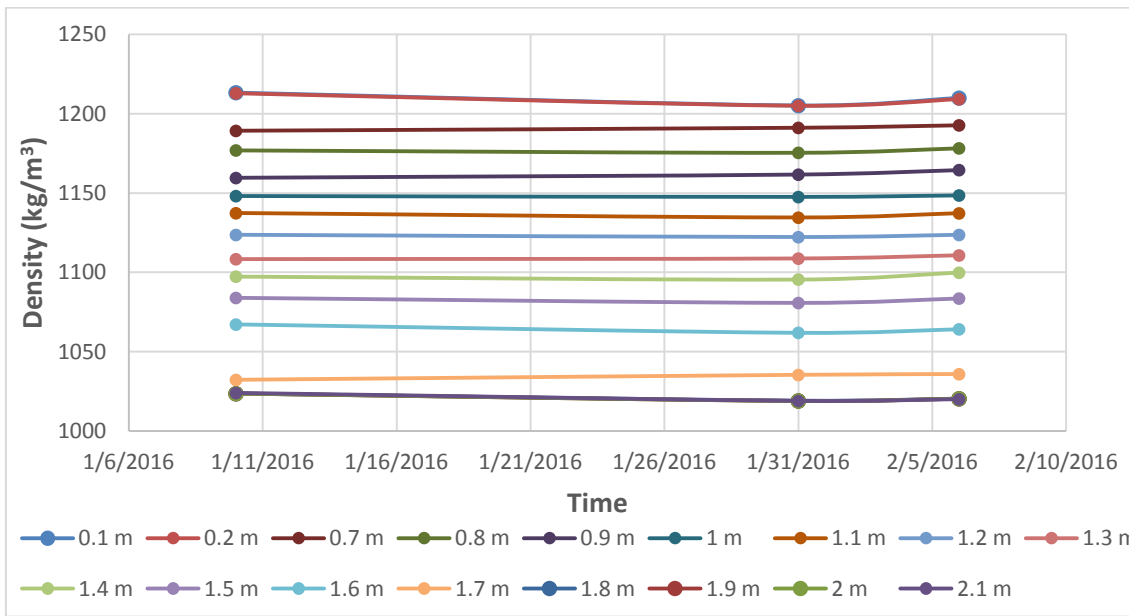
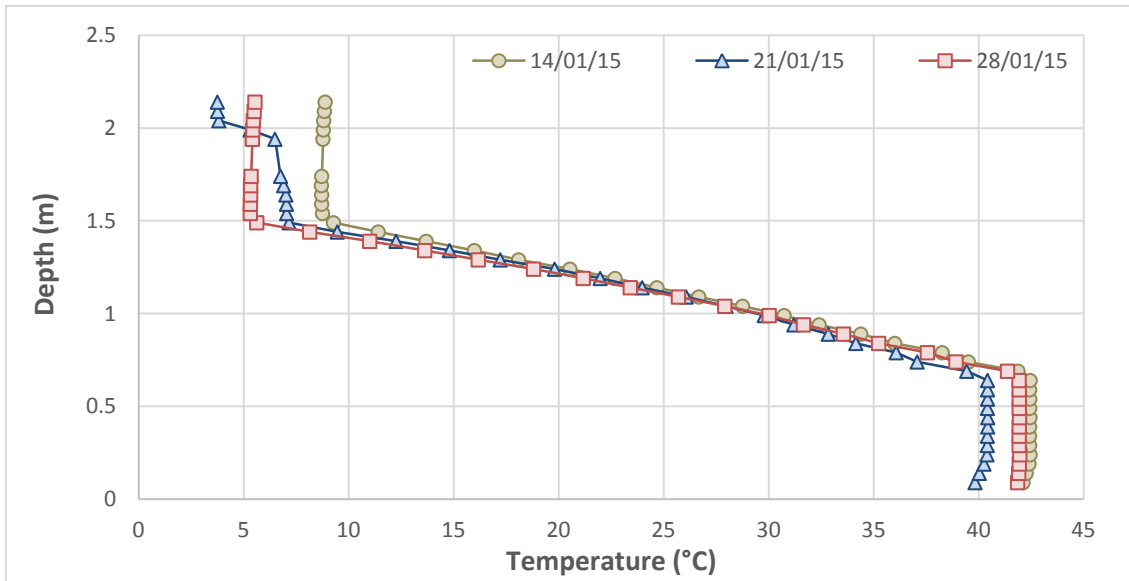
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1 Figure 2. a) Evolution of the Maximum (T_{max}), minimum (T_{min}) and average (T_{avg}) air
2 ambient temperature and incident solar radiation evolution during January and February 2015
3 and b) photos after the snowfall on 21/01/2015 in the Granada solar pond facilities.

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5 As for the solar radiation an average value of 8.4MJ/m^2 was recorded during the snowfall.
6 Although neither the minimum incident solar radiation nor the minimum temperature were
7 reached the days around snowfall, the combination of both environmental conditions were
8 clearly unfavourable for the operation of the solar pond as can be seen in some photos of the
9 Granada solar pond facilities after the snowfall (Figure 2b). Despite the low temperatures and
10 heavy snowfall, the surface of the pond did not freeze. The thermal gradient before, during
11 and after the snowfall is shown in Figure 3. As was expected, the most affected zone was the
12 UCZ by creating a sub-gradient due to the lower temperatures at the pond surface. Then, one
13 week after the snowfall, the profile of the UCZ recovered its normal pattern with a constant
14 temperature in the layer. The NCZ remains practically at the same temperature for each
15 height regardless of the low temperatures. The storage zone remains almost constant while
16 the air ambient temperature reached values approaching to 0°C . The density gradient was not
17 measured constantly. However, considering the measurements made in January (Figure 3b),
18 it can be seen that there were no significant variations in the density of the NCZ. On January
19 31st, the surface decreased slightly, but the system was able to recover the initial values only 6
20 days later.

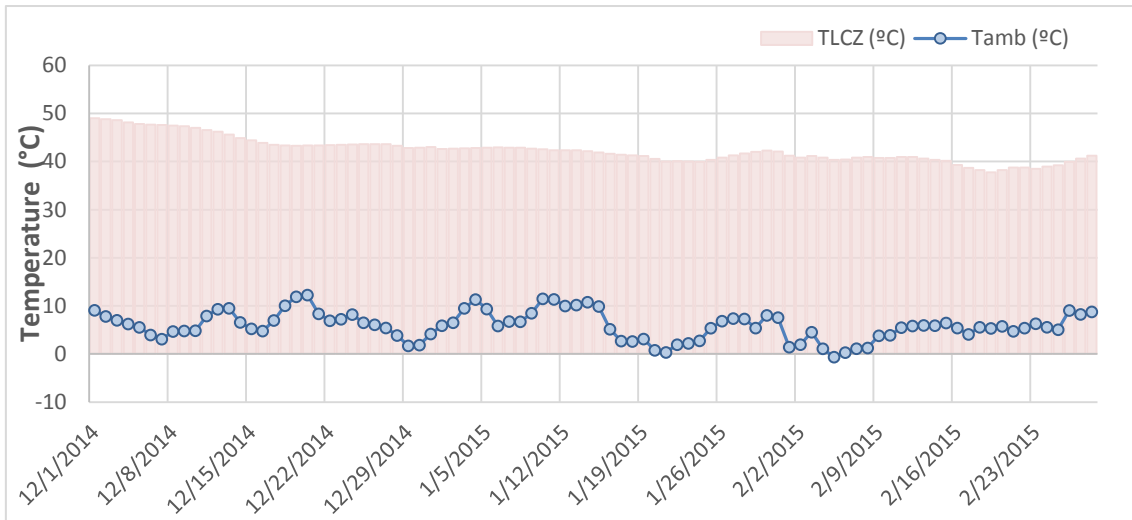


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3 Figure 3. a) Thermal gradient before, during and after the snowfall (15/01/2015) and b) the
 4 density gradient evolution in NCZ of the Granada solar pond (January 2015).

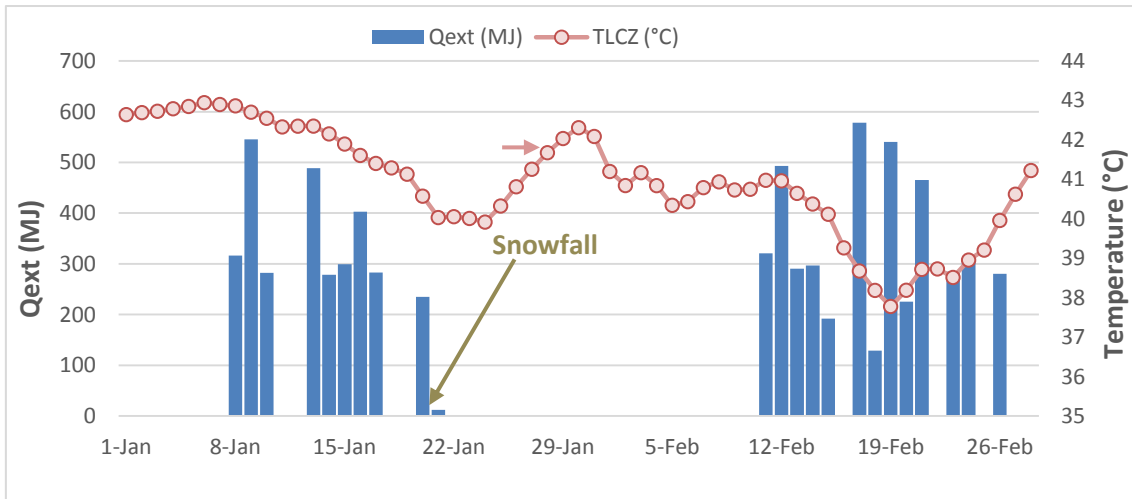
5 Despite the adverse environmental conditions and the heat extracted, the LCZ average
 6 temperature was kept around 40 °C, as can be seen in Figure 4.



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2 Figure 4. Air ambient and LCZ temperatures during the snowfall (SGSP Granada).

3 From 1st December 2013 to 28th February 2014, the solar pond was able to provide 10493 MJ
 4 of heat to the flotation unit, the amount of heat extracted per day and the evolution of the LCZ
 5 average temperature are shown in Figure 5. The amount of heat extracted from the solar pond
 6 is quantified using the data measured by the temperature sensors installed in the pond, the
 7 inlet and outlet water temperature of the system and the mass flow rate of the working fluid
 8 (Eq. 3). The day of the snowfall, the average ambient temperature was 0.3°C and 12.2 MJ of
 9 heat were extracted from the system. The day before, the average ambient temperature was
 10 slightly lower, 0.8°C, and the solar pond was able to provide 235 MJ of heat. From 1st January
 11 until the day of the snowfall, 3142.6 MJ were extracted from the system, which added to the
 12 unfavourable weather conditions, resulted in a decrease of 2.6°C in the LCZ average
 13 temperature. After the snowfall no heat was extracted from the solar pond during 20 days
 14 which allowed an increase of 1 °C in the average LCZ temperature.



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2 Figure 5. Heat extracted and LCZ average temperature during January and February 2015
 3 (SGSP Granada).

4 It is worth to mention that the amount of heat extracted depends only on the energy needs in
 5 the flotation unit. Finally, the weekly efficiencies, calculated using Eq. 1, of solar pond of
 6 Granada are depicted in Figure 6. The minimum weekly efficiency (3.8%) is achieved during
 7 the snowfall week. However, despite the adverse environmental conditions, the solar pond
 8 was able to provide 247.1 MJ to the flotation unit. The minimum average air ambient
 9 temperature was achieved the first week of February (4.6%, efficiency), despite the low
 10 temperature the system was able to partially store part of solar radiation in some periods
 11 (Figure 5) partially thanks to the fact that not heat extractions were performed from the solar
 12 pond.

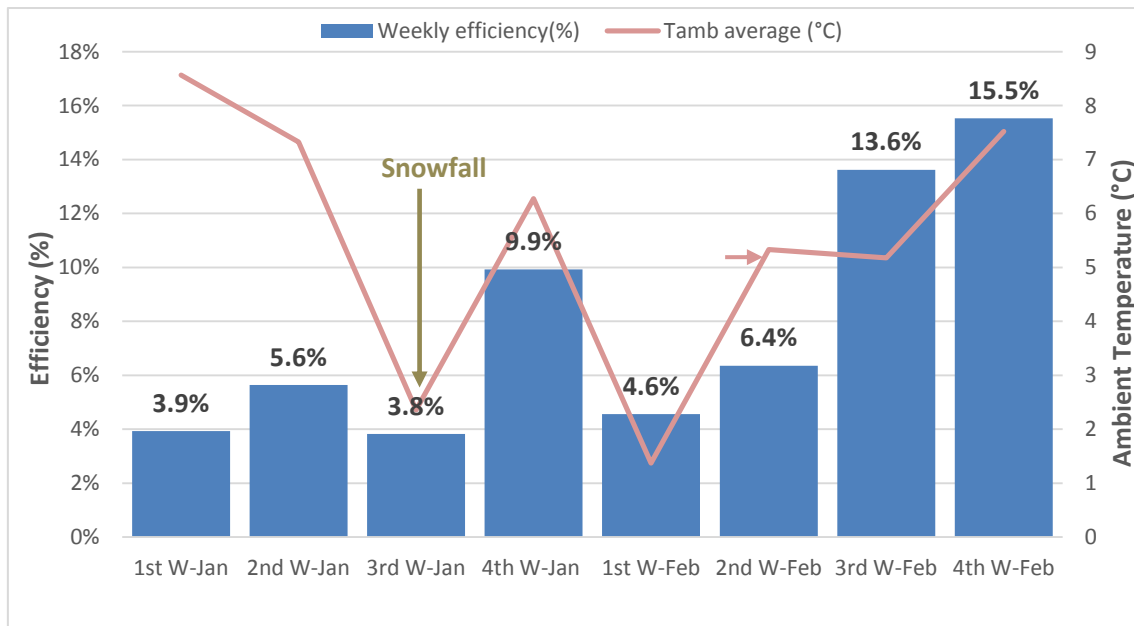


Figure 6. Weekly efficiency and weekly average ambient temperature during January and February 2015 (SGSP Granada).

5. Conclusions

The energy storage capacity of a solar pond can be affected by the weather conditions and the amount of heat extracted. This note analyses the behaviour of the solar pond technology under low temperatures and the performance of the system when it is exposed to a snowfall. The temperature of the storage zone in the Granada solar pond remained constant, which indicates that the system responds positively to weather variations, even those that are extreme and unusual, and that also confirms the fundamental role of the salinity gradient as a thermal isolation layer. It is important to note that salinity gradient and LCZ were not affected by the snowfall and only the UCZ reported some temporary instability that lasted a week approximately. The stored energy during January 2015 was 13.3GJ and the weekly efficiency reached 10%. This analysis confirms that solar pond technology is able to store energy even under extreme weather conditions and it is of greatest importance in terms of its operation as well as its capacity to supply energy to an external application.

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8 **References**

- 9 Abdullah, A.A., Fallatah, H.M., Lindsay, K.A., Oreijah, M.M., 2017. Measurements of the
10 performance of the experimental salt-gradient solar pond at Makkah one year after
11 commissioning. *Sol. Energy* 150, 212–219. doi:10.1016/j.solener.2017.04.040
- 12 Alcaraz, A., Montalà, M., Cortina, J.L., Akbarzadeh, A., Aladjem, C., Farran, A., Valderrama,
13 C., 2018. Design, construction, and operation of the first industrial salinity-gradient solar
14 pond in Europe: An efficiency analysis perspective. *Sol. Energy* 164, 316-326.
- 15 Andrews, J., Akbarzadeh, A., 2005. Enhancing the thermal efficiency of solar ponds by
16 extracting heat from the gradient layer. *Sol. Energy* 78, 704–716.
17 <https://doi.org/10.1016/j.solener.2004.09.012>
- 18 Bozkurt, I., Karakilcik, M., 2015a. The effect of sunny area ratios on the thermal performance
19 of solar ponds. *Energy Convers. Manag.* 91, 323–332.
20 <https://doi.org/10.1016/j.enconman.2014.12.023>
- 21 Bozkurt, I., Karakilcik, M., 2015b. Exergy analysis of a solar pond integrated with solar
22 collector. *Sol. Energy* 112, 282–289. doi:10.1016/j.solener.2014.12.00
- 23 Dehghan, A.A., Movahedi, A., Mazidi, M., 2013. Experimental investigation of energy and
24 exergy performance of square and circular solar ponds. *Sol. Energy* 97, 273–284.

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1 <https://doi.org/10.1016/j.solener.2013.08.013>

2 Erden, M., Karakilcik, M., Dincer, I., 2017. Performance investigation of hydrogen production
3 by the flat-plate collectors assisted by a solar pond. *Int. J. Hydrogen Energy* 42, 2522–
4 2529. <https://doi.org/10.1016/j.ijhydene.2016.04.116>

5 Ganguly, S., Jain, R., Date, A., Akbarzadeh, A., 2017. On the addition of heat to solar pond
6 from external sources. *Solar Energy* 144, 111-116.

7 Karakilcik, M., Dincer, I., Rosen, M.A., 2006. Performance investigation of a solar pond. *Appl.*
8 *Therm. Eng.* 26, 727–735. <https://doi.org/10.1016/j.applthermaleng.2005.09.003>

9 Karakilcik, M., Erden, M., Cilogulları, M., Dincer, I., 2018. Investigation of hydrogen production
10 performance of a reactor assisted by a solar pond via photoelectrochemical process.
11 *International Journal of Hydrogen Energy* 43, 10549-10554.

12 Khalilian, M., 2017a. Assessment of the overall energy and exergy efficiencies of the salinity
13 gradient solar pond with shading effect. *Solar Energy* 158, 311-320

14 Khalilian, M., 2017b. Exergetic performance analysis of a salinity gradient solar pond. *Sol.*
15 *Energy* 157, 895–904. <https://doi.org/10.1016/j.solener.2017.09.010>

16 Leblanc, J., Akbarzadeh, A., Andrews, J., Lu, H., Golding, P., 2011. Heat extraction methods
17 from salinity-gradient solar ponds and introduction of a novel system of heat extraction
18 for improved efficiency. *Sol. Energy*. <https://doi.org/10.1016/j.solener.2010.06.005>

19 Nie, Z., Bu, L., Zheng, M., Huang, W., 2011. Experimental study of natural brine solar ponds in
20 Tibet. *Sol. Energy* 85, 1537–1542. <https://doi.org/10.1016/j.solener.2011.04.011>

21 Njokua, H. O., Agashia, B. E., Onyegebu, S. O., 2017. A numerical study to predict the
22 energy and exergy performances of a salinity gradient solar pond with thermal
23 extraction. *Solar Energy* 15, 744-761

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1 Rahaoui, K., Ding, L .C., Tan, L. P., Mediouri, W., Mahmoudi, F., Nakoa, K., Akbarzadeh, A.,
2 2017. Sustainable membrane distillation coupled with solar pond. *Energy Procedia* 110,
3 414 – 419.
4 Sayer, A. H., Monjezi, A. A., Campbell, A. N., 2018. Behaviour of a salinity gradient solar pond
5 during two years and the impact of zonal thickness variation on its performance. *Applied*
6 *Thermal Engineering* 130, 1191–1198.
7 Simic, M., George, J., 2017. Design of a system to monitor and control solar pond: A review.
8 *Energy Procedia* 110, 322 – 327.
9 Swift, A.H.P., Reid, R.L., Sewell, M.P., Boegli, W.J., 1987. OPERATIONAL RESULTS FOR A
10 3355 m**2 SOLAR POND IN EL PASO, TEXAS., in: *Solar Engineering*. pp. 287–293.
11 Tabor, H., Weinberger, Z., 1981. *Non-Convecting Solar Ponds*.
12 Torkmahalleh, M. A., Askari, M., Gorjinezhad, S., Erog, D., Obaidullah, M., Habib, A. R.,
13 Godelek, S., et al., 2017. Key factors impacting performance of a salinity gradient solar
14 pond exposed to Mediterranean climate. *Solar Energy* 15, 321-329.
15 Valderrama, C., Luis Cortina, J., Akbarzadeh, A., 2016. Solar Ponds, in: *Storing Energy: With*
16 *Special Reference to Renewable Energy Sources*. pp. 273–289. doi:10.1016/B978-0-12-
17 803440-8.00014-2
18 Zangrando, F., 1980. A simple method to establish salt gradient solar ponds. *Sol. Energy* 25,
19 467–470. [https://doi.org/10.1016/0038-092X\(80\)90456-9](https://doi.org/10.1016/0038-092X(80)90456-9)
20 Zhang, G., Wu, Z., Cheng, F., Min, Z., Lee, D. J., 2016. Thermophilic digestion of waste-
21 activated sludge coupled with solar pond. *Renewable Energy* 98,142-147.
22 Ziapour, B.M., Saadat, M., Palideh, V., Afzal, S., 2017. Power generation enhancement in a
23 salinity-gradient solar pond power plant using thermoelectric generator. *Energy Conversion*
24 *and Management* Volume 136, 283-293.