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FULL-SPECTRUM SOLAR ENERGY UTILIZATION FOR HIGH-EFFICIENCY HYDROGEN PRODUCTION: A TECHNO-ECONOMIC ANALYSIS

Summary

This work presents a full-spectrum solar energy utilization strategy based on a spectral-splitting photovoltaic–thermal hydrogen (SSPVTH) system. A parabolic concentrator and spectral-selective filter enable simultaneous photovoltaic power generation and high-temperature assistance for a membrane-less electrolyzer. Under AM1.5D conditions, high solar-to-hydrogen (STH) efficiency of 21.1% is achieved through thermal decoupling. Climate-resolved annual simulations using real DNI and temperature data from four regions demonstrate strong geographic adaptability. High-irradiance sites deliver higher hydrogen yield and more competitive levelized cost of hydrogen (LCOH), reaching values as low as 5.6 €/kg, with sun tracking strategy influencing overall performance. The SSPVTH architecture provides a viable pathway for scalable green hydrogen production.

Keywords: solar hydrogen, spectral splitting, photovoltaic–thermal system, levelized cost of hydrogen

Field of application for the findings: Electrical Energy Storage & Hydrogen

Addressed audience: Researchers and engineers in solar energy systems and techno-economic assessment of renewable hydrogen technologies

1. Introduction

Solar hydrogen is widely regarded as a promising pathway toward carbon-neutral energy systems (*Li* et al., 2023). However, conventional photovoltaic–electrolysis (PV–EC) configurations suffer from incomplete spectral utilization, as photons with energies below the photovoltaic (PV) bandgap are dissipated as heat rather than being harnessed for fuel production. This intrinsic limitation restricts the overall solar-to-hydrogen (STH) efficiency and reduces system-level effectiveness (*Holmes-Gentle* et al., 2023).

To address this challenge, a full-spectrum solar energy utilization concept based on a spectral-splitting photovoltaic–thermal hydrogen (SSPVTH) system is investigated. As illustrated in **Fig. 1**, incident sunlight is first collected and concentrated by a parabolic reflector, and the concentrated beam is then directed to a spectral-splitting optical filter. The filter separates the spectrum into two wavelength ranges: short-wavelength photons are transmitted to a GaAs-based photovoltaic–thermal (PVT) receiver to generate electricity with active thermal management, while long-wavelength photons are reflected to a solar thermal absorber to produce high-temperature heat (*Tian* et al., 2025). The harvested thermal energy is subsequently transferred to the electrolyte to enable high-temperature operation of a membrane-less electrolyzer (*Hashemi* et al., 2019), thereby reducing electrolysis losses and enhancing hydrogen production. By combining concentrated PV electricity with spectral-split solar thermal input, the SSPVTH architecture enables simultaneous electrical and thermal contributions to hydrogen generation and provides a pathway toward high-efficiency solar hydrogen production. Beyond device-level efficiency improvements, this study extends the analysis toward climate-dependent annual performance and techno-economic feasibility. The system is evaluated under realistic solar conditions in four representative regions: Karlsruhe (Germany), Barcelona (Spain), Cairo (Egypt), and Dunhuang (China)., and compared under single axis and dual axis tracking strategies. The resulting annual hydrogen production and levelized cost of hydrogen (LCOH) are analyzed to assess both technical and economic viability.

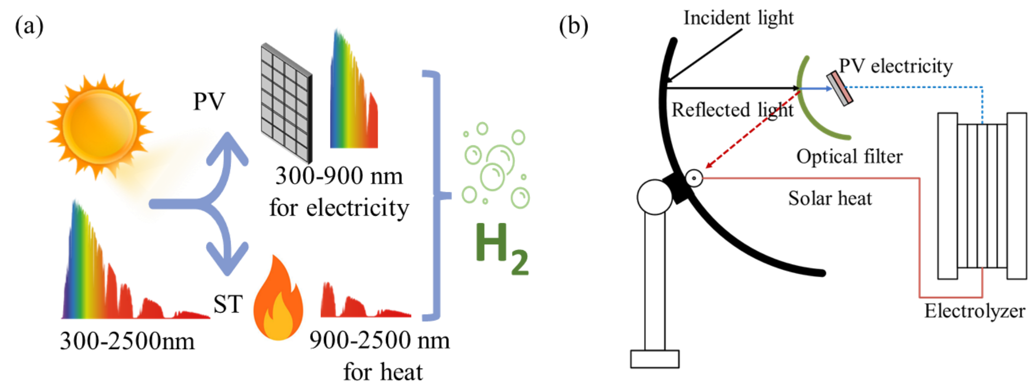

Fig. 1: Concept of full-spectrum solar energy utilization in the SSPVTH system. (a) Spectral-splitting configuration directing short-wavelength photons to photovoltaics and long-wavelength photons to the thermal for high-temperature electrolysis. (b) Integrated SSPVTH system layout.

2. Results and discussion

2.1 SSPVTH system performance

The coupled electro-thermal characteristics of the SSPVTH system are shown in Fig. 2. The results are obtained under standard AM1.5D irradiance conditions. The operating point is determined by the intersection of the PV and electrolyzer I–V curves, as illustrated in **Fig. 2(a)**. Under these conditions, the photovoltaic module operates at a temperature of 56.4 °C, while the electrolyzer reaches a significantly higher working temperature of 179.6 °C.

The pronounced temperature difference demonstrates effective thermal decoupling between the PV and the electrolyzer subsystems. The photovoltaic unit is actively cooled to maintain stable electrical performance, whereas the thermal branch efficiently transfers long-wavelength solar energy to elevate the electrolyte temperature. As a result, spectral splitting enables efficient photovoltaic operation while the elevated electrolyte temperature reduces the required electrolysis voltage, allowing both subsystems to operate close to their respective high-efficiency regimes.

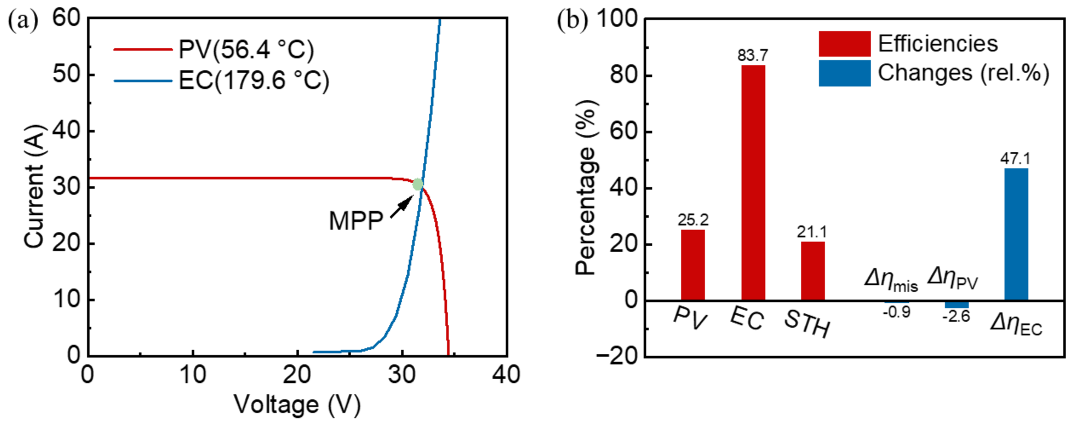

Fig. 2: Electro-thermal coupling characteristics of the SSPVTH system. (a) PV and electrolyzer I–V curves determining the operating point. (b) Efficiency contributions of PV, electrolysis and overall STH performance.

The corresponding efficiency contributions are summarized in **Fig. 2(b)**. Under the adopted control strategy, the mismatch between the PV maximum power point (MPP) and the system working point is minimized, resulting in only a marginal efficiency loss. Meanwhile, the temperature rise of the PV module leads to only a limited reduction in photovoltaic efficiency due to effective cooling and thermal decoupling. In contrast, the elevated electrolyte temperature significantly enhances the electrolysis efficiency, yielding an improvement of approximately 47% compared with operation at near-ambient conditions. As a result of the reduced mismatch losses, controlled PV temperature effects, and substantial electrolysis efficiency gain, the overall solar-to-hydrogen (STH) efficiency reaches 21.1% under standard AM1.5D irradiance.

2.2 Techno-economic assessment of the SSPVTH system

The techno-economic performance of the SSPVTH system is evaluated through climate-resolved annual simulations using real geographical data. Direct normal irradiance (DNI) and ambient temperature data are obtained from the JRC PVGIS database (*European Commission JRC*, 2026). Hourly inputs are applied to simulate annual hydrogen production for Karlsruhe, Barcelona, Cairo and Dunhuang under both single-axis and dual-axis tracking configurations.

Fig. 3(a) presents the normalized annual hydrogen yield. Cairo achieves the highest hydrogen production under both tracking modes due to its abundant DNI and relatively high ambient temperature, while Dunhuang shows similarly strong performance. In contrast, Karlsruhe exhibits the lowest yield owing to reduced solar resources at higher latitude, with Barcelona showing intermediate results. Across all regions, single-axis tracking consistently produces less hydrogen than dual-axis tracking due to azimuthal misalignment losses and reduced effective irradiance.

Economic feasibility is assessed using the LCOH, as shown in **Fig. 3(b)**. Although dual-axis tracking increases capital cost, the higher hydrogen output in high-irradiance regions offsets the additional investment and results in lower LCOH. In moderate solar climates, the economic advantage of dual-axis tracking is less pronounced.

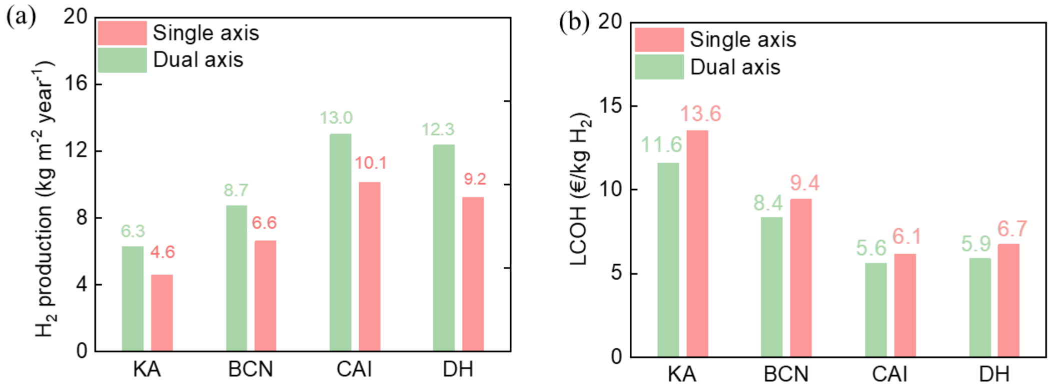

Fig. 3: Climate-dependent annual hydrogen production and economic performance. (a) Annual hydrogen yield across Karlsruhe (KA), Barcelona (BCN), Cairo (CAI) and Dunhuang (DH). (b) LCOH under single axis and dual axis tracking configurations for the four regions.

Overall, the SSPVTH system demonstrates strong adaptability across diverse climatic conditions, maintaining high solar-to-hydrogen STH efficiency while achieving competitive LCOH values. The combined optical–electrical–thermal integration provides a promising pathway for scalable and economically viable green hydrogen production, offering a new system-level option for accelerating renewable hydrogen deployment.

3. References

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