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Open SolWat System with Cooling of the Secondary Wastewater Effluent from a WWTP on the Front Surface of the Photovoltaic Module for efficient Energy Generation and Reclaimed Water Production †

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Abstract: Energy consumption in wastewater treatment plants (WWTP) is a critical part of their operation and maintenance costs, with tertiary treatments being one of the most energy demanding stages, although as they are not required by law, they are not usually included in the wastewater treatment line. In this research, a photochemical–photovoltaic hybrid system was developed and studied: Open SolWat, which allows solar disinfection of the water while cooling the temperatures on the front surface of the photovoltaic module by means of a thin layer of water flowing from the top, thanks to a pumping system. In comparison to the SolWat technologies studied so far, the improved system allowed better quality reclaimed water (RD1620/2007, R(EU)2020/741) to be obtained from the secondary effluent of a WWTP, with the simultaneous generation of energy. However, this time it also productively improved its energy efficiency (15–21%). The tests were carried out under a 4 h SODIS treatment with real sunlight. Therefore, the possible implementation of the system as a tertiary treatment of a WWTP is considered, as it could improve environmental sustainability and reduce energy consumption.

Keywords: solar energy; photovoltaics; active water cooling; reclaimed water

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1. Introduction

Solar energy is a renewable energy source capable of addressing environmental concerns and concerns about energy sustainability. The best known and most widely used technology in renewable energy generation is the use of photovoltaic (PV) modules that convert solar energy into electrical energy through photovoltaic cells. Admittedly, much of the solar energy absorbed by PV cells causes an increase in the temperature of the PV module, which causes a reduction in power output and energy efficiency, and negatively affects its performance and lifetime [1]. In addition, the most common climatic factors that influence the conversion efficiency of PV modules are solar radiation [2], ambient temperature and module surface temperature [1], relative humidity, wind speed and accumulated dust or shading problems on the module surface [3].

In recent years, researchers have conducted many reviews and comparative analyses on various proposed cooling techniques [4,5], of which water cooling systems stand out as a good solution to improve electrical efficiency and decrease the degradation rate of PV cells. On the other hand, Vivar et al., 2010 [6], proposed a novel technology called SolWat, which was later proposed [7,8] to improve environmental sustainability (scarcity, water stress and deterioration of water quality) and reduce the energy consumption of a wastewater treatment plant (WWTP) by implementing this technology as a tertiary treatment. This proposal would be very beneficial since energy consumption in the WWTP is a critical part of its operation and maintenance costs, especially for tertiary treatments that require high energy consumption, although as they are not required by law, they are not usually included in the wastewater treatment line. In view of these problems, possible solutions can be found in the use of renewable treatment plants [9,10] (to obtain energy) that also allow water to be reused.

The results obtained by Vivar et al., 2021 [7], and Torres et al., 2022 [8], managed to obtain reclaimed water from the secondary effluent of wastewater from a WWTP, after SODIS disinfection treatment [11] under real sunlight for 4 h, and to produce energy simultaneously. Now, this study proposes a new design in SolWat technology, the Open SolWat system. Following the objectives already proposed in previous research, this work aims to: (a) improve the final quality of reclaimed water for reuse and for final discharge to the environment; and (b) obtain energy, but this time the new prototype will significantly increase the energy efficiency in the SolWat PV module by means of a cooling system based on a thin film of water on the front surface of the module.

2. Materials and Methods

The SolWat technology is based on a solar–photovoltaic hybrid system (water disinfection reactor coupled to a photovoltaic module) that uses only solar energy to purify water and generate electricity. This technology receives solar radiation and uses its broad electromagnetic spectrum for (1) water disinfection thanks to the germicidal effect of ultraviolet (UV) radiation and the thermal effect of far infrared radiation (FIR) that drastically reduce the amount of pathogenic microorganisms present in the water, and (2) electricity production thanks to the visible (VIS) and near infrared (NIR) radiation reaching the photovoltaic module.

The new prototype is called the "Open SolWat system" (Figure 1) and has a dynamic operation mode (with water recirculation). The system consists of a PV module through which a thin water film (1 mm) circulates, allowing cooling of the PV module and solar disinfection of the water, from the top of the module until it is collected in an open water tank, which is exposed to solar radiation and therefore also acts as a solar water disinfection reactor. A reference PV module was also used experimentally as a control system.

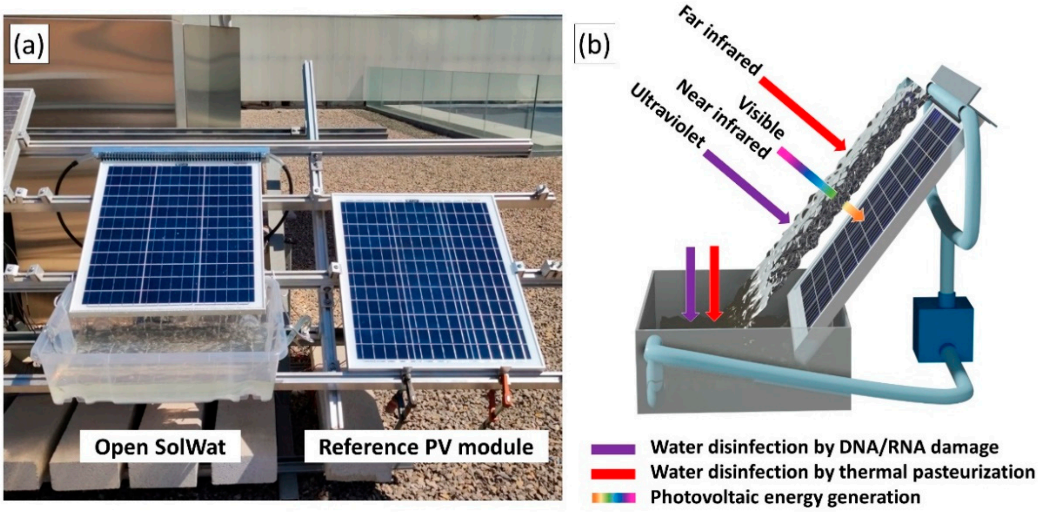

Figure 1. (**a**) Open SolWat system and reference photovoltaic module. (**b**) Use of the electromagnetic spectrum in Open SolWat.

The PV modules were polycrystalline silicon cells (PV LOGIC, Bredon, UK) consisting of 36 solar cells connected in series with dimensions of 634 × 535 × 25 mm (0.251 m^2 cell area) and a nominal power of 45 Wp. This prototype has two water reactors: (a) a reactor formed only by an L-shaped aluminium profile at the top of the photovoltaic module, where the perforated pipe with 53 water outlet microtubes (3 mm water inlet and 2 mm water outlet) with a separation of 1 cm between them is attached; and (b) the open and translucent water tank (62 × 45 × 18 cm). Water recirculation in the SolWat was performed by a pumping system, with a Xylem Flojet magnetic coupling water pump (NDP14/2, supply voltage: 230 V, input power: 10 W) through a set of pipes that propelled the water sample from the open water tank to the SolWat, with an average flow rate of 8.9 L/min. The water pump was primed with 200 mL of the experimental sample. Experimental tests with 4.2 and 6.2 L volumes were carried out with wastewater and purified and ultrapure (Milli-Q) water samples to study the influence of water flow and turbidity on PV performance. The homogenisation of the samples was achieved thanks to the drop of the water sheet into the open tank and the water pipe with 7 orifices distributed inside the tank.

Experimental Set-Up

Six experiments were carried out during the spring and summer of 2022, on the rooftop facilities of the E.P.S. de Linares (Spain), at the University of Jaén. Linares has a temperate climate. The tests were carried out outdoors, under sunny weather conditions.

The Linares WWTP provided the wastewater samples of the wastewater effluent obtained directly after secondary treatment in different seasons of the year and with varying microbiological loads. The experiments always started around 11:00–12:00 p.m. local time (2–3 h before solar noon). The total exposure of the water samples was carried out under sunlight (SODIS treatment) for 4 h, as this provided an adequate treatment that could be carried out during 3 shifts over the course of a day. Microbiological analyses of the initial raw water and after 4 h of SODIS treatment were performed, which included *E. coli*, *E. faecalis* and *C. perfringens* (including spores) as microbiological indicators, to assess the microbiological quality of the water according to Spanish Royal Decree 1620/2007 and Regulation (EU) 2020/741 for water reuse. Similarly, the basic physicochemical parameters of the water samples were analysed. The climatic conditions were monitored and the electrical parameters of this experiment were measured in the same way and under the same methodology previously explained in Vivar et al. (2021) [7] as a first stage of research to obtain reclaimed water and simultaneous energy production.

3. Results and Discussion

Table 1 shows the results obtained from the meteorological conditions in Open SolWat, together with the temperature of the water sample, the initial and final sample volumes obtained, the evaporation percentage and the leakage of the water sheet after 4 h of SODIS treatment.

Water temperature is one of the most important parameters of water quality, as it affects water chemistry and the functions of water microorganisms. The water samples used showed increases between 8.1–10.7 °C, during the experimental tests, in their temperature, influenced by: solar radiation, ambient temperature, heat transfer of the SolWat PV module and the volumes used experimentally (4.2 and 6.2 L). The water losses were mainly due to the evaporation of the water sample (with full exposure to the environment during the experimental treatment), which was related to the heat loss in the PV module cooling, and to the leakage of the water sheet in the PV module, which reached 37.1–52.4%. These water losses varied with the solar intensity, PV module temperature, water sample temperature and water volume used. On the other hand, the turbidity of the water samples (experimental studies carried out with wastewater and Milli-Q) and the thin water film did not show significant evidence with regards to the final energy production.

Under similar experimental conditions, it was observed that, when using a larger sample volume, bacterial inactivation became slightly more difficult. At no time was total bacterial inactivation (*E. coli*, *E. faecalis* or *C. perfringens*) achieved in the treated water samples, but optimal disinfection results were obtained for *E. coli* (99.79–99.98%) and *E. faecalis* (92.65–97.75%), as shown in Figure 2. *C. perfringens* was shown to be the most resistant of the bacteria tested, with low inactivation percentages.

Table 1. Volumes of the water samples, evaporation and leakage volume percentage, climatic conditions and water temperature during the experimental tests, 4 h under sun exposure, in the Open SolWat systems. Avg.: average, Max.: maximum.

Date/Parameter	Water Sample	Initial Volume (L)	Final Volume (L)	Evaporation Volume and Leaks (%)	Solar Global Irradiance (W/m^2)		UV Irradiance (W/m^2)		UV Radiation dose		T_{Water} (°C)		$T_{Ambient}$ (°C)		Wind Speed (m/s)		Relative Humidity (%)	
					Max.	Avg.	Max.	Avg.	(Wh/m^2)	(kJ/m^2)	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.
9 May 2022	Wastewater	4.2	2.4	43.8	1036	944	50.3	45.3	89.81	323.30	32.7	29.7	32.9	29.4	9.4	4.2	38.5	27.5
10 May 2022		6.2	3.8	38.7	1036	930	50.4	44.8	89.95	323.81	38.5	35.7	32.4	29.2	11.0	5.0	36.9	27.7
3 June 2022	Milli-Q	4.2	2.3	45.2	1021	939	51.3	47.0	94.41	339.87	27.1	25.0	28.5	25.8	10.9	5.7	58.3	43.7
7 June 2022		6.2	3.7	40.3	1007	930	50.0	46.1	92.67	333.61	32.7	30.3	37.3	34.3	10.3	4.6	18.7	14.6
7 July 2022	Wastewater	4.2	2.0	52.4	1106	907	50.2	44.1	88.49	318.56	36.9	33.4	40.7	36.4	8.9	4.2	37.3	26.5
8 July 2022		6.2	3.9	37.1	1002	942	48.7	45.2	90.80	326.87	35.7	33.6	40.5	37.0	9.0	4.8	32.7	19.8

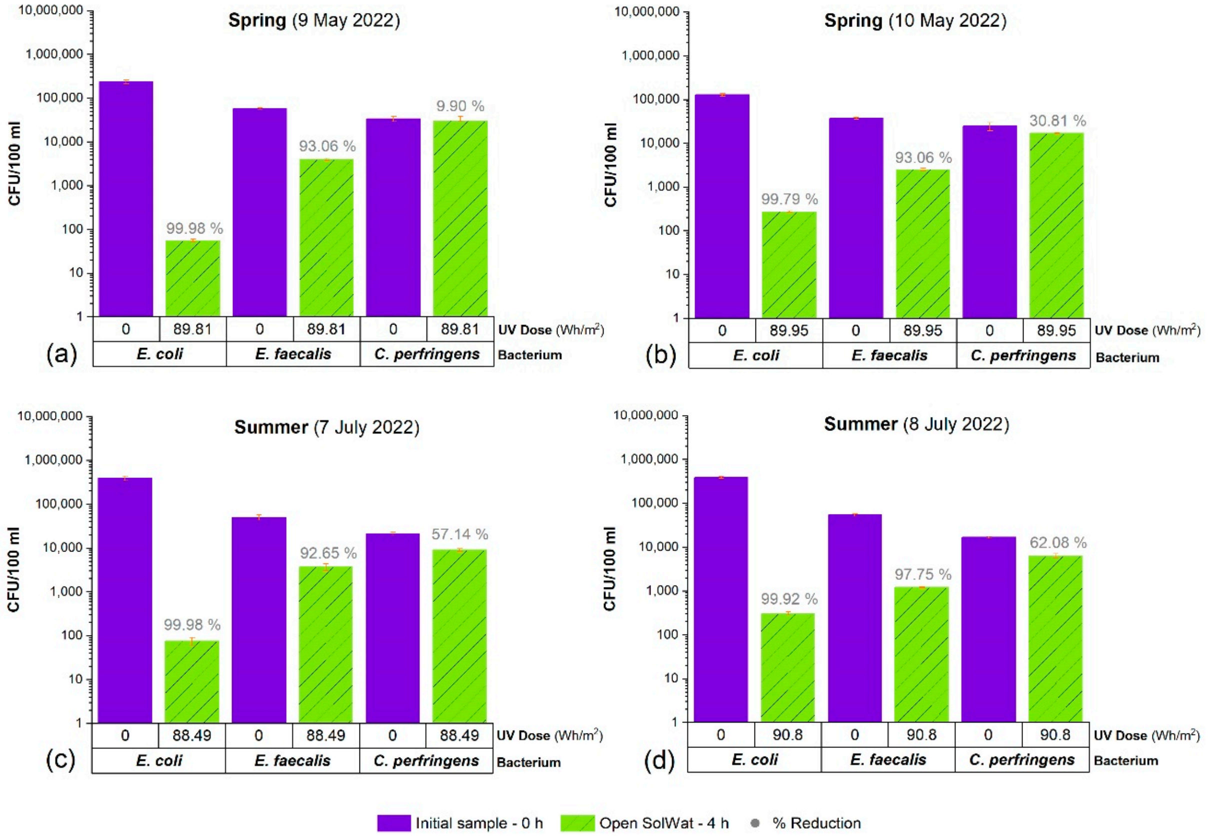

Figure 2. Concentration of *E. coli*, *E. faecalis* and *C. perfringens* in the experimental water samples vs. UV dose for the Open SolWat. Tests carried out in spring, (**a**) 9 May 2022 and (**b**) 10 May 2022, and in summer, (**c**) 7 July 2022 and (**d**) 8 July 2022.

However, due to the exposure of the water sample to the environment there was a tendency for certain physicochemical parameters to increase in concentration as a consequence of climatic conditions and water losses during the SODIS treatment. Moreover, together with the incorporation of other particles in suspension in the water sample, this caused an increase in the most important parameters, turbidity and TSS, which were detrimental to the possible uses for reclaimed water according to Spanish and European regulations. Even so, this problem could be solved with the use of filters in the system, which could also help in the microbiological disinfection of the experimental water. The quality of the reclaimed water obtained during the experimental tests was good and covered the possible uses shown in Table 2.

Table 2. Summary of the possible uses of the reclaimed water obtained experimentally thanks to the Open SolWat, according to the maximum admissible values (bacteriological and physicochemical limits (TSS, turbidity, BOD_5 and other established criteria) established in RD 1620/2007 [12] and in RD (EU) 2020/741 [13].

	Use/Experiment		***E. coli*** **(CFU/100 mL)**	**TSS (mg/L)**	**Turbidity (NTU)**	**Other Criteria**	**Open SolWat (4 h)**			
							9 May 2022	**10 May 2022**	**7 July 2022**	**8 July 2022**
RD 1620/2007	Urban	Quality 1.2: SERVICES (a), (b), (c), (d) Quality type: B	≤200	20	10	***	** Turbidity = 14.4 UNT		** Turbidity = 27.17 NTU	
	Agricultural	Quality 2.1: (a) Quality type: B	≤100	20	10	***	** Turbidity = 14.4 UNT, ** Cr > 0.1 mg/L	** Cr > 0.1 mg/L	** Turbidity= 27.17 NTU	✔
		Quality 2.2: (a), (b), (c) Quality type: C	≤1000	35	*	***	** Cr > 0.1 mg/L	** Cr > 0.1 mg/L	✔	✔
		Quality 2.3: (a), (b), (c) Quality type: D	≤10,000	35	*		** Cr > 0.1 mg/L	** Cr > 0.1 mg/L	✔	✔
	Industrial	Quality 3.1: (a), (b) Quality type: C	≤10,000	35	15	***	✔	✔	** Turbidity = 27.17 NTU	✔
		Quality 3.1: (c) Quality type: C	≤1000	35	*		✔	✔	✔	✔
	Recreational	Quality 4.1: (a) Quality type: B	≤200	20	10		** Turbidity = 14.4 UNT		** Turbidity = 27.17 NTU	
		Quality 4.2: (a) Quality type: D	≤10,000	35	*	*** P_{total}: 2 mg P/L (in standing water)	** $P_{total} > 2$ mg/L	✔	** $P_{total} > 2$ mg/L	** $P_{total} > 2$ mg/L
	Environmental	Quality 5.1: (a) Quality type: C	≤1000	35	*	N_{total}: 10 mg N/L, NO_3^-: 25 mg NO_3/L. Art. 257 to 259 of RD 849/1986.	✔	✔	✔	✔
		Quality 5.3: (a), (b) Quality type: E	*	35	*	***	✔	✔	✔	✔
		Quality 5.4: (a) Quality type: F	The minimum quality required will be studied on a case by case basis.				✔	✔	✔	✔
R(EU)2020/741	Agricultural	Quality type: B	≤100	In accordance with Directive 91/271/EEC. ≤35 mg/L	*	BOD_5 (mg/L): In accordance with Directive 91/271/EEC, ≤25 mg/L O_2	✔		✔	
		Quality type: C	≤1000		*		✔	✔	✔	
		Quality type: D	≤10,000		*		✔	✔	✔	✔

* No limit is set. ** The problem must be solved for the possible use of reclaimed water. *** OTHER POLLUTANTS (Annex II of RD 849/1986 of 11 April) contained in the wastewater discharge authorization → limit entry into the environment. In the case of dangerous substances (Annex IV of RD 907/2007, of 6 July), respect for the NCA must be ensured [12].

Table 3 shows the electrical results from Open SolWat and the reference photovoltaic module, after 4 h of solar exposure. Open SolWat allowed the front surface of the SolWat photovoltaic module to be cooled by a thin sheet of water that constantly flowed from the top of the module, thanks to a pumping system. The influence of the water cooling and the effect of the evaporation of the water sample allowed the high temperatures reached in the PV module during the spring and summer tests to be reduced, with a decrease of 16.2–30.6 °C with respect to the reference photovoltaic module, which resulted in increased electrical performance. As a consequence, energy efficiency was simply and effectively improved by 15–21%, which at the same time guarantees a longer service life. Thus, the system managed to generate an average of 18.6 ± 1.8% more energy compared to the individual photovoltaic module in the experimental studies. In addition, cooling with water allowed cleaning of the module surface.

Table 3. Main electrical results obtained from the photovoltaic module integrated in the Open SolWat system and the reference photovoltaic module, after 4 h of experimental treatment under real sun, on the roof of the E.P.S. of Linares. Avg.: average, Max.: maximum.

Experiment/Date			**9 May 2022**	**10 May 2022**	**3 June 2022**	**7 June 2022**	**7 July 2022**	**8 July 2022**
Global irradiance (W/m^2)		Max.	1036	1036	1021	1007	1106	1002
		Avg.	944	930	939	930	907	942
Ambient temperature (°C)		Max.	32.88	32.44	28.54	34.33	40.68	40.54
		Avg.	29.39	29.22	25.75	37.28	36.41	36.97
Generated energy (Wh)		Single PV module	132.99	132.82	138.62	131.14	125.42	130.55
		Open SolWat	157.75	156.60	160.17	155.76	151.25	157.12
SolWat energy losses vs. the single PV system (%)		Open SolWat Energy/Single PV Energy	−18.62	−17.90	−15.55	−18.77	−20.58	−20.35
PV module temperature (°C)	Single PV module	Max.	68.9	67.9	53.8	71.8	73.8	70.8
		Avg.	61.3	59.8	46.2	64.7	63.3	66.1
	Open SolWat	Max.	39.4	38.5	30.0	38.1	43.0	41.0
		Avg.	36.2	35.7	32.6	35.6	38.6	38.9
Temperature difference between the SolWat PV module and the Single PV module—($T_{SolWat} - T_{Single}$) (°C) Average			−25.1	−24.1	−16.2	−30.6	−27.1	−28.2
I_{SC} (A)	Single PV module	Max.	2.604	2.605	2.528	2.529	2.781	2.504
		Avg.	2.350	2.325	2.315	2.327	2.246	2.358
	Open SolWat	Max.	2.650	2.649	2.586	2.570	2.884	2.586
		Avg.	2.389	2.369	2.372	2.368	2.337	2.437
Equivalent to radiation losses (%)		I_{SC} Open SolWat/I_{SC} Single, Avg	−1.65	−1.89	−2.44	−1.73	−4.07	−3.35

4. Conclusions

A hybrid system, Open SolWat, was developed that uses only solar energy to purify water and generate electricity. The system consists of a PV module through which a thin film of water (1 mm) circulates, allowing cooling of the module and solar disinfection of the water, from the top of the module until it is collected in an open water tank, which is exposed to solar radiation and thus also acts as a solar water disinfection reactor. The experiments took place in spring and summer during sunny days, on the rooftop at the E.P.S. of Linares (Jaén, España), with a duration of 4 h under real sunshine. Water samples from the secondary effluent of a WWTP were used. In comparison to the SolWat technologies studied so far, Open SolWat was able to obtain better quality reclaimed water and generate energy simultaneously, but this time it also productively improved its energy efficiency (15–21%). Finally, this technology showed a potential that should be studied in more detail to fulfil the final objective of being implemented as s tertiary treatment in a WWTP (the system would have water availability, and three batches per day of 4 h each could be carried out in sunny conditions), with the use of larger photovoltaic modules and solving the problems mentioned above. With the use of energy-efficient pumps and thanks to the electrical energy generated in the prototype, the energy obtained would be able to be used for the consumption of the pumping system and for other energy costs in a WWTP facility. Furthermore, other parameters stipulated in the Spanish regulations for the use of reclaimed water (e.g., intestinal nematodes, *Salmonella* and *Legionella*) that have not been taken into account in this study should be analysed.

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