Comparative analysis of the SolWat photovoltaic performance regarding different PV technologies and hydraulic retention times

N. Pichel[a,*], M. Vivar[b], M. Fuentes[b,c]

[a]Nanotechnology and BioEngineering Centre, Ulster University, Northern Ireland BT37 0QB, United Kingdom
[b] Grupo IDEA, EPS Linares, Universidad de Jaén, Linares 23700, Spain
[c] IMDEA Water Institute, Alcalá de Henares 28805, Spain.

*Corresponding author e-mail: nataliapichelccamb@gmail.com

Abstract

SolWat is a hybrid photovoltaic (PV) and photochemical technology, which integrating a PV module and a water disinfection reactor on top of it, was developed to meet the needs of safe drinking-water and electricity in developing countries. This paper assessed the effects of the water disinfection reactor on the electrical performance of the PV module integrated into the SolWat system regarding different hydraulic retention times (HRT) and PV technologies. With this aim, several tests were conducted outdoors under natural climatic conditions. Results showed that while no clear benefits were observed from the water disinfection reactor and reduced HRT on the electrical performance of both monocrystalline and multicrystalline technologies, the final energy output of a-Si thin film PV panels benefited from the cooling effect of water on its front surface being able to produce even more energy than a single PV panel when working at shorter HRT. In addition, the working module temperature was always lower when HRT was shorter; its efficiency under the diffuse light conditions created by the water disinfection reactor was better than monocrystalline and multicrystalline technologies; and its black surface enhanced the absorption of far infrared light and heat by the water disinfection reactor favouring higher water temperatures and thus higher disinfection rates. In conclusion, thin film PV technology is the most suitable to be integrated into the hybrid SolWat systems when comparing with monocrystalline and multicrystalline technologies.

Keywords: comparative analysis, photovoltaic, SolWat, hydraulic retention time, water disinfection, drinking-water

1. Introduction

A close association between waterborne and respiratory diseases has been found, indicating that the same people who lack access to safe drinking-water also lack access to electricity [1]. Currently, 2.1 billion people commonly rely on drinking-water sources that are not safe due to faecal contamination putting them at high risk of contracting waterborne diseases [2]. In addition, 840 million people do not have access to electricity, and more than 2.6 billion rely on solid biomass, kerosene or coal as their primary cooking fuel [3], which is responsible for indoor air pollution. The Sustainable Development Goals (SDG) 6 and 7 reflect the relevance of water safety and energy access on the international agenda [4]. SDG Target 6.1 concerns achieving equitable and universal access to safe drinking-water by 2030, with priority placed on delivering “safely managed” water supplies, defined as drinking water that is free from faecal and priority chemical contamination. The SDG 7 has an ambitious policy in achieving affordable, reliable, sustainable, and modern energy for all (SDG 7) with a special focus on renewable energy included in the SDG Target 7.2. Most of the countries with limited availability to safe water and electricity are located within a large area called ‘sun belt’ zone where irradiance conditions are the most favourable for the use of solar based technologies such as photovoltaic (PV) technology and solar water disinfection (SODIS), which are promising options to improve the coverage of drinking-water and electricity in developing countries.

In this regard, SolWat is a new hybrid photovoltaic and photochemical technology for simultaneous renewable electricity generation and solar water disinfection [5]. It has been developed based exclusively on the use of solar energy for two final applications: (1) visible and near-infrared light for renewable electricity generation, and (2) far-infrared and UV (UVA-UVB) light for pathogenic microorganisms inactivation. SolWat consists of a PV module and a water disinfection reactor fully integrated into a single unit (Fig. 1). The PV module serves as the base of the water disinfection reactor with a layer of water on top; the layer of water is transparent to visible and near-infrared light. Water disinfection occurs between the glass cover of the water disinfection reactor and the PV module. This system is especially suitable for drinking-water treatment and electricity production at household level in developing countries [6, 7], but since it is up-scalable it could also be used for industrial and municipal water treatment applications at a low energy usage but high performance.

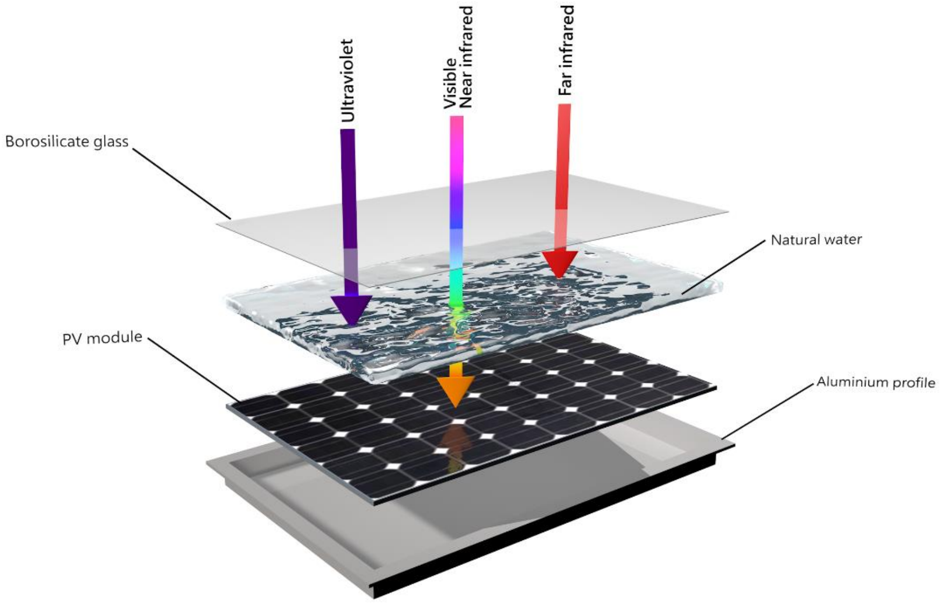


Figure 1. Schematic diagram of the SolWat system including the usage of solar radiation (ultraviolet and far infrared light for water disinfection and visible and near infrared for electricity generation).

The feasibility of this concept has been demonstrated in previous works [8, 9], which show that the hybrid system (PV + SODIS) achieves the same electrical and disinfection results as two independent systems (PV module and a disinfection reactor separately) during 6 h of experimentation. Pichel *et al.* (2018) [10] have also demonstrated that under strong climate conditions (UV levels > 45 W/m^2 and ambient temperature > 33.5 ºC), *E. coli,* total coliforms, *Enterococcus spp.* and *Clostridium perfringens* were completed inactivated after 3 hours of solar treatment, reducing the treatment time recommended for conventional SODIS reactors (6 h) by half. The cited works show that the PV module integrated into SolWat does not lead to major losses caused by the reduced solar irradiation received (lower current, I) due to absorption and dispersion of sunlight by the water purification reactor placed above the PV module, as such losses are compensated by the cooling effect of the water layer being purified on top of the module (higher voltage, V).

Photovoltaic module overheating is along with the received irradiance the major cause of electrical losses and thus one of the major challenges [11]. The received irradiance introduces current losses (I) at lower radiation received by the PV module. Conversely, as the temperature of the PV module increases due to exposure to more than required solar radiation and high-level ambient temperatures, the efficiency as well as the power output of the module decreases (lower voltage, V). Under real operation conditions, the energy output of the SolWat system is affected by the water disinfection reactor located on top of the PV module which introduces energy losses (lower current, I) as consequence of the scattering and absorption effects of sunlight by the water layer and the borosilicate glass. However, the water chamber also presents a positive effect on the energy production since it reduces the working module temperature increasing the voltage values. The water disinfection reactor located on top of the PV module reduce the module temperature by 9 ºC on average [8, 9]. This refrigeration effect is maximum at the beginning of the treatment process and then the water rises its temperature along the disinfection process as it works in batch mode (3 - 6 h static) [8 - 10]. Therefore, the energy output of the PV module integrated into the SolWat system could benefit from lower operational temperatures in shorter treatment times if properly optimised in combination with a smart water disinfection process strategy on top. On the other hand, despite it was initially suggested that PV cells of any technology could be integrated into the SolWat system [12], a comparative analysis of the SolWat electrical performance regarding different PV technologies has never been conducted. Studies performed since the SolWat concept development in 2010 [5] have indistinctly used monocrystalline [6, 7, 10, 13, 14], multicrystalline [11] and thin film [8, 9] panels with no any consolidated criteria on which the choice was based. This is because the effects of the water disinfection reactor on the electrical performance of the PV module integrated into the

SolWat system has not been assessed considering different PV technologies yet. As well as their effect on the disinfection process has not been considered either.

Based on the identified needs, the main objective of the present work is to study the effect of the water disinfection reactor on the electrical performance of the PV module integrated into the SolWat system regarding different hydraulic retention times (HRT) and PV technologies. This will be helpful not only to assess the possible benefits on the final energy output derived from lower module temperatures in less time of treatment, but also to provide adequate criteria to choose the most suitable PV technology to be integrated into the SolWat system.

2. Materials and methodology

2.1 The experimental set-up

Several tests were carried out in the rooftop facilities of the IMDEA Water Institute (Alcalá de Henares, Spain) from July to September 2018. Two experimental sets can be distinguished: (I) tests conducted to study the effect of the water disinfection reactor on the electrical performance of the PV module integrated into the SolWat system by applying different HRT; and (II) tests carried out to compare the electrical performance of the hybrid system regarding different photovoltaic technologies. All the experiments were undertaken placing the systems on a fixed solar structure tilted 40° (Alcalá de Henares is at 40° N latitude) and N-S oriented. A pyranometer was also located on the same structure.

On one hand, regarding the experimental set (I) three hybrid SolWat systems, plus a single PV module acting as reference, were placed on a fixed solar structure. The hybrid systems were filled with Milli-Q water (initially at room temperature, 25 °C) and exposed to natural sunlight for 6 hours. However, each SolWat system was subjected to different hydraulic retention times: (1) SolWat A, HRT of 6 h, the system was filled once at the beginning of the experiment and emptied at the end; (2) SolWat B, HRT of 3 h, the system was filled and after 3 hours emptied, to be again refilled with fresh Milli-Q water; and (3) SolWat C, HRT of 2 h, the system was filled and emptied a total of three times during the 6-hour experimentation period. The four systems, three hybrids plus the reference PV module (without the water chamber on top), were of the same photovoltaic technology and they were evaluated simultaneously. The effect of HRT on the SolWat PV panel was assessed for monocrystalline, multicrystalline and thin film PV technologies (Fig. 2). This experimental configuration was performed at least once per each photovoltaic technology tested.

Figure 2. Reference panels and SolWat systems of monocrystalline, multicrystalline and a-Si thin film technologies to assess the effect of the water disinfection reactor on top of the PV module at different hydraulic retention times (6, 3 and 2 hours). Each experiment was composed by three SolWat systems and a reference panel (without the water chamber on top) of the same PV technology and characteristics. It is included the schematic diagram of data acquisition and recording system including the flow chart of the hydraulic retention and the reactors layout.

On the other hand, regarding the experimental set (II), monocrystalline PV performance was compared with multicrystalline and thin film photovoltaic technologies. With this aim, two tests were carried out: (1) one comparing monocrystalline vs. multicrystalline PV technology, and another one (2) comparing monocrystalline vs. thin film technology. In the first test, a single PV module and a hybrid SolWat system, both of monocrystalline technology, were placed on the solar structure along with a single multicrystalline PV panel and a hybrid multicrystalline SolWat system (Fig. 3a). In the second one, the monocrystalline single module and the SolWat system were placed on the structure along with a single thin film PV panel and a thin film SolWat system (Fig. 3b). The hybrid systems were filled with Milli-Q water an exposed to natural sunlight for 6 hours (HRT of 6 h). In each experiment, the four panels were evaluated simultaneously (Fig. 3 c).

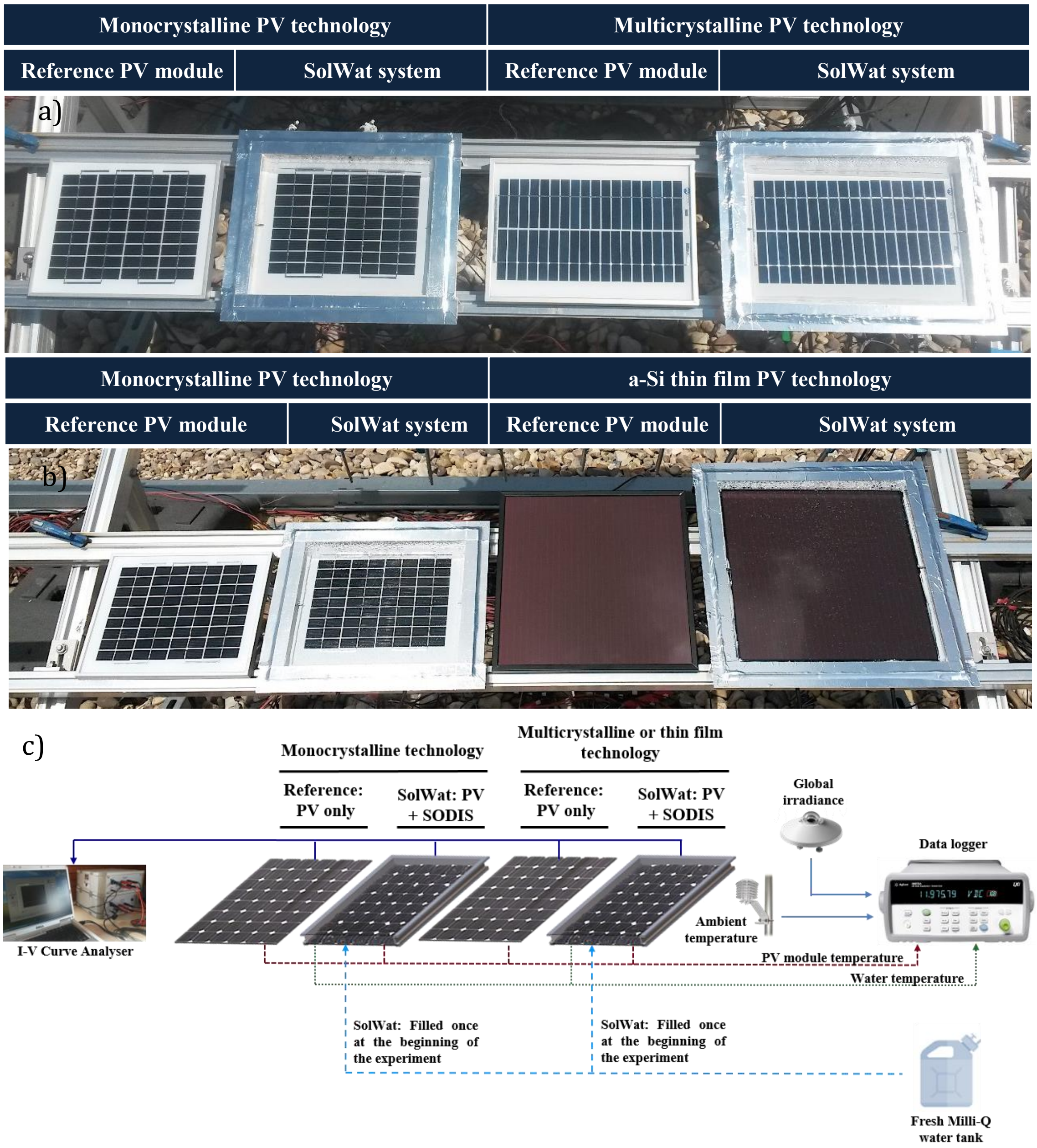


Figure 3. Experimental configuration for the comparison of the electrical performance of SolWat systems of different technologies: a) monocrystalline vs. multicrystalline technology; b) monocrystalline vs. thin film technology; and c) schematic diagram of data acquisition and recording system including the flow chart of the hydraulic retention and the reactors layout.

2.2 The SolWat systems

Three groups of reactors were manufactured attending the PV technology employed. Monocrystalline, multicrystalline and thin film (amorphous silicon, a-Si) PV modules were selected. Each group comprised a total of 3 hybrid SolWat systems (water disinfection reactor coupled with a PV module) plus one single PV module (without the water disinfection reactor on top) acting as reference. Three hybrid systems per each PV technology were manufactured to have one per each HRT (6, 3 and 2 hours). So, a total of 12 PV modules, 4 of each technology presenting the same electrical and physical characteristics, were acquired. Table 1 shows the modules characteristics provided by the manufacturers at standard test conditions (STC).

Table 1. Photovoltaic modules specifications at STC (*) provided by the manufacturers.

	Monocrystalline	Multicrystalline	Thin film (a-Si)
$P^*_{MOD,M}$ (W)	5	5	7
$V^*_{MOD,OC}$ (V)	22.6	21.0	21.5
$I^*_{MOD,SC}$ (A)	0.29	0.39	0.46
P_M T coef (%/°C)	- 0.47	- 0.675	- 0.36
V_{OC} T coef (%/°C)	- 0.38	- 0.13	- 0.29
I_{SC} T coef (%/°C)	+ 0.04	+ 0.003	-
Dimensions (mm)	260 x 210	306 x 218	315 x 315
No of cells	36	36	multi-layered a-Si solar cells
Total cell area (m^2)	0.028	0.034	0.086
Manufacturer	Techno Sun (Spain)	RS Pro (UK)	Xunzel (Spain)

T coef: temperature coefficient

All panels were electrical characterised under real sun (solar irradiance <800 W/m^2) before the manufacturing process. The characterisation was performed after subjecting the monocrystalline and multicrystalline PV modules to an initial degradation under 55 kWh/m^2 of sun exposure according to IEC 61215 standard for crystalline silicon terrestrial photovoltaic modules [15]. The thin film modules were exposed to 60 kWh/m^2 according to IEC 61646 standard for thin film PV modules [16]. The characterisation was carried out taking the main electrical parameters (maximum power $P_{MOD,M}$, open circuit voltage $V_{MOD,OC}$ and short circuit current $I_{MOD,SC}$), which were then turned to STC (*) by equations 1-3, respectively [17]:

$$P^*_{MOD,M} = (P_{MOD,M} \cdot G^{STC}/G)/(1+\delta_{Pmax}\,(T_{cell} - T^{STC}) \tag{1}$$

$$V^*_{MOD,OC} = (V_{MOD,OC} \cdot G^{STC}/G)/(1+\delta_{Voc}\,(T_{cell} - T^{STC}) \tag{2}$$

$$I^*_{MOD,SC} = (I_{MOD,SC} \cdot G^{STC}/G)/(1+\delta_{Isc}\,(T_{cell} - T^{STC}) \tag{3}$$

where $P^*_{MOD,M}$ is the maximum power at STC (W), $P_{MOD,M}$ is the measurement of the maximum power (W), δ_{Pmax} is the power temperature coefficient (%/°C), $V^*_{MOD,OC}$ is the open circuit voltage at STC (V), $V_{MOD,OC}$ is the measurement of the open circuit voltage (V), δ_{Voc} is the voltage temperature coefficient (%/°C), $I^*_{MOD,SC}$ is the short circuit current at STC (A), $I_{MOD,SC}$ is the measurement of the short circuit current (A), δ_{Isc} is the current temperature coefficient (%/°C), T_{cell} is the measurement of the module temperature (°C) corrected by equation 5, T^{STC} is the standard test module temperature of 25 °C, G is the measurement of the global solar irradiance (W/m^2), G^{STC} is the standard test irradiance of 1000 W/m^2. The module/cell efficiency, referring to the ratio of energy output from the solar module/cell to input energy from the sun, was calculated by equation 4. The module efficiency was calculated considering all the PV module surface (area covered by PV cells, area without PV cells and the module frame), while the PV cell efficiency only considers PV cells area of the module:

$$ŋ^* = (P^*_{MOD,M}/(G^* \cdot A))\ 100 \qquad (4)$$

where $ŋ^*$ is the module or cell efficiency at STC (%), $P^*_{MOD,M}$ is the maximum power at STC (W), G^{STC} is the standard test irradiance of 1000 W/m^2 and A is the module area (m^2) for module efficiency or PV cell area (m^2) for cell efficiency. Main results from the electrical characterisation are shown in table 2.

Table 2. Electrical characterisation (at STC) of the photovoltaic modules used for the SolWat and reference panels of monocrystalline, multicrystalline and a-Si thin film technology.

		Global irradiance (W/m^2)	Cell Temperature (°C)	$P_{MOD,M}$ (W)	$P^*_{MOD,M}$ (W)	$V^*_{MOD,OC}$ (V)	$I^*_{MOD,SC}$ (A)	Cell efficiency (%)	Module Efficiency (%)
Monocrystalline	Reference	970.6	56.3	4.3	5.2	23.0	0.30	15.2	7.8
	SolWat A	970.6	55.5	4.3	5.0	23.2	0.30	15.3	7.9
	SolWat B	952.4	59.8	4.5	5.6	23.6	0.32	16.0	8.2
	SolWat C	910.1	48.8	4.4	5.4	24.6	0.31	15.6	8.0
Multicrystalline	Reference	1084.9	37.8	6.0	5.7	20.0	0.37	17.8	9.1
	SolWat A	1084.9	37.7	6.1	6.1	20.2	0.36	17.8	9.1
	SolWat B	1084.9	37.7	5.9	5.9	20.0	0.36	17.3	8.8
	SolWat C	1084.9	37.7	5.6	5.6	20.2	0.36	16.5	8.4
Thin film (a-Si)	Reference	934,2	52.4	5.6	7.4	24.5	0.47	8.6	7.4
	SolWat A	830.8	35,9	4.7	6.1	27.2	0.51	7.1	6.1
	SolWat B	830.8	37.6	4.6	6.0	26.7	0.52	6.9	6.0
	SolWat C	830.8	35.9	4.8	6.2	26.6	0.48	7.2	6.2

Having initially degraded and electrically characterised the PV modules, the manufacturing process of the water disinfection reactors started. This process followed the same steps for all the hybrid systems independently of the PV technology. Firstly, an aluminium frame was built and fixed to the frame of the solar panels to create the space for the water disinfection treatment. The aluminium frame included the water temperature sensors and connectors to provide the systems with water inputs and outputs. A water layer of 18 mm height was established for all the systems, which gave a reactor capacity of approximately 1 L, 1.2 L and 1.8 L for monocrystalline, multicrystalline and thin film SolWat systems, respectively. Secondly, borosilicate glass of 2 mm thickness with high transmittance for UVA-UVB, visible and infrared spectrum [9, 18] was used to cover the water disinfection reactor. Glazing silicone was used for structural adhesion and sealing functions. Finally, the water reactors were filled by a pump that propelled the water through a network of pipes.

2.3 Environmental conditions and electrical parameters monitoring

Parameters monitored include global irradiance (Kipp & Zonen CMP-21 pyranometer, ISO 9060 spectrally flat Class A, 1 % accuracy), ambient temperature (PT100 sensor with shield protector, standard tolerance PT100 A class ± 0.15 °C + 0.002 [t°C]), and water temperature within the water disinfection reactors (NTC immersion sensors -10 K-, accuracy ± 0.5 °C). NTC sensors were placed at the aluminium frame of each SolWat reactor. Back-of-module temperature was also measured using PT100 sensors (standard tolerance PT100 A class ± 0.15 °C + 0.002 [t°C]) located at the back part of the PV modules integrated into the SolWat systems and at the reference PV modules following IEC 60904 [19]. In addition, since the cell temperature for the open-rank mounted PV module is higher than rear module temperature by 2 – 3 ºC, cell temperature was determined by [20]:

$$T_{PV} = T_{BF} + 3G/G^{STC} \tag{5}$$

where T_{PV} is the photovoltaic cell temperature (°C), T_{BF} is the measurement of the back-of-module temperature (°C), G is the global solar irradiance (W/m^2) and G^{STC} is the standard test irradiance of 1000 W/m^2. Module and cell efficiency was calculated as follow:

$$\eta = (P_{MOD,M}/(G \cdot A))\ 100 \tag{6}$$

where η is the module or cell efficiency (%), $P_{MOD,M}$ is the measurement of the maximum power (W), G is the measurement of the global solar irradiance (W/m^2), and A is the module area (m^2) for module efficiency or PV cell area (m^2) for cell efficiency.

In order to assess the electrical performance of the PV panels, a PV-KLA 4.4 I-V Curve Analyser (basic accuracy 0.1 % from fullscale) manufactured by Ingenieurbüro with a multiplexer was used. It has capacity to monitor four photovoltaic panels simultaneously. Thus, since each experimental test comprises a total of four panels, they were always evaluated simultaneously. Complete I-V curves that provided the main electrical parameters including maximum power $P_{MOD,M}$, open circuit voltage $V_{MOD,OC}$ and short circuit current $I_{MOD,SC}$ were obtained every 60 s. Data was recorded by an Agilent 34972 data logger. Equipment, monitoring process and data analysis were in compliance with standard 61724 from the International Electrotechnical Commission (IEC) [21].

3. Results and discussion

A total of seven tests were conducted in the rooftop facilities of IMDEA Water (Alcalá de Henares, Spain) in summer 2018. Monocrystalline (5 W), multicrystalline (5 W) and a-Si thin film (7 W) photovoltaic modules were used to: (I) study the effect of different hydraulic retention times (6, 3 and 2 hours) on the electrical performance of the PV panel integrated into the SolWat system; and (II) compare the electrical performance of the hybrid system regarding different photovoltaic technologies. Experiments were conducted under average global irradiance levels exceeding 800 W/m^2 and average ambient temperatures above 25 ºC, with corresponding maximum values above 1000 W/m^2 and 28.0 ºC, respectively. Table 3 summarise the tests performed and the meteorological conditions for each experimental day.

Table 3. Description of the main experimental features in terms of experimental set, characteristics, date and meteorological conditions.

Experimental set	Test number	Characteristics	Date (dd/mm/yyyy)	Global irradiance (W/m^2)		Ambient temperature (ºC)	
				Average	Maximum	Average	Maximum
(I) Study of the effect of the water disinfection reactor on the PV module at different HRT	Test #1	Monocrystalline	12/09/2018	854.9	1032.1	26.8	30.4
	Test #2	Monocrystalline	24/09/2018	921.8	1049.2	28.6	32.7
	Test #3	Multicrystalline	31/07/2018	872.3	1034.5	33.5	35.6
	Test #4	Thin film	13/09/2018	894.4	1040.9	30.4	32.7
	Test #5	Thin film	20/09/2018	898.1	1041.0	28.2	31.7
(II) Comparison of the performance of PV technologies integrated into the SolWat system	Test #6	Monocrystalline vs. multicrystalline	01/08/2018	880.6	1015.8	35.2	38.3
	Test #7	Monocrystalline vs. thin film	05/09/2018	818.3	1113.0	26.1	28.6

3.1 Effects of the water disinfection reactor on the SolWat PV performance

Table 4 summarise the main electrical results obtained from monocrystalline, multicrystalline and a-Si thin film PV modules acting as references (without the water chamber on top) and integrated into the SolWat systems for hydraulic retention times of 6, 3 and 2 hours, including the average water temperature.

As to the a-Si thin film PV technology, after 6 h of sun exposure, the final energy output of the reference panel was always higher than the hybrid systems, regardless of the HRT. The energy output of the reference module was 31.2 Wh, SolWat A 27.4 Wh, SolWat B 27.7 Wh and SolWat C 29.9 Wh in test #4 (Fig. 4), and 31.6 Wh, 28.1 Wh, 28.0 Wh and 30.0 Wh in test #5, respectively. However, these differences can also be attributed to the different efficiencies of the four panels under STC, without the water disinfection reactor on top, which they were also different, being slightly higher for the reference panel: 7.4 %, 6.1 %, 6.0 % and 6.2 %, respectively. Relative measurements would need to be use instead of absolute measurements to evaluate the effect of the different HRT. In fact, if each module's electrical losses were compared to its electrical output under STC, the real effect would be seen. In this case, electrical losses were minimum for the system with the shorter HRT (19.7 % in test #4 - 17.9 % in test #5), followed by the system with a 3-hour HRT (22.1 % in test #4 - 21.3 % in test #5) and a 6-hour HRT (24.6 % in test #4 - 22.9 % in test #5), and were maximum for the single PV module acting as the reference (28.9 % in test #4 - 28.4% in test #5). This means that the thin film PV module integrated into the SolWat system actually benefits from the cooling effect of water on its front surface, and this benefit is greater the shorter the HRT. This is better understood by observing the average working temperature of all four modules (Fig. 4). While the temperature for the reference PV module was of 57.9 °C in test #4 and 55.1 ºC in test 5, the PV modules integrated into the SolWat systems worked at lower temperatures, which were lower when HRT was shorter: 53.2°C SolWat A, 51.6°C SolWat B and 49.2°C SolWat C in test #4 and 49.7 ºC, 48.9 ºC and 46.7 ºC in test #5, respectively.

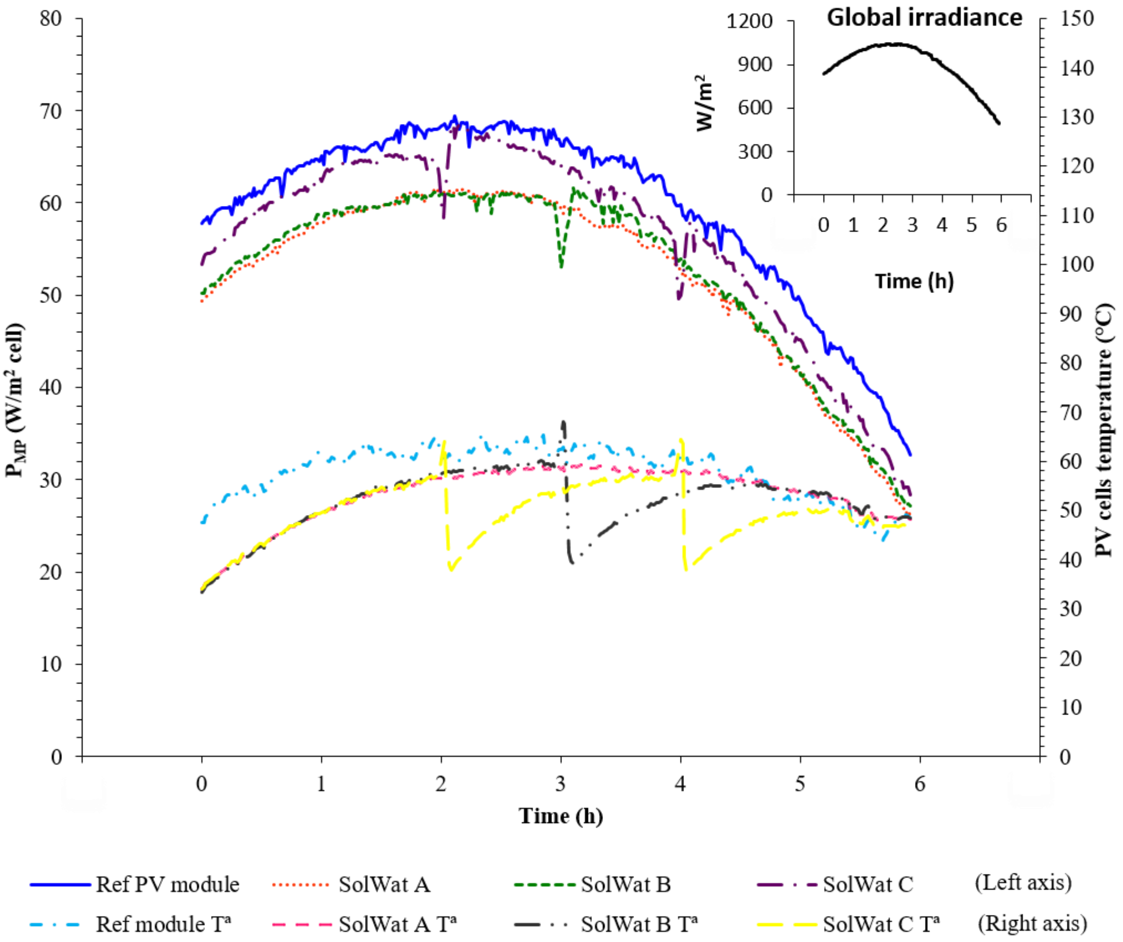


Figure 4. Power and PV cell temperature of a-Si thin film PV panels acting as reference and integrated into SolWat A (6-h HRT), SolWat B (3-h HRT) and SolWat C (2-h HRT). Test #4 performed on 13rd September 2018. It is observed how the power output of the reference panel is slightly higher than the SolWat hybrid systems, which can be attributed to a higher efficiency at STC. However, when relative measurements were applied, electrical losses were maximum for the reference module and minimum for the SolWat systems with shorter HRT. Working module temperatures were lower for the hybrid systems (which were lower when HRT was shorter) and higher for the single panel acting as reference. It can be clearly seen how the module temperature dropped every time the SolWat systems were refilled with Milli-Q water (initially at 25 °C), and how the power of the modules integrated into the SolWat systems increased immediately after as consequence of the reduction in module temperature (higher voltage).

The energy output of the multicrystalline reference panel was 21.6 Wh, SolWat A 21.6 Wh, SolWat B 20.9 Wh and SolWat C 20.2 Wh. Once again, the energy produced by the reference module, and in this case also by the SolWat A (both with 9.1 % efficiency at STC), was higher than the hybrid systems with shorter HRT. However, if we compare the electrical output decrease of each module in relation to their electrical output at STC, multicrystalline PV technology showed a completely different behaviour from thin film technology. Contrary to what happened with thin film panels, electrical losses were minimum for the reference panel (21.8 %) and maximum for the hybrid system with the shorter HRT (30.8 %). No differences were observed between SolWat A and SolWat B, despite they worked at different HRT (6 and 3-h HRT, respectively) and thus at different temperatures (54.9 ºC and 50.6 ºC on average, respectively), both presenting 28.4 % of electrical losses vs. STC. In addition, the average module temperature was slightly lower for the reference panel (54.4 ºC) than for SolWat A (54.9 ºC) so, the refrigerated effect was not observed in the hybrid system with 6-hour HRT vs. a reference panel without the water chamber on top. When the HRT was reduced to 3 h and 2 h, module temperature dropped 3.8 ºC (reference panel vs. SolWat B) and 4.3 ºC (reference panel vs. SolWat C). However, a positive effect of the lower working module temperature on the electrical performance of multicrystalline panels integrated into the SolWat systems B and C was not observed. This shows that when working with multicrystalline technology, the water chamber located on top of the PV panel presented a negative effect on its electrical performance, not benefiting from the refrigerating effect of the water layer. Therefore, the current losses introduced by light scattering were not compensated by reducing the temperature losses.

In monocrystalline modules, although the final energy output was slightly higher for SolWat B (3 h HRT) and C (2 h HRT), with corresponding values of 22.8 Wh and 22.6 Wh in test #1 (21.8 Wh in reference module and 21.4 Wh in SolWat A) and 24.8 Wh and 24.4 Wh in test 2 (24.0 Wh in reference module and 23.4 Wh in SolWat A), these modules presented the higher efficiencies at STC with corresponding values of 8.3 % and 8.2 % vs. 8.0 % for reference module and 7.7 % for SolWat A. However, energy losses in relation to STC were maximum for the SolWat B despite it presented the lowest working temperature, which was even lower than the hybrid system with the shorter HRT (2 h). Differences in module temperature between SolWat C and B were of 3 ºC (test #1) and 8.3 (test #2). As it happened with multicrystalline technology, under same irradiation conditions lower working temperature did not correspond with higher energy production. In addition, lower HRT did not mean lower module temperatures.

Regarding water temperature, maximum levels always exceeded 48.0 ºC with a peak of 58.8 ºC in thin film hybrid systems. Attending to the average values, differences were observed for the three HRT tested. Water in SolWat A presented the higher average temperature, which was always lower in SolWat C. This is due to the longer exposition of water to solar radiation in SolWat A (a total of 6-h), compared with SolWat systems B (HRT of 3-h) and C (HRT of 2-h), which were refilled with fresh Milli-Q water during the 6 hours of experimentation. In addition, the last cycle of the SolWat C started 1-2 h after the solar noon, when received solar radiation is lower. Differences were also observed when comparing the PV technologies. Water exceeded ambient temperature in 18.7 ºC in thin film technology, while this value dropped to 14.7 ºC in multicrystalline modules and to 13.7 ºC in monocrystalline panels.

Table 4. Main electrical results obtained from monocrystalline, multicrystalline and a-Si thin film PV modules acting as references and integrated into the SolWat systems for hydraulic retention times of 6 (SolWat A), 3 (SolWat B) and 2 (SolWat C) hours.

			Generated energy (Wh)	Efficiency (%)	I_{SC} (A)	P_{MP} (W)	P_{MP} loss ratio in relation to STC (%)	Average cells temperature (ºC)	Average water temperature (ºC)
Monocrystalline	Test #1	Reference	21.8	8.0	0.36	3.7	28.5	56.5	-
		SolWat A (6-h HRT)	21.4	7.7	0.33	3.6	27.2	46.9	43.0
		SolWat B (3-h HRT)	22.8	8.3	0.33	3.9	30.5	42.0	42.9
		SolWat C (2-h HRT)	22.6	8.2	0.35	3.9	28.5	45.0	41.8
	Test #2	Reference	24.0	8.1	0.36	4.0	22.1	50.2	-
		SolWat A (6-h HRT)	23.4	7.8	0.33	4.0	20.9	43.8	40.1
		SolWat B (3-h HRT)	24.8	8.3	0.33	4.2	25.2	35.0	40.8
		SolWat C (2-h HRT)	24.4	8.2	0.35	4.1	23.5	43.3	39.8
Multi crystalline	Test #3	Reference	21.6	7.5	0.35	4.4	21.5	54.4	-
		SolWat A (6-h HRT)	21.6	7.5	0.34	4.4	28.4	54.9	48.9
		SolWat B (3-h HRT)	20.9	7.3	0.34	4.2	28.4	50.6	48.4
		SolWat C (2-h HRT)	20.2	7.1	0.34	4.1	30.8	50.1	47.3
a-Si thin film	Test #4	Reference	31.2	5.9	0.55	5.3	28.9	57.9	-
		SolWat A (6-h HRT)	27.4	5.2	0.55	4.6	24.6	53.2	51.5
		SolWat B (3-h HRT)	27.7	5.2	0.55	4.7	22.1	51.6	49.8
		SolWat C (2-h HRT)	29.6	5.6	0.55	5.0	19.7	49.3	46.8
	Test #5	Reference	31.6	5.9	0.55	5.3	28.4	55.1	-
		SolWat A (6-h HRT)	28.1	5.3	0.55	4.7	22.9	49.7	47.9
		SolWat B (3-h HRT)	28.0	5.3	0.55	4.7	21.3	48.9	46.9
		SolWat C (2-h HRT)	30.3	5.7	0.55	5.1	17.9	46.7	44.8

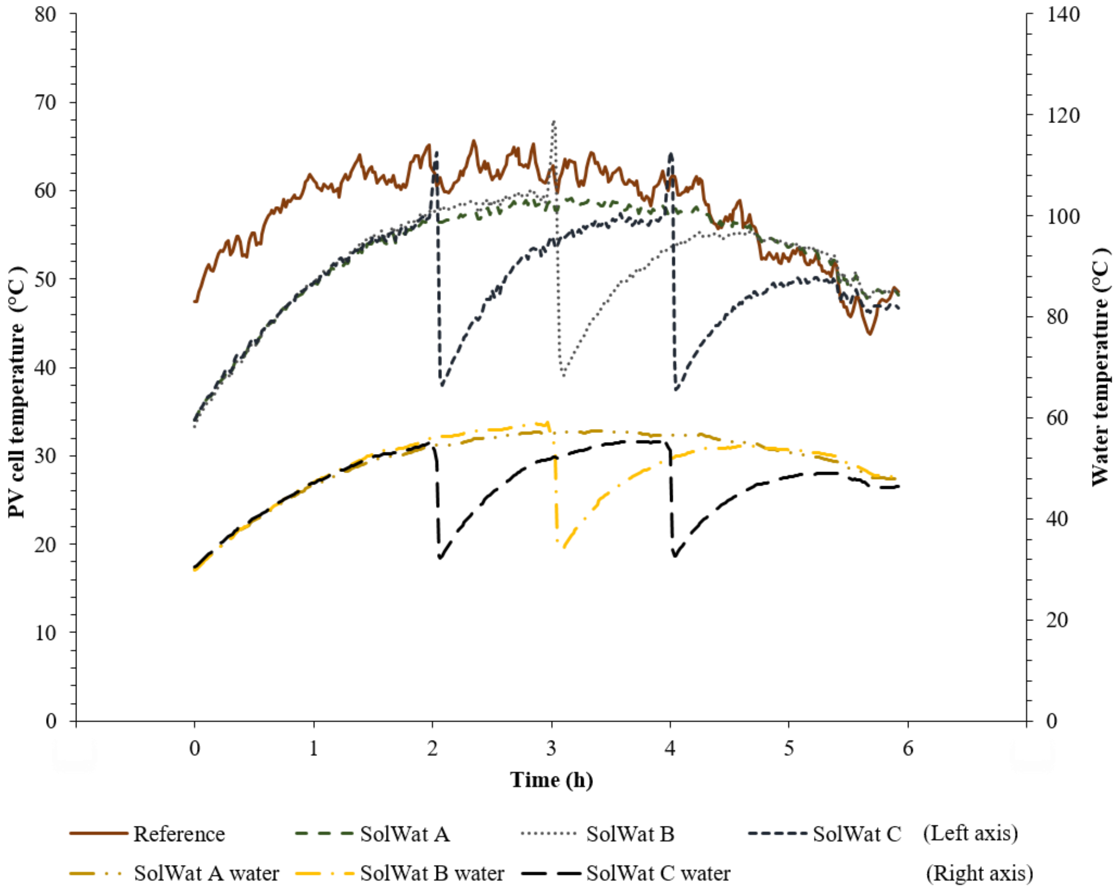


Figure 5. PV cell and water temperature in the reference and SolWat systems A (6-h HRT), B (3-h HRT) and C (2-h HRT) of thin film technology for the 6 h of experimentation. Test #4 performed on 13rd September 2018. The SolWat PV modules benefit from the cooling effect of the water chamber located on top vs. the single panel that operates at higher temperature (4.7 °C, 6.3 °C and 8.7 °C higher on average vs. SolWat A, B and C, respectively).

3.2 Photovoltaic technology

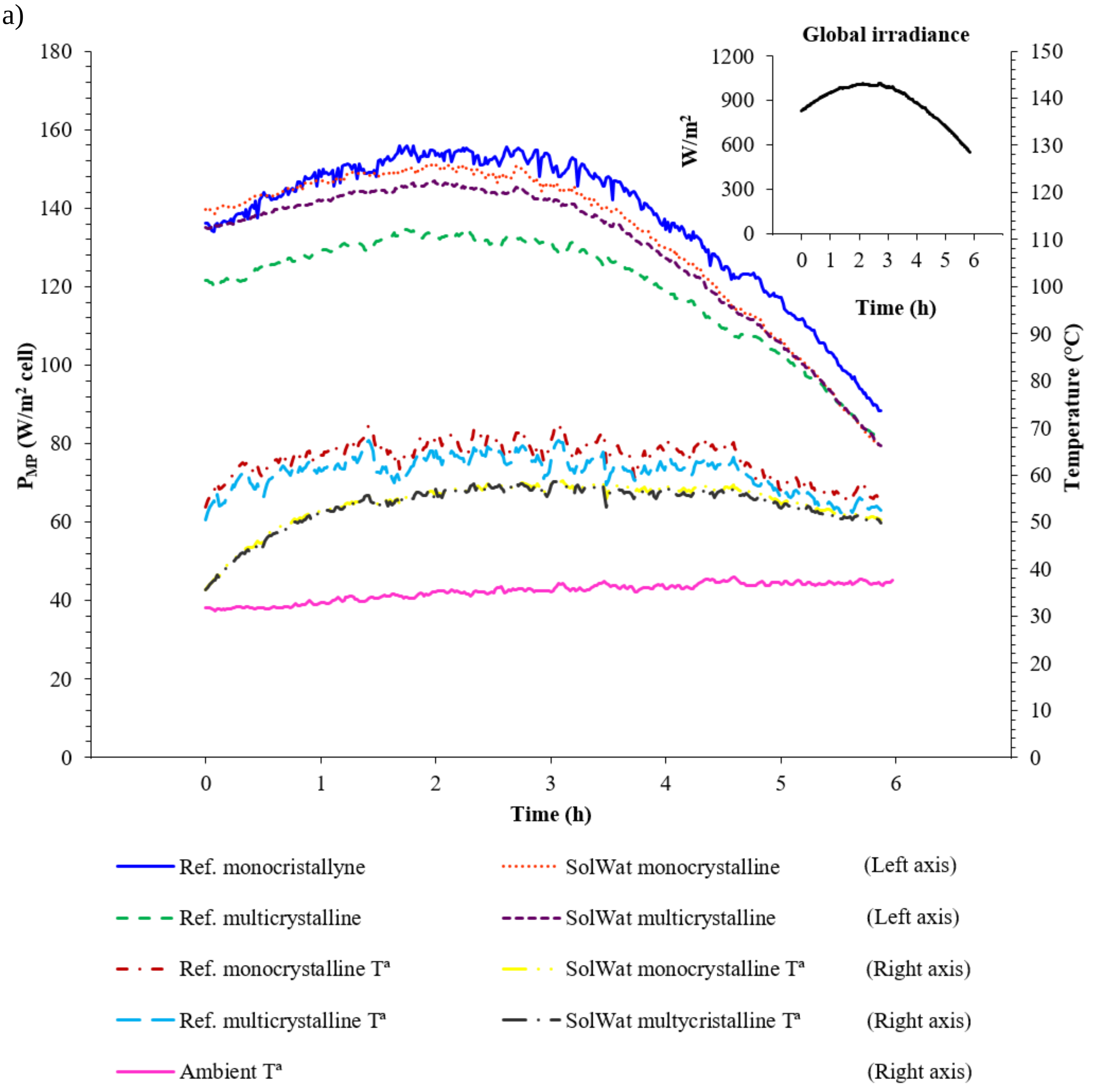
Main electrical results obtained from the comparison of monocrystalline vs. multicrystalline and thin film technologies, including water temperature, are shown in table 5.

Under the same climatic conditions (solar radiation and ambient temperature), the energy output of the PV module integrated into the multicrystalline SolWat system was higher than the reference panel (both modules with 7.5 % efficiency at STC), while it was slightly lower for the monocrystalline SolWat system in comparison with a single panel (SolWat system 22.1 Wh vs. reference panel 23.0 Wh) (Fig. 6a). However, monocrystalline modules presented different efficiencies at STC, being slightly lower for the module integrated into SolWat (table 2). The solar radiation received by the module integrated into the SolWat systems was 16.7 % (monocrystalline) and 7.9 %

(multicrystalline) lower than the radiation received by the single modules acting as reference, in terms of I_{SC}. Despite the PV modules integrated into the hybrid systems received less solar radiation than the reference panels, their average working temperature was also lower: 63.3 ºC reference panel vs. 54.0 ºC SolWat panel (monocrystalline) and 60.3 ºC reference panel vs. 53.4 ºC SolWat panel (multicrystalline). While the lower radiation received by the module integrated into SolWat introduces current losses (I), the lower module temperature benefits the electricity production by increasing the voltage values at lower temperature. As result, after 6-h of sun exposure, electrical losses of the reference and SolWat panels vs. their electrical losses at STC were similar: 27.2 % and 27.3 % in multicrystalline technology and 26.0 % and 25.9 % in monocrystalline technology for the reference and SolWat panels, respectively. On the other hand, with an average ambient temperature of 35.2 ºC, water temperature reached a maximum of 55.1 ºC in the monocrystalline SolWat system and 56.2 ºC in the multicrystalline SolWat system, with corresponding averages levels of 50.8 ºC and 51.8 ºC.

From the comparison of monocrystalline and thin film PV technologies (Fig. 6b), which was performed in a partially cloudy day, it was observed that the energy output of the reference panels was higher than the energy produced by the hybrid SolWat systems. The generated energy of SolWat and reference panels was 20.6 Wh and 21.2 Wh in monocrystalline technology, and 24.5 Wh and 28.7 Wh in thin film technology. However, attending to relative measurements it was observed that the electrical losses vs. STC were higher for the single panels acting as reference without the water chamber on top than for the hybrid systems after 6 hours of solar radiation. Monocrystalline and thin film SolWat PV modules received 5.3 % and 10.5 % less solar radiation in comparison with the reference panels, but they also worked at lower temperatures: 4.6 ºC (monocrystalline) and 4.1 ºC (thin film) below the single panels. Average water temperature reached 39.3 ºC and 37.0 ºC in thin film and monocrystalline SolWat systems with corresponding maximum levels of 43.8 ºC and 41.2 ºC respectively. This test was performed under an average ambient temperature of 26.1 ºC (maximum of 28.6 ºC).

a)


Global irradiance
W/m^2
1200
900
600
300
0
0 1 2 3 4 5 6
Time (h)
P_{MP} (W/m^2 cell)
180
160
140
120
100
80
60
40
20
0
Temperature (°C)
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6
Time (h)
Ref. monocristallyne
SolWat monocrystalline
(Left axis)
Ref. multicrystalline
SolWat multicrystalline
(Left axis)
Ref. monocrystalline Tª
SolWat monocrystalline Tª
(Right axis)
Ref. multicrystalline Tª
SolWat multycristalline Tª
(Right axis)
Ambient Tª
(Right axis)

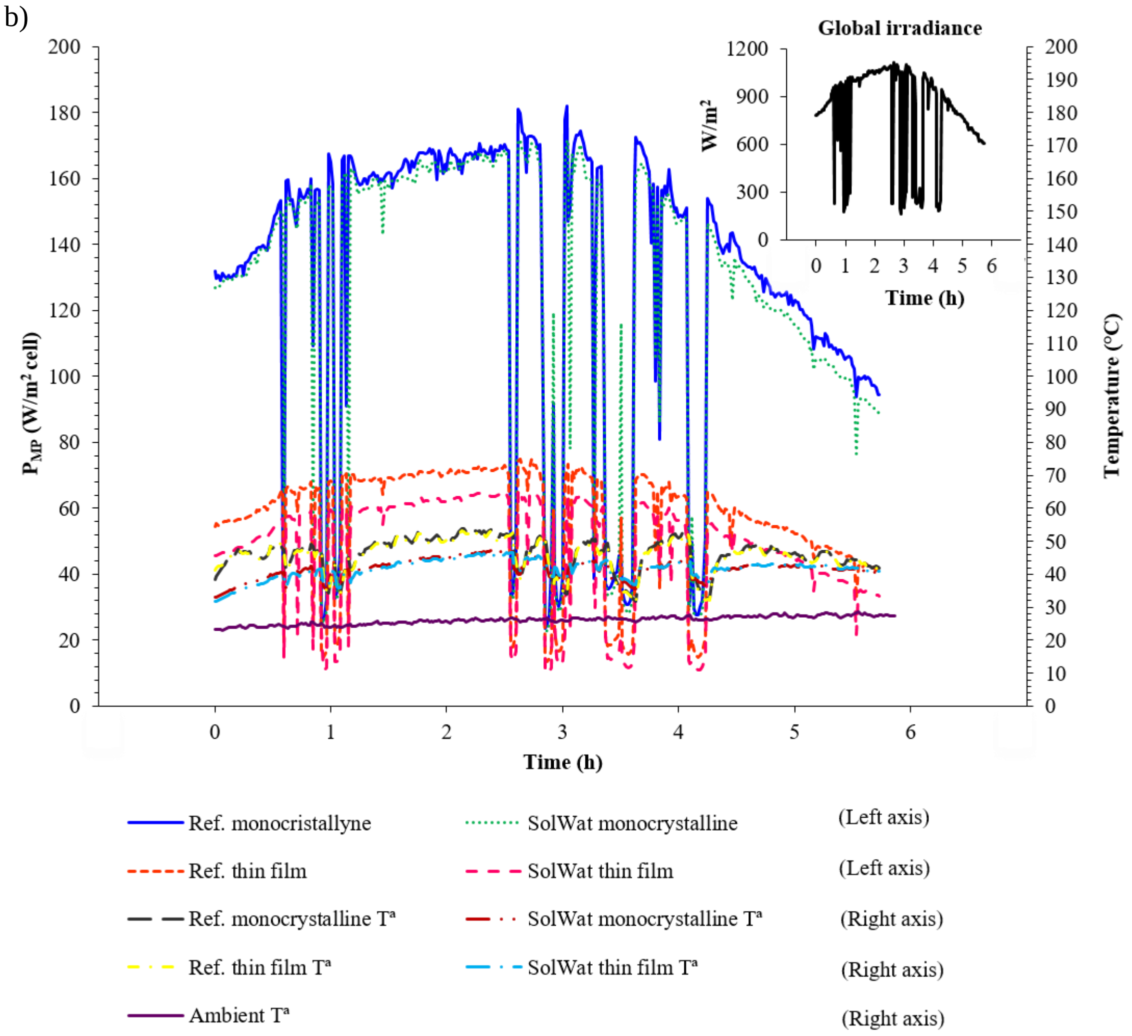


Figure 6. Ambient temperature (Tª), back module temperature and power output of reference panel and the SolWat system registered from the comparison of (a) monocrystalline vs. multicrystalline technology; and (b) monocrystalline vs. thin film technology. It can be observed that the energy output of the SolWat monocrystalline PV module was higher than the reference panel, while it was lower for the monocrystalline and thin film SolWat system in comparison with the single panels. However, while both SolWat and reference multicrystalline modules presented the same efficiency at STC (7.5 %), monocrystalline and thin film modules presented different efficiencies, being slightly lower for the modules integrated into SolWat. Working module temperatures of SolWat PV modules were lower than the single panels. As result, electrical losses of both reference and SolWat PV modules vs. their electrical losses at STC were similar in monocrystalline and multicrystalline, but these losses were higher for the single thin film panel when comparing with a SolWat thin film hybrid system, showing that this technology actually benefited from the presence of the water chamber on top.

Table 5. Summary of main results obtained from the comparison of the electrical performance of SolWat and reference panels of different technologies: monocrystalline vs. multicrystalline technology and monocrystalline vs. a-Si thin film technology.

			Generated energy (Wh)	Efficiency (%)	I_{SC} (A)	P_{MP} (W)	P_{MP} loss ratio in relation to STC (%)	Average cells temperature (ºC)	Average water temperature (ºC)
[1] Test 6	Monocrystalline	Reference	23.0	8.0	0.36	3.9	26.0	63.3	-
	Monocrystalline	SolWat	22.1	7.7	0.30	3.7	25.9	54.0	50.8
	Multicrystalline	Reference	24.2	7.5	0.38	4.1	27.2	60.3	-
	Multicrystalline	SolWat	26.1	7.5	0.35	4.4	27.3	53.4	51.8
[2] Test 7	Monocrystalline	Reference	21.2	8.0	0.38	3.6	30.1	46.2	-
	Monocrystalline	SolWat	20.6	7.7	0.36	3.5	29.3	41.6	37.0
	a-Si thin film	Reference	28.7	5.9	0.57	4.9	33.6	45.6	-
	a-Si thin film	SolWat	24.5	5.3	0.51	4.2	31.3	41.5	39.3

[1] Monocrystalline vs. multicrystalline PV technology; [2] Monocrystalline vs. a-Si thin film PV technology

3.3 Discussion

As to the HRT tests, contrary to what happened with monocrystalline and multicrystalline technologies, the final energy output of thin film PV panels integrated into the SolWat system benefited from the water layer on top. The behaviour of monocrystalline and multicrystalline modules can be explained by the mayor cause of electrical losses in photovoltaic modules, the received irradiance. This is crucial in the SolWat system due to its configuration, with a water reactor on top of the PV panel. This reactor is made up of borosilicate glass and water that contribute to the absorption and dispersion of sun-light, resulting in a lower received irradiance by the PV module, and therefore in a lower I_{SC}. However, this phenomenon could unevenly affect the different technologies tested. The monocrystalline PV modules integrated into the SolWat systems A and B received 8.3 % less solar radiation than the reference panel attending the I_{SC} values. Losses that dropped to 2.9 % in SolWat C. Multicrystalline SolWat systems received 2.9 % less solar radiation, while no I_{SC} losses were observed in thin film modules vs. the reference panel. The photovoltaic technologies used in this study are based on silicon solar cells, whose spectral response (or EQE) absorbs mainly visible + near infrared (NIR) radiation. Borosilicate (2 mm thickness) and Milli-Q water transmittance is high in those wavelengths, but they cause light that is reaching the solar cells is mainly diffuse. The average wavelength in diffuse radiation is shorter than of direct light. A-Si thin film silicon solar cells have narrow spectral response peaking at short wavelengths. Thus, the efficiency of thin film amorphous silicon modules is therefore better under diffuse conditions, than monocrystalline and multicrystalline technologies.

Wang *et al.*, (2014) [22] showed I_{SC} data for a SolWat system made of monocrystalline technology which was filled with deionized water. This hybrid system consisted of 25 mm of water layer and a borosilicate cover of 3.2 mm thickness. The I_{SC} received by the SolWat system was 16 % lower than the reference system after 4 h of sun exposure. Vivar *et al.*, 2020 [7] testing natural water sources (turbidity levels ranging from 2.5 to 5 NTU) in a monocrystalline SolWat system with the same structural characteristics of our hybrid systems (18 mm water layer and 2 mm borosilicate glass), reported an average I_{SC} losses of 11 % (maximum of 13 %) after 3 hours of sun exposure. Pichel et al., 2018 [10] using the same SolWat reactors and testing river water with maximum turbidity levels of 2.5 NTU indicated 6 % I_{SC} losses (6-h sun exposure). This is in agreement with our results where average I_{SC} losses were of 9 % when testing monocrystalline SolWat systems with a maximum of 16.7 %. I_{SC} losses of 5 % were reported when working with CIGS (Copper-Indium-Gallium-Selenide Sulphide) thin film technology, 18 mm water thickness and 2 mm of borosilicate glass vs. its I_{SC} at STC [9]. In our study no I_{SC} losses vs. STC conditions were observed for a-Si thin film modules. A maximum of 10.5 % I_{SC} losses were observed vs. a single panel acting as reference in a partially cloudy day. On the other hand, monocrystalline SolWat energy output was reported to be 5.6 % - 10.3 % [7] and 3.8 % - 4.6 % [10] lower than a reference PV module. Our results showed 2.8 % losses vs. the reference system, but as reported by Pichel et al., 2018 [10], the efficiency of the SolWat panel at STC was also lower (3.9 %). The same trend was observed in thin film systems. However, in multicrystalline technology working with two panels (reference and SolWat) of same efficiency (7.5 %), after 6-h of sun exposure the energy produced by the module integrated into the hybrid system was the same (test #3) or even higher (7.3 % higher in tests #6) than the energy produced by the single panel.

The cooling effect of the water chamber on top of the PV module was reported to reduce, on average, the working module temperature from 8.0 to 9.0 ºC at 6-h HRT, value that raised up to 11.3 ºC at 3-h HRT [7, 9, 10]. The maximum difference vs. a single panel was reported to occur at the beginning of the treatment process and it was about 20.0 ºC. However, it progressively decreased as the water heated up. In our work, module temperature was on average 7.5 ºC (monocrystalline), 6.9 ºC (multicrystalline), and 4.7 ºC (thin film) lower than the reference system for 6-h HRT, and it was lower at shorter HRT. Thin film modules worked 4.7 ºC, 6.3 ºC and 8.5 ºC lower than the reference module at 6-h, 3-h and 2-h HRT, respectively. However, this trend was not observed in monocrystalline and multicrystalline tests. In monocrystalline tests #1 and #2 SolWat C (2-h HRT) presented higher temperatures than SolWat B (3-h HRT), while in multicrystalline test #3, the module temperature of SolWat A (6-h HRT) was slightly higher than the single panel acting as reference. Previous works [8 - 10] showed that the refrigeration effect of the water reactor compensated the lower received irradiance by the module integrated into SolWat, getting both single and SolWat panels the same electrical losses after 6-h of sun exposure, and thus indicating that the water disinfection did not affect the final energy output produced by the SolWat system. From test #2 and test #6 it was observed that electrical losses were the same for the SolWat system and the reference module in monocrystalline and multicrystalline technologies after 6-h of sun exposure (6-h HRT). However, lower HRT did not necessarily mean lower module temperature and thus lower electrical losses vs. a single panel. On the contrary, when working with thin film technology, shorter HRT always corresponded with lower working module temperature and lower electrical losses vs. STC. Thus, the thin film PV module actually benefits from the cooling effect of water on its front surface, while this benefit is not clear in monocrystalline and multicrystalline technologies.

Regarding the water disinfection process, water temperature plays a key role since it triggers both synergetic and antagonistic effects on UV disinfection. A strong synergetic effect has been observed when water temperature exceeds 45 ºC [23-26], while temperatures between 20 - 40 ºC were reported to enhance bacteria growth hindering the disinfection process [25, 27]. In the set of tests performed, average water temperature always exceeded the 45 ºC threshold. However, thin film SolWat systems presented the highest temperatures when comparing with the ambient temperature of the experimental day, probably because of its black surface that could enhance the absorption of far infrared light and heat by the water disinfection reactor. This is in agreement with our previous works [6-10], where average water temperature always exceeded the 45 ºC threshold, with the exception of tests performed in autumn and winter with average ambient temperatures below 18 ºC.

4. Conclusion

The SolWat system was tested in order to assess the effect of different hydraulic retention times (6, 3 and 2 hours) on the electrical performance of the PV panel integrated into it; and to compare the electrical performance of the hybrid system regarding three different photovoltaic technologies (monocrystalline, multicrystalline and thin film).

No clear benefits were observed from the water disinfection reactor and reduced hydraulic retention times on the electrical performance of both monocrystalline and multicrystalline technologies. In monocrystalline systems, the electrical losses were minimum for the single panel acting as reference (without the water chamber on top) and maximum for the SolWat system with the shorter HRT (2-h), despite it worked at lower temperatures. The same trend was observed in monocrystalline technology, where energy losses were maximum for the hybrid system presenting the lower module temperature; and shorter HRT did not correspond with lower module temperatures. This indicated a strong negative effect of the lower received irradiance as consequence of the absorption and scattering effects of the solar radiation by the water reactor (lower current, I), that could not be compensated by the positive effect of working at lower temperatures (higher voltage, V).

The set of tests performed demonstrated that the thin film PV technology is the most suitable to be integrated into the SolWat system since: 1) the working module temperature was always lower when HRT was shorter; 2) its electrical performance (final energy output) benefited from the cooling effect of water on its from surface being able to produce even more energy than a single panel when working at shorter HRT; 3) its efficiency under the diffuse light conditions created by the water chamber was better than monocrystalline and multicrystalline technologies; and 4) its black surface enhance the absorption of far infrared light and heat by the water disinfection reactor favouring higher water temperatures and thus higher disinfection rates than monocrystalline and multicrystalline panels.

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