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Performance analysis of a solar photovoltaic hybrid system for electricity generation and simultaneous water disinfection of wild bacteria strains

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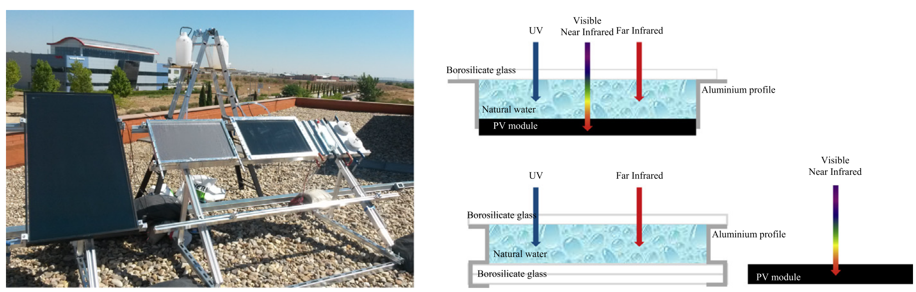
HIGHLIGHTS

- A new hybrid solar water disinfection and energy generation system was designed and tested.
- SOLWAT comprises a water disinfection reactor and a PV module fully integrated into a single unit.
- Natural water with wild strains of *E. coli*, *Enterococcus* spp. and *C. perfringens* were studied.
- The water disinfection reactor located above the PV module did not affect the final energy output.
- The SOLWAT disinfection results were always higher than conventional PET bottles.

GRAPHICAL ABSTRACT



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ABSTRACT

A hybrid solar water disinfection and energy generation system for meeting the needs of safe drinking water and electricity was designed and tested in Alcalá de Henares (Spain) under summer climatic conditions to demonstrate the feasibility of the concept. Natural water sources with wild strains of *Escherichia coli*, total coliforms, *Enterococcus* spp. and *Clostridium perfringens* (including spores) were studied. Results showed that SOLWAT disinfection efficiency was higher than conventional PET bottles and that the water disinfection reactor located above the PV module did not affect the total energy output produced by the hybrid system in comparison to the single PV module, achieving the same power losses over the 6 h of sun exposure in relation to their power at standard test conditions (STC).

1. Introduction

The lack of access to safe drinking water and energy is one of the main challenges of the 21st century. Globally, at least 1.8 billion people use a drinking water source contaminated with faeces, which is the cause of more than half-million diarrhoeal deaths each year [1]; and 1.1 billion people still do not have access to electricity [2]. In an effort to develop new technologies that contribute to palliate this situation, a solar water disinfection system combined with photovoltaic (PV) technology [3] has been proposed as one of the most appropriate technologies for integrating water purification and energy generation functions in a single device that is simple, cost-effective and easy to operate and maintain.

Hybrid devices combining photovoltaic energy and different water applications have been previously investigated as a solution

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to reduce the energy demand of water treatment systems [4,5] and also as a promising option to increase the total efficiency of PV systems by reducing the solar cell operating temperature or by combining thermal and photovoltaic production [6,7], the so-called photovoltaic-thermal hybrid systems (PVT).

PVT systems consist of a hybridisation of photovoltaic and solar thermal systems which produce both electricity and heat for hot water domestic applications from one integrated component [8], and were developed to diversify and decarbonise the energy supply, lowering the reliance on fossil fuels. More recently, Herrando et al. [9] and Herrando and Markides [10] studied the feasibility of this system for the provision on electricity and hot water at household levels in UK, while Romero-Rodrígez et al. [11] developed a study assessing the performance of several designs of this technology in Spain.

Another type of hybrid system combining photovoltaics and water applications based on photochemistry was developed by Zamfirescu and Dincer [12]. It consisted of a solar energy system for hydrogen and sulphur production from sulphurous water specific to chemical and petrochemical industries, where high energy spectrum (<500 nm) was used to generate hydrogen from water photolysis, and the middle spectrum (500–800 nm) and the long wave spectrum (>800 nm) were used to generate electricity from photovoltaic which was also used to generate additional hydrogen by electrolysis. Huang et al. [13] reported a photochemical-photovoltaic hybrid device that generates hydrogen and oxygen from water in sulphuric acid solution by electrolysis using the electricity generated from PV cells, and Oruc et al. [14] also proposed a photovoltaic system that integrates a PV module with an electrolyzer, referred to as a photovoltaic thermal water electrolyzer (PTVE), where the electrolyte reduced the PV module temperature increasing the electrical efficiency and the heat absorbed by he electrolyte was used to enhance the electrolytic process leading to more efficient production of hydrogen.

The previous hybrid photochemical/thermal/photovoltaic systems are focused on extracting some elements (hydrogen, sulphur or oxygen) from water using solar energy (PV-photochemical) or on producing electricity and hot water simultaneously (PV-thermal), but water was not subjected under any treatment with the objective to produce safe drinking water.

On the other hand, hybrid devices that integrate photocatalysis reactors and photovoltaic modules have been recently investigated for the field of water purification. Vivar et al. [3] developed a physicochemical water treatment combining a water purification reactor and PV technology, which was after tested at lab-scale conditions [15–18]. However, microbiological water disinfection was not tested using this system, either using other types of hybrid devices that combine PV energy generation and water disinfection.

The hybrid solar water purification and photovoltaic system (SOLWAT) comprises two devices, a water disinfection reactor and a PV module, fully integrated into a single unit which uses the solar spectrum more efficiently (Fig. 1), combining the germicidal effects of UV light and the thermal pasteurization effects of far infrared light for bacterial disinfection purposes; and the visible and near infrared light for solar photovoltaic electricity generation. The benefits provided also include the no dependence on electrical energy or chemical components, the use and generation of renewable energy and no residues generation, plus the compact and long lasting system characteristics with a simple and low cost design.

This concept was previously used for water treatment applications, specifically for photocatalytic degradation (with suspended TiO_2 as photocatalyst) of organic dyes (Methylene Blue, Acid Red 26 and 4-Chlorophenol) as water pollutant. It was analysed in terms of dye decolourisation and photovoltaic output generation [15–18] showing that both photocatalytic and photovoltaic technologies could work simultaneously producing purified water and electricity. However, this technology has not been used yet for water microbial disinfection applications and this study constitutes the **first SOLWAT utilization for microbial inactivation** purposes.

The SOLWAT system would be especially suitable in developing countries where access to safe drinking water and electricity is limited or not available. Most of these countries are located within a large area called 'sun belt' zone, which covers the majority of the population in need of clean drinking water and electricity and where irradiance conditions are more favourable for the use of this technology, which could be also applied for treating wastewater from industrial effluents and in emergency situations at community levels.

The aim of this paper is to assess the performance of a new SOLWAT system design under real operation conditions using natural water sources, evaluating both the water disinfection efficiency and power output generation.

Results from the comparison between SOLWAT (new hybrid device that integrates a water disinfection reactor and a PV module) and two independent systems, (single water reactor and single PV module, not coupled) are also discussed, analysing for the case of the SOLWAT system: (a) the possible influence of the PV module in the solar disinfection process by affecting the water temperature, and (b) the possible influence of water purification reactor in the solar energy generation by affecting the radiation received and the module temperature. The water disinfection results are also compared with PET bottles, which are currently the traditional and most widespread form of SODIS containers.

2. Design, materials and manufacturing

2.1. Design

A new SOLWAT system was designed to combine the functions of solar water purification and renewable electricity generation in a single and compact device, with the final objective of improving solar spectrum utilization and minimising space requirements. A planar system consisting of two sub-modules was used. The two sub-modules were assembled together, one above the other, where the photovoltaic module serves as the base of the water purification reactor, which is transparent to visible and near infrared component of solar light. Water disinfection occurs between the glass cover of the water purification sub-module and the PV module (Fig. 1a).

A reference system set was also designed with the objective of comparing the SOLWAT water purification performance and electricity generation output in relation to an uncoupled system where the PV module and the water purification reactor were independent units. The water disinfection module was the same size and of identical structural characteristics as the SOLWAT water purification sub-module but with the PV module replaced by two borosilicate glasses with a black sheet between both glasses. The single photovoltaic module was of the same PV technology as the SOLWAT but with different dimensions (Fig. 1b).

2.2. Materials and manufacturing

CIGS (Copper–Indium–Galium–Selenide Sulphide) photovoltaic modules (Würth Solar, Germany) consisting of multi-layered CIGS solar cells connected in series were used. Their costs are lower than other PV modules technologies and their black surface could enhance the solar disinfection process by increasing the water temperature. Two different module dimensions were used, 405×605 mm for the SOLWAT receiver ($0.20\ m^2$ cell area) and 605×1205 mm for the reference system ($0.65\ m^2$ cell area) as an