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Proof of concept of a novel solar photoreactor in real sunlight conditions for the production of solar fuels

Summary

This work presents the design and outdoor validation of a novel solar photoreactor for the production of solar fuels, specifically photoelectrochemical hydrogen (H_2), from (waste) water under real sunlight. A tubular photoreactor integrating $BiVO_4$ photoanodes and oscillatory flow was developed to enhance photon utilization and mass transfer. Outdoor tests under fluctuating irradiance (250–800 W m^{-2}) demonstrated stable performance and a strong linear correlation between H_2 production and solar input, achieving solar-to-hydrogen efficiencies of ~2%. The results highlight the importance of reactor design alongside material development and demonstrate the potential of scalable solar photoreactors for real-world applications.

Keywords: solar fuels, solar photoreactors, photoelectrochemistry, hydrogen production, outdoor operation, photon management, multi-product collectors

Field of application for the findings: Solar fuels production, renewable hydrogen generation, wastewater valorization, sustainable energy systems

Addressed audience: Researchers and engineers in solar energy, photoelectrochemistry, chemical engineering, reactor design, and energy systems integration

1. Introduction

The transition to a sustainable energy system requires technologies capable of converting abundant, low-value molecules such as CO_2, N_2, and H_2O into fuels and chemicals using renewable energy. In this context, solar fuels offer a promising route to store solar energy in chemical bonds. Among the available pathways, direct solar energy conversion via photochemical (PC) and photoelectrochemical (PEC) processes has gained increasing attention in recent years. But, despite significant progress, these systems remain limited by low efficiencies and challenges in coupling light absorption with photocatalytic conversion under realistic operating conditions, particularly under natural sunlight. To date, most reported results are based on small-scale laboratory experiments, with limited focus on solar photoreactor concepts suitable for outdoor operation in full spectral irradiance. At the same time, advanced solar thermal collector technologies provide proven strategies for efficient solar energy capture, optical & heat management, and scalable system design. From this perspective, a major barrier to practical implementation for PC and PEC systems lies not only in the development of photocatalysts that efficiently utilize the solar spectrum while maintaining long-term stability, but also in the design of solar photoreactors that ensure effective photon utilization, optimized mass transfer, heat management and scalability. In this context, the IEA Solar Heating and Cooling Programme Task 72 on solar photoreactors addresses these challenges, with Subtask B specifically focusing on the development and optimization of solar photoreactor designs.

2. Research Objective

The objective of the presented work is the design and experimental validation of a novel solar photoreactor concept integrating a PEC process, which is evaluated under real sunlight conditions. The proposed system exemplarily targets hydrogen (H_2) production from (waste) water, enabling direct solar-to-fuel conversion in an outdoor environment, with the possibility to be transferred to also CO_2 or N_2 reduction.

Although PC and PEC approaches have demonstrated solar-to-hydrogen (STH) efficiencies exceeding 6% (Zhou et al., 2023) and ~19% (Song et al., 2022), respectively, under controlled laboratory conditions, real-world performance remains significantly lower, typically in the range of 1–3% for PC systems and 3–4% for

PEC systems (Tembhurne, Nandjou & Haussener, 2019). This discrepancy is mainly attributed to non-ideal light distribution, insufficient photon utilization, and environmental influences such as spectral variability and temperature fluctuations. Therefore, this work focuses on bridging the gap between laboratory-scale performance and outdoor operation by presenting a novel solar photoreactor design, optimized in artificial light operation and further tested in real sunlight operation.

3. Methodology

A novel tubular flow solar photoreactor (Meitz et al., 2024), integrating a PEC process, was developed and evaluated under both indoor (artificial sunlight) and outdoor (natural sunlight) conditions. For this, a teststand was developed, illustrated in Figure 1. Upscaled $BiVO_4$ electrodes (1 × 11 cm²) were synthesized and integrated into the reactor system, while a platinum counter electrode (1 × 1 cm²) served as the cathode. $BiVO_4$ material was selected due to its ability to absorb visible light. The tubular reactor had a diameter of 24 mm, a length of 170 mm. Indoor, H_2 production experiments were conducted using synthetic wastewater containing glucose and EDTA (ethylenediaminetetraacetic acid) as sacrificial agents at concentrations of 10–1000 mg·L⁻¹. H_2 evolution was continuously monitored via gas chromatography (GC). To enhance mass and energy transfer, the reactor was operated under oscillatory flow conditions, systematically investigated by varying oscillatory Reynolds numbers (250–2600), adjusted via amplitude (2.5–9 mm) and frequency (0.5–2 Hz). Outdoor experiments assessed the system performance under fluctuating solar irradiation and environmental conditions. Solar irradiance was measured using a pyrheliometer. H_2 production rates were recorded over time and normalized to both electrode surface area and incident solar power. Glucose (1000 mg·L⁻¹) was used as a model compound in outdoor experiments due to its superior performance in preliminary indoor studies in artificial light source. The $BiVO_4$-coated photoanode was oriented toward a reflective mirror surface to maximize light absorption.

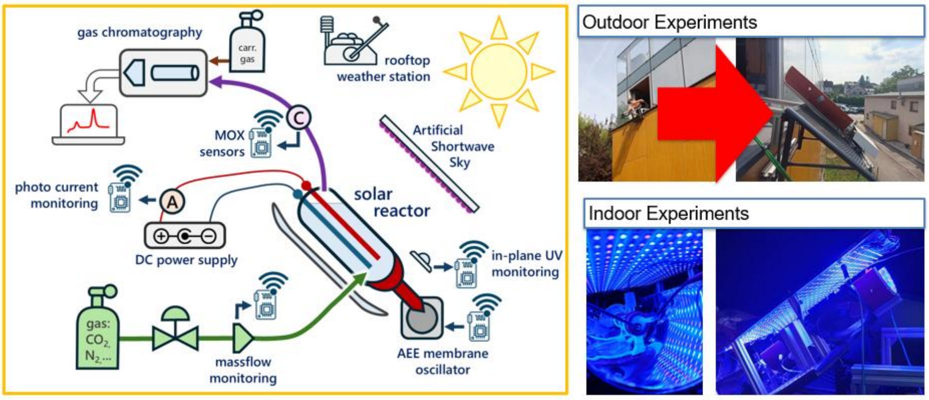

Figure 1: Overview of the teststand available for outdoor testing in real sunlight and indoor testing with "artificial sky" (3070 to 470 nm wavelength testing range)

4. Results

Indoor experiments focused on evaluating the influence of operating parameters on H_2 production, with particular emphasis on optimizing oscillatory flow conditions within the photoreactor. The implementation of oscillatory flow significantly enhanced H_2 yield, resulting in an increase by a factor of 1.5–5 compared to non-oscillating operation. Optimal performance was observed at oscillatory Reynolds numbers between 250 and 750. Based on superior performance in preliminary small-scale experiments, glucose was selected as the model compound (1000 mg·L⁻¹) for outdoor testing of the upscaled $BiVO_4$ photoanode. Experiments were conducted under real sunlight during summer conditions, with solar irradiance ranging from approximately 250 to 800 W m⁻². The temporal evolution of H_2 production closely followed the variation in solar irradiance, demonstrating a strong dependence on incident solar energy. Maximums in both, irradiance and H_2 production were reached showing approximately 0.5 g m⁻² h⁻¹ of H_2 production at irradiance levels of 750–800 W m⁻². Despite continuous fluctuations in solar intensity, the system exhibited stable and robust operation under real outdoor conditions. A strong linear correlation between H_2 production rate and solar irradiance was observed, indicating photon-limited behavior within the investigated range. This confirms the rapid dynamic response of the PEC system to changing solar input. While deviations from linearity may occur at higher irradiance levels (f.i. in high solar concentration factors) due to kinetic or mass transfer limitations, the results demonstrate predictable system performance under the presented solar conditions. Calculated StH ratios, representing the efficiency of converting solar irradiation into H_2 , showing values of around 2%. Furthermore, the experiments indicate good stability of the $BiVO_4$ photoanode under real sunlight operation. Overall, the findings highlight the effectiveness of oscillatory flow in enhancing reactor performance and underline the potential of solar photoreactors for solar H_2 production.

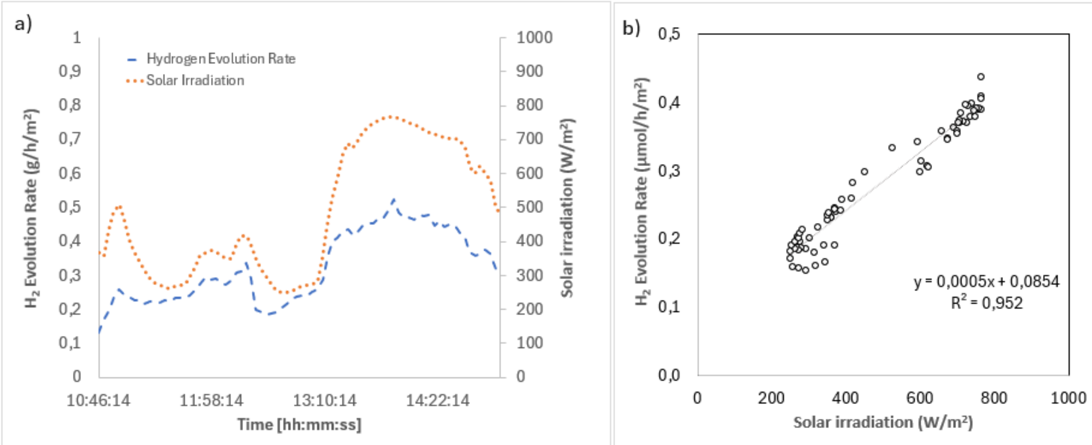

Figure 2: Performance under real sunlight conditions; a) results of H_2 evolution rate (g/h/m^2) and solar irradiation (W/m^2) over experimental time; b) correlation of H_2 evolution rate (g/h/m^2) and solar irradiation (W/m^2)

5. Outlook

The results highlight the strong impact of process intensification strategies and advanced reactor design on improving PEC performance in solar photoreactos. Future work should focus on transferring photoreactor concepts from controlled laboratory environments to real outdoor operation, which requires not only robust reactor engineering but also continued development of efficient and stable photocatalytic materials. Optimized photon management—through improved optical design, reflector integration, and ray-tracing-based simulations—will be essential to maximize solar energy utilization. In addition, multi-product approaches that enable full spectral utilization, from UV to visible and infrared light, represent a promising pathway toward higher overall efficiencies. Such concepts could allow the simultaneous production of electricity, fuels or chemicals, and heat within integrated reactor systems. Given the current limitations in the economic viability of pure PC and PEC systems, these integrative and multifunctional photoreactor designs will be key to enabling scalable and cost-effective solar energy conversion technologies.

6. References

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