OPTICAL ANALYSIS OF A SOLAR POLYGENERATION COLLECTOR FOR COMBINED ELECTRICITY, HEAT, HYDROGEN FUEL AND WASTEWATER TREATMENT

Summary

The growing need for the decarbonisation of industry and the transition to renewable energy calls for more effective utilisation of solar energy than conventional solar technologies. One pathway towards this goal is the implementation of poly-generators: combined units for the generation of electricity, heat, and additional vectors. Herein, we present an analysis of a solar collector that integrates water treatment with heat, electricity, and hydrogen generation. Different parts of the solar spectrum are utilised for different purposes to enhance the total exergy efficiency of the collector. In this study optical performance curves for 3 different configurations are presented, discussed and compared. The tube-array configuration demonstrates nearly the same optical efficiency as the single-channel setup. Both configurations outperform the two-channel configuration. The single-channel configuration is chosen for the further analysis because it is simpler and less prone to numerical instability.

Keywords: PV-T, PV-X, Spectral splitting, Green hydrogen, Photocatalysis, Solar water-treatment,

Field of application for the findings: solar-thermal plants, industry

Addressed audience: industry, academia

1. Introduction

Industrial production processes account for a significant share of energy consumption and environmental pollution in the European Union (EU), including greenhouse gas emissions, air pollutants, wastewater discharges, and waste generation (Procházková et al., 2023). Water plays a critical role across multiple stages of industrial processes, making water and wastewater management essential to operations and highlighting the potential of treated effluent to reduce freshwater demand. However, current wastewater reuse levels remain low in Europe due to regulatory, technological, and economic barriers (Malinauskaite et al., 2024). Aligned with the Paris Agreement goal of limiting global temperature rise to below 2 °C compared to pre-industrial levels, the EU has committed to becoming the first climate-neutral continent by 2050. Through initiatives such as the European Green Deal, the EU is accelerating the deployment of clean energy technologies (Bäckstrand, 2022).

Herein, we present an optical analysis of a polygeneration solar collector for heat, electricity and hydrogen fuel, where the latter is achieved via photocatalytic water treatment. A general schematic of the collector is presented on the left side of Fig. 1. Irradiance is concentrated via a concentrator and split to IR radiation, which is used for heating a heat transfer fluid (HTF); UV radiation, which is used for photocatalytic wastewater remediation, generating hydrogen in the process; and visible and near-IR radiation, which is used for photovoltaic electricity generation. The Solar spectrum and approximate cut-off wavelengths are presented on the right side of Fig. 1. Exact cut-in wavelengths are to be determined as part of the design process, via material selection for various components of the poly-generator.

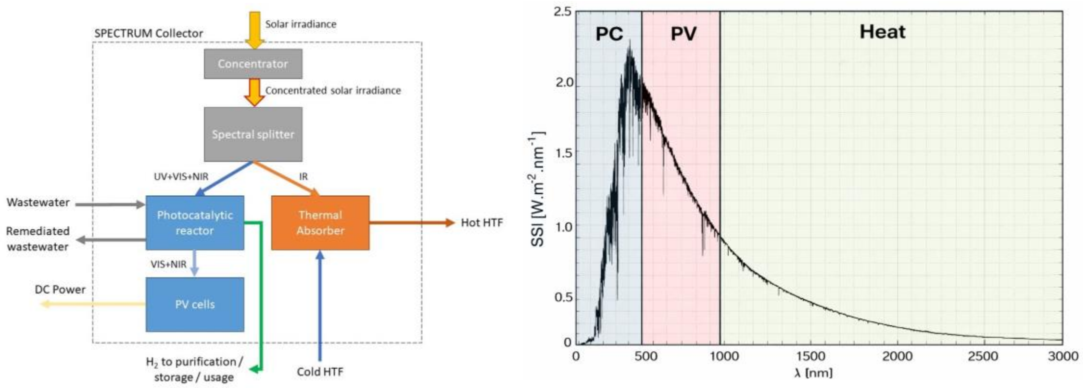

Fig. 1: General schematic of the concept behind this work. Left: process-diagram of the conversion process, including heat, electricity and hydrogen generation, as well as photocatalytic waste-water remediation. Right: The solar spectrum and the different methods used to harness its various regions.

1.1 Collector configuration

The general schematic of the collector is shown in Fig. 2. It includes a glass cover to reduce convective losses, a Solarus solar concentrator to achieve a concentration ratio of 1.3, and a generator apparatus, which is the heart of the system. Three configurations are considered: single-channel configuration, two-channel configuration, and the tube array. The first configuration, known as the single-channel configuration, uses a single filter channel, with the thermal absorber integrated into the PV modules. In this configuration, the cooling channels of the PV modules also serve as the thermal absorber. In contrast, the two-channel configuration includes a separate thermal absorber channel. This allows heating the absorber water for thermal utilisation without heating the PV module, maintaining separate optimal temperatures (one for high-efficiency PV and another for heat utilisation). The third configuration is also single channel, with the absorber integrated into the PV module. However, the filter channel is replaced by the more realistic tube array.

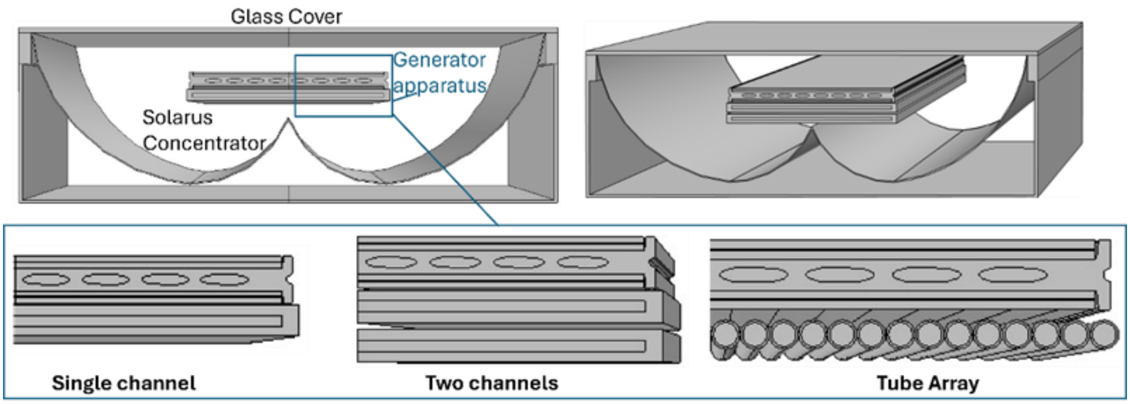

Fig. 2: Detailed description of poly-generator, including a solar concentrator, and a generator apparatus including three configurations: a two-channel configuration with a separate photocatalytic channel and thermal channel, and a single-channel configuration where the thermal channel is integrated within the PV module.

2. Methodology

2.1 Simulation methodology and boundary conditions

The optical model was developed in COMSOL Multiphysics using ray optics module to evaluate the optical performance of polygenerating collector under simplified assumptions, in which solar radiation is modelled as parallel rays and surface roughness and material inhomogeneities are neglected. A parabolic trough concentrator reflects incoming radiation toward the solar cells, enhancing the incident flux, with a constant reflectance of 95%. The reflected radiation then passes through a cover glass and an optical filter, each assumed to have a transmittance of 90% under clean conditions. Only a fraction of the transmitted radiation is converted into electricity, while the remainder is converted into thermal energy. The spatial distribution of the incident flux is determined through optical modelling.

The spectral irradiance reaching the photovoltaic cells is expressed using equation 1:

$$G_{pv}(\lambda) = G_{AM\ 1.5}\ (\lambda)\ \rho_c \tau_g \tau_{fl}\ (\lambda) \quad \text{(eq. 1)}$$

where $G_{AM\ 1.5}\ (\lambda)$ is the incident solar spectral irradiance, ρ_c is the concentrator reflectivity, τ_g is the glass transmittance, and $\tau_{fl}\ (\lambda)$ represents the wavelength-dependent filter transmittance.

3. Result Outline and selected results

Ray trajectories from a typical simulation are presented in Figure 3 (top). To improve visibility, only 300 rays (~10% of the total simulated rays) are presented. As can be seen, the concentrator works well, directing most of the rays towards the generator apparatus. Some rays are deflected by the sides, and others are not reflected due to the imperfect reflectance of the simulator.

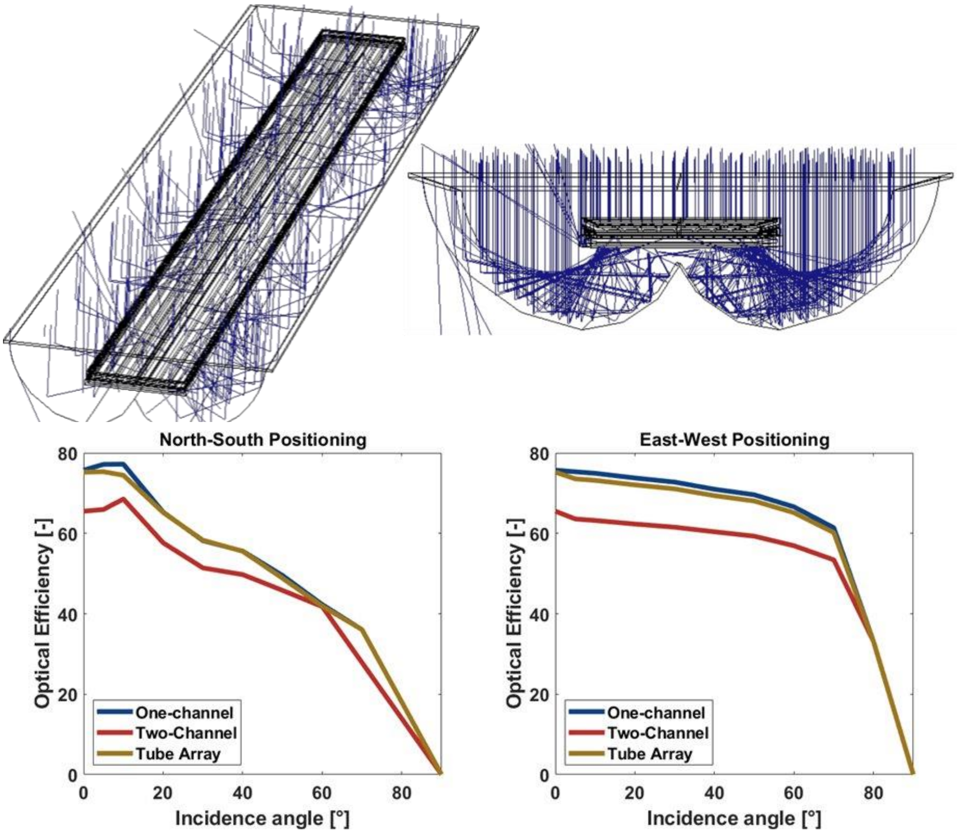

Fig. 3: Selected results: Top: ray distribution following the concentrator. Bottom: optical efficiency of all the configurations as a function of the incidence angle.

For all three configurations, the optical efficiency is between 65-75% for an incidence angle of 0° (vertical incidence) and drops to very low values above 70° (in both positioning). With east-west positioning, optical efficiency remains very stable up to the critical angle, with no significant drop. In the north-south configuration, deterioration is faster, and efficiency drops even at angles as low as 30°. This indicates that the north-south positioning is preferable and that the Solarus collector responds well to variations in angle. In both orientations, there is a significant difference between the two-channel and single-channel configurations in terms of optical efficiency. For example, in the 0° incidence angle, the one-channel configuration achieves >75% efficiency, compared to <65% for the two-channel configuration. This indicates a significant advantage for the single- channel configuration. Furthermore, the optical efficiency of the tube-array configuration is similar to that of the one-channel configuration, with only a small loss in simulation accuracy. Due to its simplicity and reduced tendency toward numerical divergence, the single-channel configuration will be used for thermal analysis.

4. Conclusion

A novel concept for combined generation of electricity, heat, and hydrogen fuel was presented and analysed via a multi-physics simulation approach. Optical efficiency for different configurations and conditions was presented. Additional results, including the radiation distribution, will be presented in more detail.

References

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